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Recommended nuclear data for medical radioisotope production: diagnostic positron emitters

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Abstract

An IAEA coordinated research project that began in 2012 and ended in 2016 was primarily dedicated to the compilation, evaluation and recommendation of cross-section data for the production of medical radionuclides. One significant part of this work focused on diagnostic positron emitters. These particular studies consist of 69 reactions for direct and indirect or generator production of ^{44}Sc (^{44}Ti), $^{52\text{m}}\text{Mn}$ (^{52}Fe), $^{52\text{g}}\text{Mn}$, ^{55}Co , ^{61}Cu , ^{62}Cu (^{62}Zn), ^{66}Ga , ^{68}Ga (^{68}Ge), ^{72}As (^{72}Se), ^{73}Se , ^{76}Br , ^{82}Rb (^{82}Sr), $^{82\text{m}}\text{Rb}$, ^{86}Y , ^{89}Zr , ^{90}Nb , $^{94\text{m}}\text{Tc}$, $^{110\text{m}}\text{In}$ (^{110}Sn), ^{118}Sb (^{118}Te), ^{120}I , ^{122}I (^{122}Xe), ^{128}Cs (^{128}Ba), and ^{140}Pr (^{140}Nd) medical radionuclides. The resulting reference cross-section data were obtained from Padé fits to selected and corrected experimental data, and integral thick target yields were subsequently deduced. Uncertainties in the fitted results were estimated via a Padé least-squares method with the addition of a 4% assessed systematic uncertainty. Experimental data were also compared with theoretical predictions available from the TENDL-2015 and TENDL-2017 libraries. All of the numerical reference cross-section data with their corresponding uncertainties and deduced integral thick target yields are available on-line at the IAEA-NDS medical portal www-nds.iaea.org/medicalportal and also at the IAEA-NDS web page www-nds.iaea.org/medical/positron_emitters.html.

Keywords IAEA coordinated research project · Diagnostic medical isotopes · Positron emitters · Cross-section evaluation · Uncertainty estimation · Padé fit · Bayesian inference · Recommended σ and yield data

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Introduction

The importance of positron-emitting radionuclides in molecular imaging (Positron Emission Tomography, PET) has constantly increased over the years, especially to follow metabolic processes and to quantify radiation dose in internal radiotherapy. Nuclear data identified with these radionuclides are important for the optimisation of their production routes and medical applications. Judicious selection of the projectile energy range will maximise the yield of the product and minimise that of any radioactive impurities. Several charged-particle and neutron production routes exist for the production of such radionuclides. The International Atomic Energy Agency (IAEA) initiated and supported a Coordinated Research Project (CRP) from 1997 to 2001 with the primary aim of establishing a reference nuclear reaction database for the most important gamma-ray and positron emitters and associated monitor reactions in order to optimise their production [1]. No uncertainties in the recommended data were produced at that time. The list of positron emitters that was included in this earlier effort is shown in Table 1. The reference cross-section data and integral thick target yields were made available in a hard-copy technical document, and later became accessible on the medical portal of the IAEA Nuclear Data Section (IAEA-NDS) with further updates from 2001 to 2007 [2].

Over the previous two decades new experimental data have been measured for the earlier evaluated reactions, and numerous new and potentially suitable candidate PET-isotopes have appeared in the literature along with pre-clinical studies. Therefore, a new CRP was initiated at the end of 2012 in order to redefine the production routes and upgrade the production data for the previously studied radionuclides, and to complement the database with the equivalent results for emerging prospective radionuclides. An additional goal of the working programme was to provide uncertainties for

the recommended cross sections of all the reactions studied [3]. The results of this evaluation work are summarised for production routes applicable to diagnostic positron emitters, including generator systems for short-lived radionuclides.

Evaluation method

The evaluation process was performed in a similar manner to previous studies [1, 6], and includes the following steps that will be discussed in more detail below:

- thorough compilation of experimental data (Section "Thorough compilation of experimental data");
- undertake new measurements if required (Section "New CRP measurements");
- correct and normalise earlier experimental data (decay data, enriched target abundances, monitor data, recognised systematic errors) (Sections "Status of earlier experimental data" and "Correction of earlier experimental data");
- compare with theoretical predictions (Section "Comparisons with theoretical predictions");
- critical comparison of all experimental datasets, and rejection of unreliable and erroneous sets (Section "Critical comparisons and selection of the most reliable experimental data");
- least-square fit of selected experimental datasets to derive mean values and corresponding uncertainties of the resulting recommended reference data (Section "Data fitting and resulting uncertainties- Padé fit of selected experimental data");
- calculate integral yield as a function of the incident particle energy (Section "Integral yields for thick targets as a function of particle energy").

Table 1 Earlier evaluated nuclear reactions for the production of diagnostic PET isotopes (1995–1999), and also made available as an IAEA nuclear database [1, 2]

| PET radionuclide | Half-life | Decay (%) | End-point energy (keV) | Reaction product | Half-life | Decay (%) | Production reaction |
|------------------|------------|-------------------|------------------------|------------------|------------|-------------------|--|
| ^{11}C | 1221.8 s | 99.7669 β^+ | 960.4 | ^{11}C | 1221.8 s | 99.7669 β^+ | $^{14}\text{N}(\text{p},\alpha)^{11}\text{C}$ |
| ^{13}N | 9.965 min | 99.8036 β^+ | 1198.5 | ^{13}N | 9.965 min | 99.8036 β^+ | $^{16}\text{O}(\text{p},\alpha)^{13}\text{N}$ |
| ^{15}O | 122.24 s | 99.9003 β^+ | 1732.0 | ^{15}O | 122.24 s | 99.9003 β^+ | $^{15}\text{N}(\text{p},\text{n})^{15}\text{O}$ $^{14}\text{N}(\text{d},\text{n})^{15}\text{O}$ |
| ^{18}F | 109.77 min | 96.73 β^+ | 633.5 | ^{18}F | 109.77 min | 96.73 β^+ | $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ $^{\text{nat}}\text{Ne}(\text{d},\text{x})^{18}\text{F}$ |
| ^{68}Ga | 67.71 min | 88.91 β^+ | 1899.1 | ^{68}Ge | 270.95 d | 100 EC | $^{69}\text{Ga}(\text{p},2\text{n})^{68}\text{Ge}$ $^{\text{nat}}\text{Ga}(\text{p},\text{xn})^{68}\text{Ge}$ |
| ^{82}Rb | 1.2575 min | 95.43 β^+ | 3378 | ^{82}Sr | 25.35 d | 100 EC | $^{85}\text{Rb}(\text{p},4\text{n})^{82}\text{Sr}$ $^{\text{nat}}\text{Rb}(\text{p},\text{xn})^{82}\text{Sr}$ |

Decay data as tabulated have been taken from NuDat (NuDat 2.6 or 2.7), a user-friendly form of ENSDF [4, 5]

Thorough compilation of experimental data

Detailed searches for published experimental cross sections were made, including the following sources: primary publications in journals, EXFOR database of IAEA-NDS [7], IAEA INIS database [8], evaluated libraries (ENDF) [9], bibliographies of Brookhaven National Laboratory (Burrows and Dempsey [10], Holden et al. [11], Karlstrom and Christman [12]), reports of the International Atomic Energy Agency (Dmitriev [13], Gandarias-Cruz and Okamoto [14]), Landolt Börnstein Series [15], Landolt Börnstein New Series [16], Tobailem et al. [17], Albert et al. [18], Münzel et al. [19], PhD theses, other relevant evaluations, private communications, etc. All experimental references are cited in each of the subsections that describe specific reaction paths.

The cut-off for inclusion of new data was set at June 2016, and therefore some results published in the final year of this compilation exercise were not added into the already completed fits but are still shown among the datasets retrieved. Duplications of original data published in the numerous review papers on production and/or use of medical radionuclides are explicitly mentioned in this study.

New CRP measurements

Additional experiments were performed by various CRP participants as crucial support in defining the excitation functions of the $^{45}\text{Sc}(d,3n)^{44}\text{Ti}$, $^{\text{nat}}\text{Ni}(p,x)^{52}\text{Fe}$, $^{55}\text{Mn}(p,4n)^{52}\text{Fe}$, $^{50}\text{Cr}(\alpha,2n)^{52}\text{Fe}$, $^{58}\text{Ni}(p,\alpha)^{55}\text{Co}$, $^{61}\text{Ni}(p,n)^{61}\text{Cu}$, $^{60}\text{Ni}(d,n)^{61}\text{Cu}$, $^{\text{nat}}\text{Ga}(p,x)^{68}\text{Ge}$, $^{\text{nat}}\text{Ge}(p,xn)^{72}\text{As}$, $^{\text{nat}}\text{Ge}(d,xn)^{72}\text{As}$, $^{89}\text{Y}(d,2n)^{89}\text{Zr}$, $^{93}\text{Nb}(p,x)^{90}\text{Nb}$, $^{92}\text{Mo}(\alpha,x)^{94\text{m}}\text{Tc}$, $^{110}\text{Cd}(p,n)^{110\text{m}}\text{In}$, $^{107}\text{Ag}(\alpha,n)^{110\text{m}}\text{In}$, $^{\text{nat}}\text{Sb}(p,xn)^{118}\text{Te}$ and $^{141}\text{Pr}(d,3n)^{140}\text{Nd}$ reactions. Details of these studies have been reported individually and separately in other dedicated publications (see references for specific reactions given below).

Status of earlier experimental data

Large sets of experimental data are available for some reactions, but only one or two relevant measurements exist for other reactions. Investigation of the published data permits some general remarks and conclusions to be made:

- Early investigations from 1945 to 1970 were mostly dedicated to the study of nuclear reaction mechanisms, and were performed on accelerators possessing somewhat limited technology of that time. The information on decay data and estimated uncertainties adopted for these experiments are poor in most cases.
- Production of medical radionuclides used in clinical practice would normally involve monoisotopic or at least

enriched targets. However, production cross sections are sometimes determined by evaluators from data obtained with natural targets over limited energy ranges (up to the threshold of the next contributing reaction) in order to derive suitable data for subsequent evaluation. These data are in many cases more reliable due to the higher quality of the targets employed (with respect to thickness and uniformity).

- Nowadays, excitation functions are commonly measured over a broader energy range by means of the stacked-foil technique. This method possesses significant advantages in irradiation time and the determination of good relative values because of the fixed number of bombarding particles in each sample. However, long stacks suffer from an accumulation of effects caused by uncertainties in foil thicknesses that result in a possible increasing energy shift throughout the stack. The precise energy in each foil can be controlled by simultaneous measurements of the excitation function of reference monitor reactions over the whole energy range, but this is very rarely undertaken.
- Another possibility is to irradiate a large number of targets simultaneously in conjunction with rotating wheels in which different energy absorbers with well-measured thicknesses are inserted before each target. The number of bombarding particles incident on each target is the same and well controlled, although one disadvantage is the much longer irradiation time needed when compared with stacked-foil irradiations.
- Overwhelming parts of the datasets exhibit consistent and realistic behaviour, but in some cases points in a given set may disagree significantly from the observed trend and with other data without any obvious reason (although a most probable cause is an incorrect estimation of the real target thickness). These clearly discrepant data points were not considered as valid data during the fitting process.

Knowledge of the energy and energy distribution of the incident particle beam is important in reducing the uncertainty of the energy values of the data points. This information is preferably obtained by prior measurement. However, these incident beam parameters are rarely known for production machines in which the use of high-intensity beams causes changes in target quality (i.e., surface density and uniformity of target atoms). Gas targets are especially sensitive to density reduction caused by the heat generated from high-current beams.

Essentially two methods were used in these experiments to determine the number of incident particles: direct collection of the total charge in a Faraday cup, or indirectly by means of the reference data from a series of monitor reactions. Some experiments involve only the activity of a single

monitor foil inserted in front of the target stack compared with the activity of the same foil target measured in a Faraday cup at the same energy. An additional factor of uncertainty is the constancy over time of the number of incident particles, especially when the half-life of the radionuclide investigated is comparable to or shorter than the irradiation time. Not all laboratories have the instrumentation needed to monitor and quantify the beam intensity on the target during the irradiation.

Other factors are the method of detection of the different types of radiation emitted in order to quantify the product nuclei: X-rays, gamma rays, alpha and beta particles, and neutron emissions involve the use of detectors that possess very different energy resolution and efficiency. Nevertheless, recent developments in detector technology have resulted in greater reliability and commensurate reductions in the uncertainties. Compilations and evaluations of the measured results and assessment of the quality of the reported work from different laboratories require all these factors be taken into account, which requires detailed investigations of all of the original publications.

Correction of earlier experimental data

Where possible, published cross sections that rely on outdated decay data were corrected by taking new decay data into account by means of NuDat [4] (with the Evaluated Nuclear Structure Data File (ENSDF) [5] as the data source). This form of correction was also carried out with respect to the decay data associated with the adopted monitor reactions. As any correction with respect to updated half lives has a non-linear impact on the well-known activation equation used to determine the cross section (primarily factors related to time), caution has to be taken when applying such adjustments. They are only possible if timing information is available in the original publication. The correction for other linear factors can be more easily performed, but also requires knowledge of the decay data used by the original authors.

Excitation functions measured over a broad energy range that show often relatively small uncertainties are sometimes significantly different from more reliable data determined over a shorter energy range. These higher energy data were normalised in such cases to the well measured data to produce reference data in a broad energy range. The same method was also adopted in the case of systematic energy shifts observed in the stacked-foil technique, which can be linearly corrected with respect to data measured on accelerators with high-energy definition.

Fitting procedures require reliable uncertainties in the experimental data selected for such statistical analyses. Unfortunately, the uncertainties in the cross-section values and the beam energy are not always appropriately provided as a significant part of the published experimental data.

Therefore, missing cross-section uncertainties were estimated on the basis of the measurement methodology and the experience of the compilers/evaluators.

The experimental data for a given reaction measured with similar methods and comparable technology in different laboratories often have significantly different quoted uncertainties. Some studies report uncertainties that are unrealistically low because all contributing statistical or systematic effects have not been taken into account, or are incorrectly estimated. Therefore, such values were corrected to more realistic average uncertainties to avoid incorrect weighting in the fitting procedure.

Comparisons with theoretical predictions

Experimental data were compared with theoretical predictions of activation by charged-particle reactions, as assembled and made available in the online TENDL-2015 and TENDL-2017 libraries [20]. Both of these libraries are based on the reaction modelling adopted in the TALYS code [21]. The TENDL libraries are derived from both default and adjusted TALYS calculations, and occasionally from other sources.

The aim of the comparisons was to obtain a general impression of the shape of each excitation function over a broad energy range, including the magnitude of the maximum cross-section value and the effective threshold of reaction in cases where there were contradicting data. These predictions also permitted extrapolation of the excitation function in cases where experimental data were only available over a short and limited energy range as input for the Bayesian least-square fit (e.g., for the Padé fit). All TENDL predictions are shown along with the experimental data in the various figures of the excitation functions. Recently published results of evaluations for different activation products obtained from fitting by adjustment of theoretical codes to a compilation of existing experimental results (including some from this coordinated research project) have not been considered here, as the Bayesian non-model evaluation is the preferred evaluation method.

Critical comparisons and selection of the most reliable experimental data

Corrected and analysed experimental data were visually compared in figures that also included the theoretical predictions.

Measurement of radioactivity

The main sources of error when determining absolute activity are faulty estimates of the detector efficiency (especially in the low-energy region), self-absorption of low-energy

gamma rays, geometry deviations between point source calibrations and the activated spot size on targets, dead-time and pile-up corrections, and the adoption of incorrect decay data.

Determination of the energy scale

Errors in the energy scale are introduced by improper estimation of the energy of the primary beam, uncertainties in the effective thickness of the individual targets, the cumulative effect of the stacked-foil technique, and the ill-defined impact of absorbers introduced to vary the energy of the incoming beam. Accelerators used for data measurements in nuclear physics usually have the necessary facilities to measure the energy of the beams precisely.

Estimation of uncertainties of the cross sections and energy scale

Despite the existence of the JCGM guide for the expression of uncertainty in measurements that experimentalists are strongly advised to follow [22], we have found that no such recommended systematic procedures have been undertaken to estimate properly the uncertainty of the measured cross sections and their energy scale. Various factors contribute to the assessment of the uncertainty associated with cross-section measurements. Unfortunately, authors in many original publications present only the total uncertainty in their tables of cross sections, without discussing or defining the estimated uncertainties of the contributing processes (i.e., no sufficiently detailed uncertainty budget is given).

A number of noteworthy observations were made during the course of the evaluation process:

- data from different authors often show striking systematic disagreements over the whole energy range;
- data below the reaction threshold were frequently reported;
- sometimes the data were extensively scattered, without any explanation;
- specific laboratories carried out systematic investigations, and as a consequence generated good results for many reactions.

Due to a general lack of information reported in the original publications and earlier compilations, the quality of the data could not be assessed in most cases, nor reasons identified for disagreements with other publications apart from a few exceptions. The most likely sources of disagreement or reasons for discrepancies among the experimental data were as follows:

Beam current. While relying on monitor reactions, the main problem originates from the use of outdated monitor cross sections. Another source of error was improper use of

monitors, especially an incorrect estimation of the energy of the bombarding particle in a region where the excitation function curve has a steep slope (which will lead to an under- or overestimation of the beam flux).

Determination of the number of target nuclei. Although difficult to determine the number of target nuclei with high precision, an uncertainty below five percent can be easily achieved. The main challenges in the case of thin solid targets are uncertainties associated with the chemical state caused by surface oxidation, non-uniformity in the thickness of the foil, and improper estimation of the shape or dimensions influencing the thickness derived from weighing. Furthermore, well-known density reductions along the beam due to the heat effect play a very important role in the case of gas targets.

On the basis of emerging inconsistencies and trends, contradictory and scattered data were rejected from the analyses. Such an extensive selection process takes into account many factors, of which a few cannot be formulated in a mathematical manner, but rather are based on invaluable experienced, yet subjective, judgements by the evaluators.

Data fitting and resulting uncertainties- Padé fit of selected experimental data

Previous evaluations of the experimental cross-section data for diagnostic radionuclides were usually fitted by the spline method. Such a procedure is based on a piecemeal approximation of the data between specified points (knots of the spline) based on individual interpolating polynomials. These polynomials match in such a way that the zeroth, first and second derivatives are continuous at the knots, and are usually selected by the second (quadratic interpolation) or third order (cubic interpolation). A continuous and smooth fit is obtained with minimum twisting (oscillating behaviour) of the fitting curve, which arises from the conditions for continuity. A particular feature of the spline method is that the fit in a selected interval is independent from the data in other intervals.

The spline method is well known (e.g., see Ref. [23] and references therein), and has been applied in nuclear data evaluations. Some known shortcomings relate to the following requirements and inadequacies:

- knots have to be selected by a user, which makes the fit time consuming with partially arbitrary results;
- cubic splines are not always adequate for complex-shaped curves.

A more general class of analytical function is the rational function defined as the ratio of two polynomials. Such an approximation was proposed by Padé over one hundred

and twenty years ago [24], and has become one of the most important interpolation techniques of statistical mathematics [25, 26]. As a rational function, the Padé approximant can be expressed by a set of real polynomial coefficients, or by a set of real coefficients of the pole expansion

$$p_L(z) = c + \sum_l \frac{a_l}{z - \eta_l} + \sum_k \frac{\alpha_k(z - \varepsilon_k) + \beta_k}{(z - \varepsilon_k)^2 + \gamma_k^2}, \quad (1)$$

where $z = x + iy$ are complex variables, and L is the order of the polynomial representation of the Padé approximant (therefore all coefficients depend implicitly on L) [25, 26]. This equation is also called the resonance expansion, in which ε_k and γ_k are the energy and the total half-width of the k th resonance, respectively, while α_k and β_k are the partial widths and interference parameters. The first sum corresponds to the real poles, while the second sum relates to the complex poles.

Effective codes for practical applications of the Padé approximation were developed by the IPPE, Obninsk group [27]. The simplest version of these codes permits analyses of up to 500 experimental points, with the number of parameters $L \leq 40$ and the ratio limit of analysed functions up to $f^{\max}/f^{\min} \leq 10^6$. A more detailed description of the method can be found in Ref. [27], and some important questions of application are presented in Refs. [28, 29].

Padé approximations are also very convenient for calculations of the data uncertainties and the corresponding covariance matrices. The fitting procedure is always based on a minimisation of the deviation functional

$$\chi^2 = (N - L)^{-1} \sum_{j=1}^N (p_L(x_j) - f_j)^2 / \sigma_j^2, \quad (2)$$

where f_j are the available experimental data, σ_j are their total uncertainties (including both systematic and statistical components) and N is the number of analysed points. Such minimisation is carried out iteratively by means of the discrete optimization approach. Minimal deviation for a given L is computed by assessing and selecting L points from the available N points ($L < N$), and then determining the corresponding approximants from Eq. (2). Once this process has been completed, L is changed and the iteration is repeated until an overall minimum is found from all discrete possibilities available. Some additional details of the method are considered in our earlier paper that focused on the evaluation of charged-particle monitor reactions [30].

Along with a consistent consideration of the statistical uncertainties of experimental data, the Padé method allows the determination of some systematic uncertainties that are usually underestimated by their authors, and also establishes some implicit correlations of the data. The averaged

deviation of the full experimental dataset from the approximating function is regarded as the systematic uncertainty, while the variances of deviations around the averaged values are regarded as the statistical uncertainties. An optimal description of all data is achieved by the traditional iteration procedure of minimizing the mean squares deviations with the statistical and systematic uncertainties.

Only total uncertainties are determined in the majority of the experimental studies, and reasonable reconstructions of the corresponding systematic uncertainties are judged to be impossible to achieve in many of these cases. The method described above provides estimates of the systematic uncertainties on the basis of general statistical criteria which are valid for a reasonable number of studies. However, for a small number of the experimental measurements, underestimation of the systematic uncertainties is highly probable. Such underestimations also occur in those cases whereby the same, very similar, or other components of the same experimental equipment are used in a range of different studies, since any related correlations have been neglected.

After analysing the complete set of available data, we have come to the conclusion that realistic total uncertainties cannot be defined as less than 4% for each of the reactions considered. Therefore, an additional systematic uncertainty of 4% has been introduced as part of each systematic uncertainty derived from statistical analyses of all the recommended cross sections.

Integral yields for thick targets as a function of particle energy

Integral thick target yields as a function of energy were calculated from the recommended cross section data. We have quantified the production rates for radionuclides whose half-lives are short relative to the length of irradiation. This rate is also known as the “physical yield”, or “instantaneous production rate”, since the effect of decay of the radionuclide is small compared with the activity being created. Two other yields are also defined on the IAEA medical portal [2], namely the activity of a fixed 1 h and 1 μ A irradiation, and the saturation activity at EOB for a 1 μ A irradiation.

The activity of a fixed 1 h/1 μ A irradiation is meaningful and can be used in practice for longer-lived radionuclides where the activity is increasing linearly with irradiation time. Saturation activity is used in the case of short half-life radionuclides, when a constant activity is obtained for even relatively short irradiations. The definition of these parameters can be found in Bonardi [31], and Otuka and Takács [32]. Thick target yields for the different production routes leading to a given radionuclide are summarised within a figure at the end of every subsection.

Medically relevant radionuclides can be obtained in many cases from the decay of a parent with a different half-life (indirect production, or generator couple). Two separate figures are shown in such cases, corresponding to the yields at EOB for the shorter-lived daughter and the longer-lived parent (often orders of magnitude lower). Depending on the relative half-lives, either time-dependent partial equilibrium (indirect production in which mother and daughter have comparable half-lives), or total equilibrium (long-lived parent/short-lived daughter generators) is obtained.

Results for charged-particle reactions

The list of reactions evaluated in the present studies consists altogether of 69 charged-particle reactions for the production of 23 radionuclides of interest for PET imaging, including 11 generator systems for short-lived medically interesting radioisotopes (Table 2). There are 39 proton reactions, 16 deuteron reactions, one reaction for ^3He , and 13 reactions for α particles. Energies of incident particles cover the range from a few MeV up to 100 MeV. Every subsequent

subsection contains a summary of the most frequent use of each of the 23 medically relevant radionuclides, and the literature references found for each production route (given in both the text and figures), selected data (text and figures) and the characteristics of the Padé fit (text and figures). As mentioned previously, the physical yields are included in one or two additional figures at the end of each subsection if indirect and/or generator production is being considered.

Half-lives and limited decay-scheme data for the different radionuclides discussed in the following subsections can be found in Table 2. The γ -ray energies in keV and the corresponding absolute emission probabilities (absolute intensities, $P_\gamma(\%)$) used to identify and quantify the activity of a given radionuclide in the experimental studies (and β^+ decay fraction instead of the intensity of the 511 keV annihilation radiation) are listed, and have also been included within each of the primary subsections of this Section.

Reactions for radionuclides present in Table 1 but not considered during the course of this CRP will be evaluated in a similar manner as part of a future series of IAEA-sponsored studies and will be published elsewhere.

Table 2 Evaluated nuclear reactions and decay data adopted for production of diagnostic PET radionuclides (2012–2016) [2]. Reaction thresholds for natural targets estimated approximately from the plots, and are given in bold

| PET radionuclide | Target | Reaction | Reaction threshold (MeV) | Reaction product | Half-life ^a | Decay (%) ^a E_γ (keV), P_γ (%) | Order of Padé polynomial L | Comment |
|--------------------------|--------------------------|---|--------------------------|--------------------------|------------------------|--|----------------------------|-----------|
| ^{44}Sc | ^{44}Ca | $^{44}\text{Ca}(p,n)^{44}\text{Sc}$ | 4.537 | ^{44}Sc | 3.97 h | EC + β^+ 100 (β^+ 94.27) | 19 | Direct |
| | ^{44}Ca | $^{44}\text{Ca}(d,2n)^{44}\text{Sc}$ | 6.965 | | | γ : 1157.020, 99.9 | 9 | Direct |
| | ^{43}Ca | $^{43}\text{Ca}(d,n)^{44}\text{Sc}$ | 0 | | | | 5 | Direct |
| | ^{45}Sc | $^{45}\text{Sc}(p,2n)^{44}\text{Ti}$ | 12.65 | ^{44}Ti | 59.1 y | EC 100 | 7 | Generator |
| | ^{45}Sc | $^{45}\text{Sc}(d,3n)^{44}\text{Ti}$ | 15.25 | | | From decay of ^{44}Sc | 6 | Generator |
| $^{52\text{m}}\text{Mn}$ | $^{\text{nat}}\text{Ni}$ | $^{\text{nat}}\text{Ni}(p,x)^{52}\text{Fe}$ | 40 | ^{52}Fe | 8.275 h | EC + β^+ 100 (β^+ 55.49) | 11 | Generator |
| | ^{55}Mn | $^{55}\text{Mn}(p,4n)^{52}\text{Fe}$ | 35.00 | | | From decay of $^{52\text{m}}\text{Mn}$ | 17 | Generator |
| | ^{50}Cr | $^{50}\text{Cr}(\alpha,2n)^{52}\text{Fe}$ | 16.90 | | | | 9 | Generator |
| | ^{52}Cr | $^{52}\text{Cr}(p,n)^{52\text{m}}\text{Mn}$ | 5.60 | $^{52\text{m}}\text{Mn}$ | 21.1 min | EC + β^+ 98.22 (β^+ 96.6) | 14 | Direct |
| | ^{52}Cr | $^{52}\text{Cr}(d,2n)^{52\text{m}}\text{Mn}$ | 8.02 | | | IT 1.78 γ : 1434.092, 98.2 | 8 | Direct |
| ^{52}Mn | ^{52}Cr | $^{52}\text{Cr}(p,n)^{52\text{g}}\text{Mn}(m+)$ | 5.60 | $^{52\text{g}}\text{Mn}$ | 5.591 d | EC + β^+ 100 (β^+ 29.4) | 9 | Direct |
| | ^{52}Cr | $^{52}\text{Cr}(d,2n)^{52\text{g}}\text{Mn}(m+)$ | 8.02 | | | γ : 744.233, 90.0; 935.544, 94.5 | 8 | Direct |
| ^{55}Co | ^{58}Ni | $^{58}\text{Ni}(p,\alpha)^{55}\text{Co}$ | 1.358 | ^{55}Co | 17.53 h | EC + β^+ 100 (β^+ 76) | 10 | Direct |
| | ^{54}Fe | $^{54}\text{Fe}(d,n)^{55}\text{Co}$ | 0 | | | γ : 931.1, 75; | 13 | Direct |
| | ^{56}Fe | $^{56}\text{Fe}(p,2n)^{55}\text{Co}$ | 15.71 | | | 1316.6, 7.1 | 8 | Direct |
| ^{61}Cu | ^{61}Ni | $^{61}\text{Ni}(p,n)^{61}\text{Cu}$ | 3.07 | ^{61}Cu | 3.339 h | EC + β^+ 100 (β^+ 61) | 12 | Direct |
| | ^{60}Ni | $^{60}\text{Ni}(d,n)^{61}\text{Cu}$ | 0 | | | γ : 282.956, 12.2; | 16 | Direct |
| | ^{64}Zn | $^{64}\text{Zn}(p,\alpha)^{61}\text{Cu}$ | 0 | | | 656.008, 10.8; 1185.234, 3.7 | 12 | Direct |
| ^{62}Cu | $^{\text{nat}}\text{Cu}$ | $^{63}\text{Cu}(p,2n)^{62}\text{Zn}^{\text{b}}$ | 13.48 | ^{62}Zn | 9.193 h | EC + β^+ 100 (β^+ 8.2) | 16 | Generator |
| | $^{\text{nat}}\text{Cu}$ | $^{63}\text{Cu}(d,3n)^{62}\text{Zn}^{\text{b}}$ | 15.986 | | | γ : 548.35, 15.3; | 12 | Generator |
| | $^{\text{nat}}\text{Ni}$ | $^{\text{nat}}\text{Ni}(\alpha,xn)^{62}\text{Zn}$ | 18.5 | | | 596.56, 26 | 10 | Generator |
| | ^{62}Ni | $^{62}\text{Ni}(p,n)^{62}\text{Cu}$ | 4.818 | ^{62}Cu | 9.67 min | EC + β^+ 100 (β^+ 97.83) | 12 | Direct |

Table 2 (continued)

| PET radionuclide | Target | Reaction | Reaction threshold (MeV) | Reaction product | Half-life ^a | Decay (%) ^a E_{γ} (keV), P_{γ} (%) | Order of Padé polynomial L | Comment |
|--------------------|-------------------|--|--------------------------|--------------------|------------------------|--|----------------------------|-----------|
| | ⁶² Ni | ⁶² Ni(d,2n) ⁶² Cu | 7.192 | | | γ : 875.66, 0.147; 1172.97, 0.342 | 5 | Direct |
| ⁶⁶ Ga | ⁶⁶ Zn | ⁶⁶ Zn(p,n) ⁶⁶ Ga | 6.049 | ⁶⁶ Ga | 9.49 h | EC + β^+ 100 (β^+ 57) | 13 | Direct |
| | ⁶³ Cu | ⁶³ Cu(α ,n) ⁶⁶ Ga | 7.980 | | | γ : 833.5324, 5.9; 1039.220, 37.0 | 13 | Direct |
| ⁶⁸ Ga | ⁶⁸ Zn | ⁶⁸ Zn(p,n) ⁶⁸ Ga | 3.758 | ⁶⁸ Ga | 67.71 min | EC + β^+ 100 (β^+ 88.91) | 20 | Direct |
| | ⁶⁵ Cu | ⁶⁵ Cu(α ,n) ⁶⁸ Ga | 6.183 | | | γ : 1077.34, 3.22 | 10 | Direct |
| | ^{nat} Ga | ^{nat} Ga(p,xn) ⁶⁸ Ge | 10.5 | ⁶⁸ Ge | 270.95 d | EC 100 | 11 | Generator |
| | ⁶⁹ Ga | ⁶⁹ Ga(p,2n) ⁶⁸ Ge | 11.366 | | | From decay of ⁶⁸ Ga | 8 | Generator |
| ⁷² As | ⁷⁵ As | ⁷⁵ As(p,4n) ⁷² Se | 30.57 | ⁷² Se | 8.40 d | EC 100 | 8 | Generator |
| | ^{nat} Br | ^{nat} Br(p,x) ⁷² Se | 50 | | | From decay of ⁷² As | 10 | Generator |
| | ^{nat} Ge | ^{nat} Ge(p,xn) ⁷² As | 5 | ⁷² As | 26.0 h | EC + β^+ 100 (β^+ 87.8) | 18 | Direct |
| | ^{nat} Ge | ^{nat} Ge(d,xn) ⁷² As | 8 | | | γ : 629.92, 8.07; 833.99, 81 | 10 | Direct |
| ⁷³ Se | ⁷⁵ As | ⁷⁵ As(p,3n) ⁷³ Se | 22.024 | ⁷³ Se | 7.15 h | EC + β^+ 100 (β^+ 65.4) | 9 | Direct |
| | ⁷² Ge | ⁷² Ge(α ,3n) ⁷³ Se | 27.60 | | | γ : 67.07, 70; 361.2, 97.0 | 8 | Direct |
| ⁷⁶ Br | ⁷⁶ Se | ⁷⁶ Se(p,n) ⁷⁶ Br | 5.821 | ⁷⁶ Br | 16.2 h | EC + β^+ 100 (β^+ 55) | 8 | Direct |
| | ⁷⁷ Se | ⁷⁷ Se(p,2n) ⁷⁶ Br | 13.336 | | | γ : 559.09, 74; | 9 | Direct |
| | ⁷⁵ As | ⁷⁵ As(α ,3n) ⁷⁶ Br | 25.84 | | | 657.02, 15.9; 1853.67, 14.7 | 10 | Direct |
| ⁸² Rb | ^{nat} Rb | ^{nat} Rb(p,xn) ⁸² Sr | 30 | ⁸² Sr | 25.35 d | EC 100 | 13 | Generator |
| | ⁸⁵ Rb | ⁸⁵ Rb(p,4n) ⁸² Sr | 31.52 | | | From decay of ⁸² Rb: $T_{1/2} = 1.2575$ min EC + β^+ 100 (β^+ 95.43) γ : 776.52, 15.08 | 9 | Generator |
| ^{82m} Rb | ⁸² Kr | ⁸² Kr(p,n) ^{82m} Rb | 5.250 | ^{82m} Rb | 6.472 h | EC + β^+ 100 (β^+ 21.2) | 9 | Direct |
| | ⁸² Kr | ⁸² Kr(d,2n) ^{82m} Rb | 7.593 | | | γ : 554.35, 62.4; 619.11, 37.98; 698.37, 26.3; 776.52, 84.39; 827.83, 21.0; 1044.08, 32.07; 1317.43, 23.7; 1474.88, 15.5 | 5 | Direct |
| ⁸⁶ Y | ⁸⁶ Sr | ⁸⁶ Sr(p,n) ⁸⁶ Y | 6.093 | ⁸⁶ Y | 14.74 h | EC + β^+ 100 (β^+ 31.9) | 9 | Direct |
| | ⁸⁸ Sr | ⁸⁸ Sr(p,3n) ⁸⁶ Y | 25.86 | | | γ : 627.72, 32.6; | 8 | Direct |
| | ⁸⁵ Rb | ⁸⁵ Rb(α ,3n) ⁸⁶ Y | 25.84 | | | 1076.63, 82.5; 1153.05, 30.5 | 8 | Direct |
| ⁸⁹ Zr | ⁸⁹ Y | ⁸⁹ Y(p,n) ⁸⁹ Zr | 3.656 | ⁸⁹ Zr | 78.41 h | EC + β^+ 100 (β^+ 22.74) | 11 | Direct |
| | ⁸⁹ Y | ⁸⁹ Y(d,2n) ⁸⁹ Zr | 5.972 | | | 909.15, 99.04 | 9 | Direct |
| ⁹⁰ Nb | ⁹³ Nb | ⁹³ Nb(p,x) ⁹⁰ Nb | 29.08 | ⁹⁰ Nb | 14.60 h | EC + β^+ 100 (β^+ 51.2) | 9 | Direct |
| | ⁸⁹ Y | ⁸⁹ Y(α ,3n) ⁹⁰ Nb | 28.04 | | | γ : 132.716, 4.13; 141.178, 66.8; 1129.224, 92.7 | 16 | Direct |
| ^{94m} Tc | ⁹² Mo | ⁹² Mo(α ,x) ^{94m} Tc | 16.26 | ^{94m} Tc | 52.0 min | EC + β^+ 100 (β^+ 70.2) | 12 | Direct |
| | ⁹⁴ Mo | ⁹⁴ Mo(p,n) ^{94m} Tc | 5.092 | | | γ : 871.05, 94.2; 1522.1, 4.5; 1868.68, 5.7 | 9 | Direct |
| ^{110m} In | ^{nat} In | ^{nat} In(p,xn) ¹¹⁰ Sn | 30 | ¹¹⁰ Sn | 4.154 h | EC 100 | 17 | Generator |
| | ¹⁰⁸ Cd | ¹⁰⁸ Cd(α ,2n) ¹¹⁰ Sn | 17.76 | | | γ : 280.459, 97.06 | 10 | Generator |
| | ¹¹⁰ Cd | ¹¹⁰ Cd(p,n) ^{110m} In | 4.703 | ^{110m} In | 69.1 min | EC + β^+ 100 (β^+ 61.3) | 11 | Direct |
| | ¹¹⁰ Cd | ¹¹⁰ Cd(d,2n) ^{110m} In | 7.011 | | | γ : 2129.40, 2.15; | 5 | Direct |
| | ¹⁰⁷ Ag | ¹⁰⁷ Ag(α ,n) ^{110m} In | 7.867 | | | 2211.33, 1.74; 2317.41, 1.285 | 9 | Direct |
| ¹¹⁸ Sb | ¹¹⁵ Sn | ¹¹⁵ Sn(α ,n) ¹¹⁸ Te | 8.262 | ¹¹⁸ Te | 6.00 d | EC 100 | 7 | Generator |
| | ¹¹⁶ Sn | ¹¹⁶ Sn(α ,2n) ¹¹⁸ Te | 18.15 | | | From decay of ¹¹⁸ Sb: | 6 | Generator |

Table 2 (continued)

| PET radionuclide | Target | Reaction | Reaction threshold (MeV) | Reaction product | Half-life ^a | Decay (%) ^a E_γ (keV), P_γ (%) | Order of Padé polynomial L | Comment |
|-------------------|-------------------|--|--------------------------|-------------------|------------------------|--|----------------------------|-----------|
| | ^{nat} Sb | ^{nat} Sb(p,x) ¹¹⁸ Te | 30 | | | $T_{1/2}$ = 3.6 min | 12 | Generator |
| | ^{nat} Sb | ^{nat} Sb(d,x) ¹¹⁸ Te | 34 | | | EC + β^+ 100 (β^+ 73.5) γ : 1229.33, 2.5 | 4 | Generator |
| ¹²⁰ I | ¹²⁰ Te | ¹²⁰ Te(p,n) ¹²⁰ I | 6.451 | ¹²⁰ I | 81.6 min | EC + β^+ 100 (β^+ 68.2) | 18 | Direct |
| | ¹²² Te | ¹²² Te(p,3n) ¹²⁰ I | 23.68 | | | γ : 601.1, 5.51; 1523.0, 10.9 | 7 | Direct |
| ¹²² I | ¹²⁴ Xe | ¹²⁴ Xe(p,x) ¹²² Xe | 18.60 | ¹²² Xe | 20.1 h | EC 100 | 5 | Generator |
| | ¹²⁷ I | ¹²⁷ I(p,6n) ¹²² Xe | 45.12 | | | γ : 350.065, 7.80; and | 7 | Generator |
| | ¹²⁷ I | ¹²⁷ I(d,7n) ¹²² Xe | 47.74 | | | from decay of ¹²² I: $T_{1/2}$ = 3.63 min EC + β^+ 100 (β^+ 78) γ : 564.119, 18 | 12 | Generator |
| ¹²⁸ Cs | ¹³³ Cs | ¹³³ Cs(p,6n) ¹²⁸ Ba | 44.16 | ¹²⁸ Ba | 2.43 d | EC 100 γ : 273.44, 14.5; and from decay of ¹²⁸ Cs: $T_{1/2}$ = 3.66 min EC + β^+ 100 (β^+ 68.8) γ : 442.901, 26.8 | 18 | Generator |
| ¹⁴⁰ Pr | ¹⁴¹ Pr | ¹⁴¹ Pr(p,2n) ¹⁴⁰ Nd | 10.68 | ¹⁴⁰ Nd | 3.37 d | EC 100 | 10 | Generator |
| | ¹⁴¹ Pr | ¹⁴¹ Pr(d,3n) ¹⁴⁰ Nd | 13.02 | | | From decay of ¹⁴⁰ Pr: | 9 | Generator |
| | ^{nat} Ce | ^{nat} Ce(³ He,xn) ¹⁴⁰ Nd | 16 | | | $T_{1/2}$ = 3.39 min EC + β^+ 100 (β^+ 51) γ : 306.9, 0.147; 1596.1, 0.49 | 9 | Generator |

^aDecay data as tabulated have been taken from NuDat (NuDat 2.6 or 2.7), a user-friendly form of ENSDF [4, 5]

^bOnly contributing reaction in natural Cu targets at these energies

Production of ^{44g}Sc ($T_{1/2} = 3.97$ h) and long-lived ^{44}Ti parent ($T_{1/2} = 59.1$ y)

Applications: ^{44}Sc (av. $E_{\beta^+} = 632.0$ keV, 94.27% intensity) has emerged as an attractive radiometal candidate for PET imaging by means of e.g., DOTA-functionalised biomolecules. ^{44}Sc -labelled PET radiopharmaceuticals appear of interest for molecular imaging of medium-lasting physiological processes. Also forms a theranostic pair with therapeutic ^{47}Sc . ^{44}Sc (3.97 h): β^+ (94.27%), and E_{γ} (keV) (P_{γ} (%)): 1157.020 (99.9).

^{44}Ti (59.1 y): detected by means of radiation emitted by daughter ^{44}Sc .

$^{44}\text{Ca}(p,n)^{44}\text{Sc}$, $^{44}\text{Ca}(d,2n)^{44}\text{Sc}$ and $^{43}\text{Ca}(d,n)^{44}\text{Sc}$ direct reactions and $^{45}\text{Sc}(p,2n)^{44}\text{Ti}$ - ^{44}Sc , $^{45}\text{Sc}(d,3n)^{44}\text{Ti}$ - ^{44}Sc generator production routes were evaluated.

$^{44}\text{Ca}(p,n)^{44g}\text{Sc}$

The six experimental datasets available in the literature are shown in Fig. 1 [33–38], together with the TENDL calculations. Three sets were rejected Cheng et al. [34] and Mitchell [35] (too high values near the threshold), and Krajewski et al. [37] (strange overall shape)), while the remaining four datasets were used in the statistical fitting procedure. Both the selected data and their experimental uncertainties are shown in Fig. 2 together with the Padé fit ($L = 14$, $N = 49$, $X^2 = 1.63$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 1 Six experimental datasets for the $^{44}\text{Ca}(p,n)^{44}\text{Sc}$ reaction available in the literature [33–38], and TENDL calculations

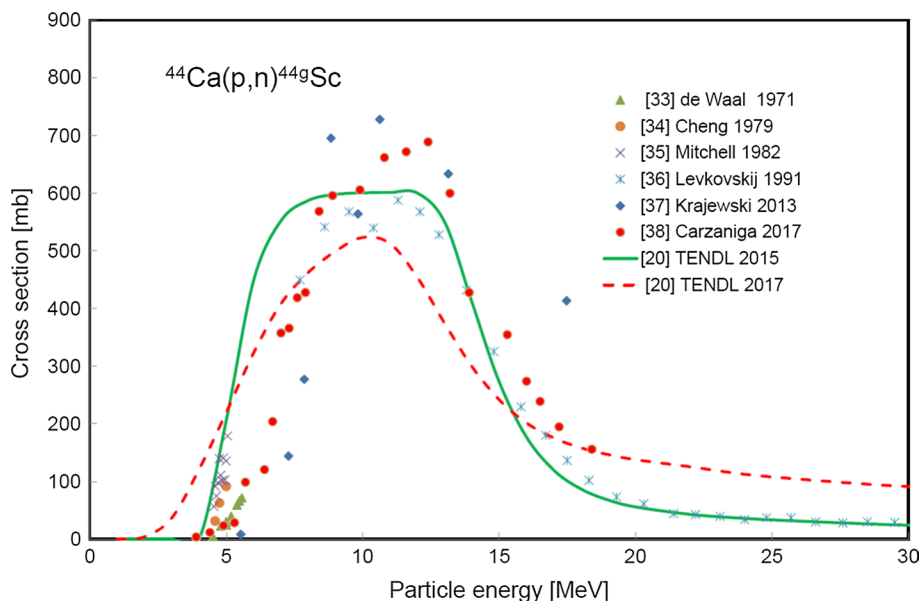
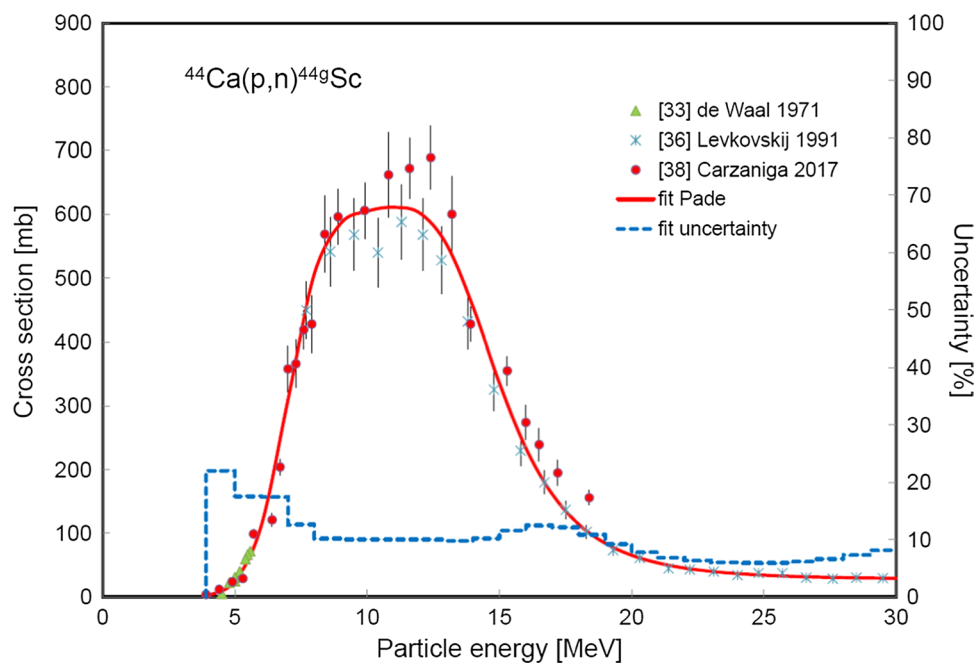


Fig. 2 Three selected experimental datasets for the $^{44}\text{Ca}(p,n)^{44}\text{gSc}$ reaction [33, 36, 38] with the Padé fit ($L=19$, $N=56$, $\chi^2=1.86$, solid line), and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{44}\text{Ca}(d,2n)^{44g}\text{Sc}$

Only one experimental dataset is available in the literature, and is shown in Fig. 3 [39] together with the TENDL calculations. These data and their experimental uncertainties

are shown in Fig. 4 together with the Padé fit ($L=9$, $N=9$, $\chi^2=0.53$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 3 One experimental dataset for the $^{44}\text{Ca}(d,2n)^{44g}\text{Sc}$ reaction available in the literature [39], and TENDL calculations

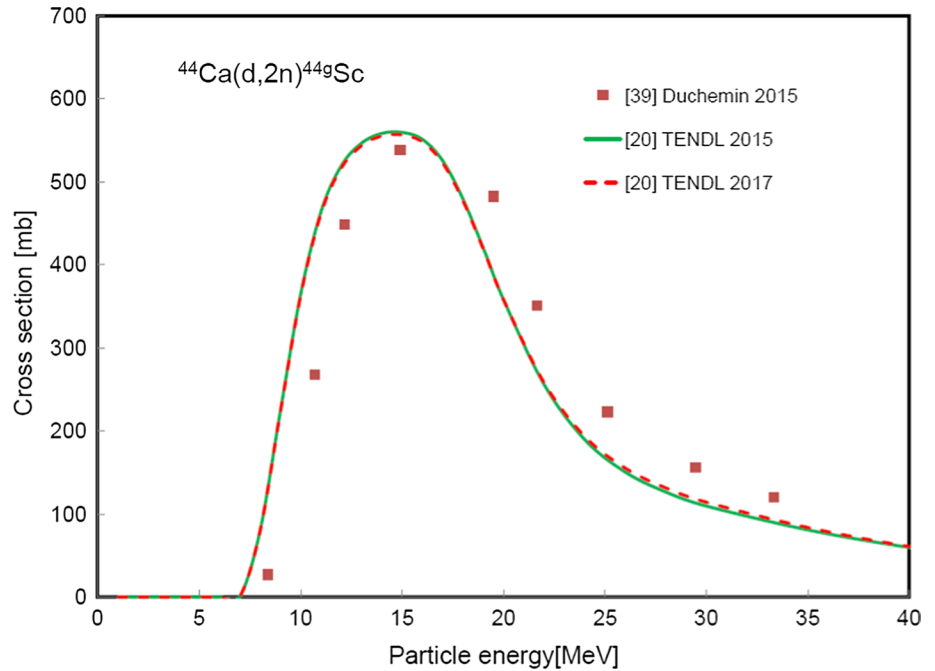
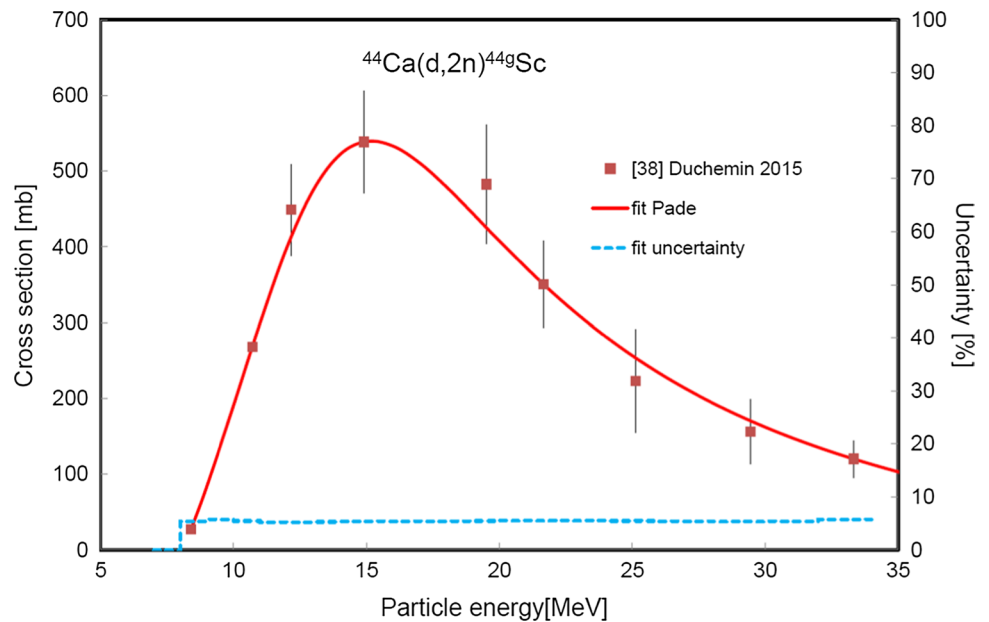


Fig. 4 Experimental dataset for the $^{44}\text{Ca}(d,2n)^{44g}\text{Sc}$ reaction [39] with the Padé fit ($L=9$, $N=9$, $\chi^2=0.53$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{43}\text{Ca}(\text{d},\text{n})^{44\text{g}}\text{Sc}$

Only one experimental dataset is available in the literature, and is shown in Fig. 5 [40] together with the TENDL calculations. These data and their experimental uncertainties

are shown in Fig. 6 together with the Padé fit ($L=5$, $N=16$, $\chi^2=1.49$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 5 One experimental dataset for the $^{43}\text{Ca}(\text{d},\text{n})^{44\text{g}}\text{Sc}$ reaction available in the literature [40], and TENDL calculations

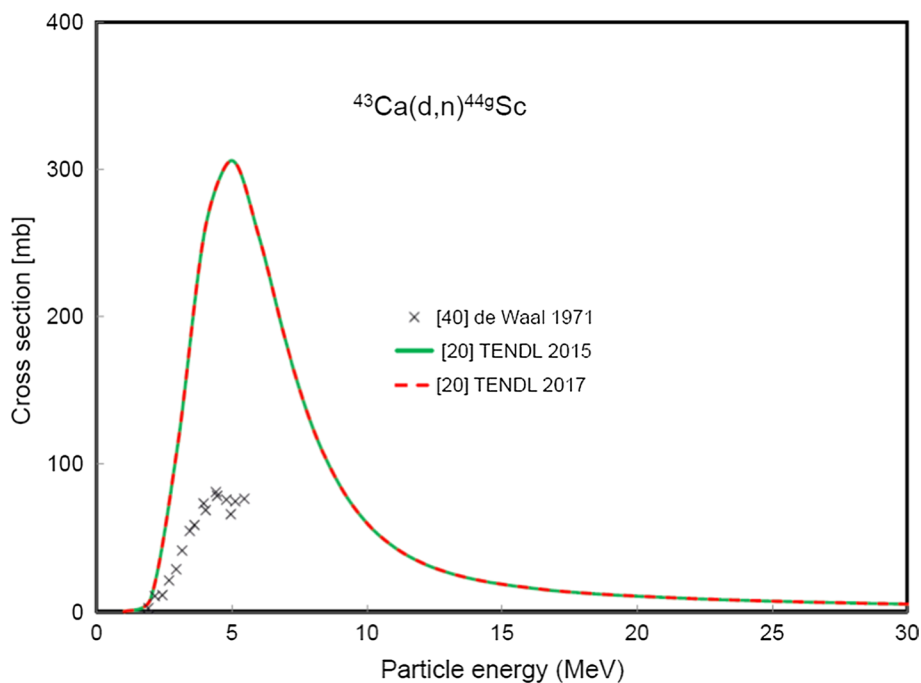
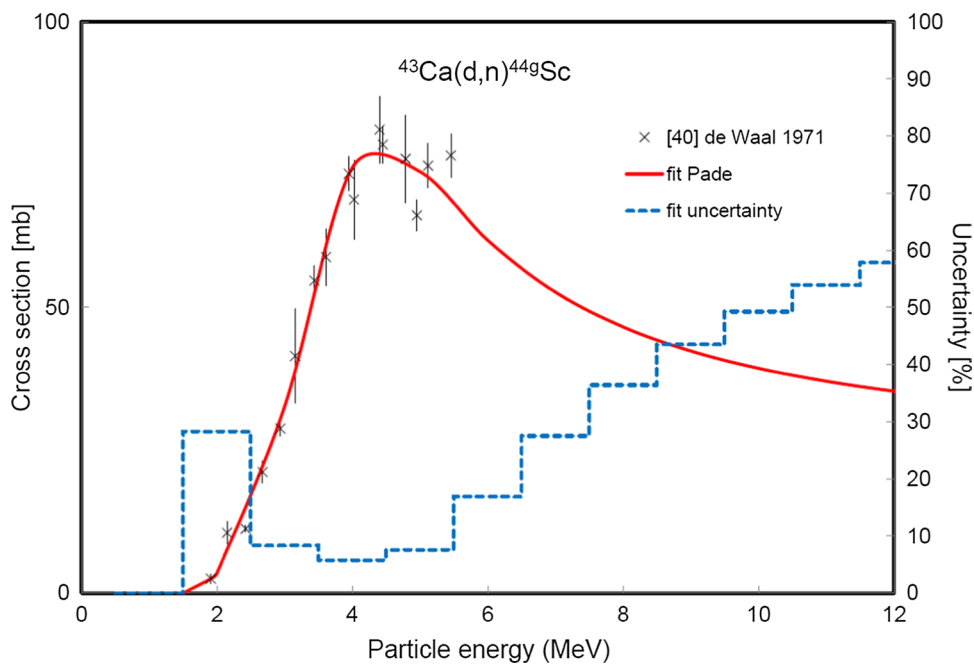


Fig. 6 Experimental dataset for the $^{43}\text{Ca}(\text{d},\text{n})^{44\text{g}}\text{Sc}$ reaction [40] with the Padé fit ($L=5$, $N=16$, $\chi^2=1.49$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{45}\text{Sc}(p,2n)^{44}\text{Ti}$

The five experimental datasets available in the literature are shown in Fig. 7 [36, 41–43] together with the TENDL calculations—Ref. [42] contains two sets labelled (a) and (b). Three datasets were rejected (both datasets of Ejnisman et al. [42],

and McGee et al. [41] exhibit significant disagreement), while the remaining two datasets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 8 together with the Padé fit ($L=7$, $N=26$, $\chi^2=1.58$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 7 Five experimental datasets for the $^{45}\text{Sc}(p,2n)^{44}\text{Ti}$ reaction available in the literature [36, 41–43], and TENDL calculations

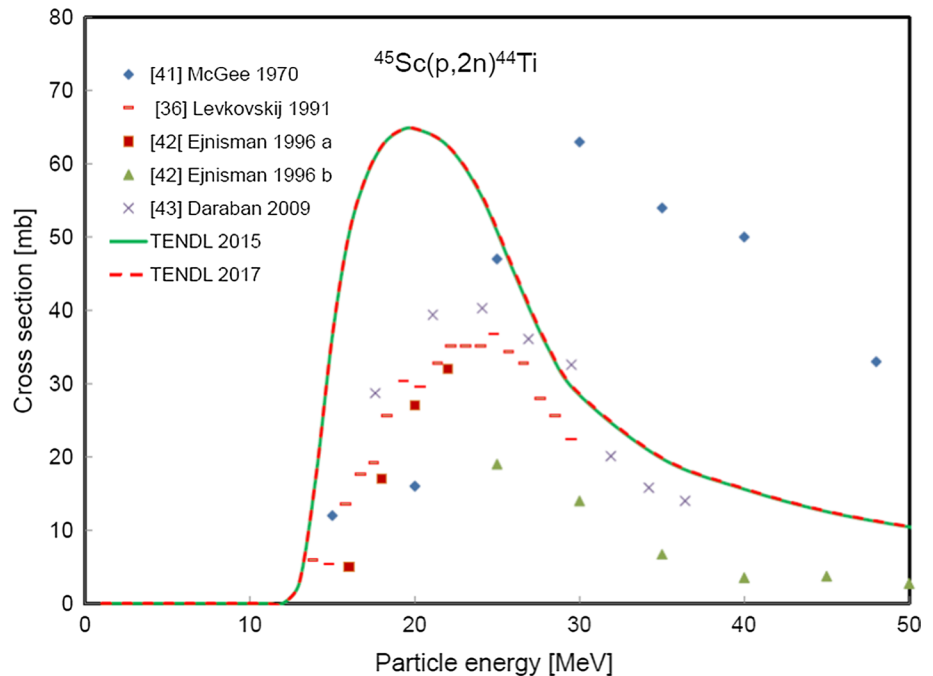
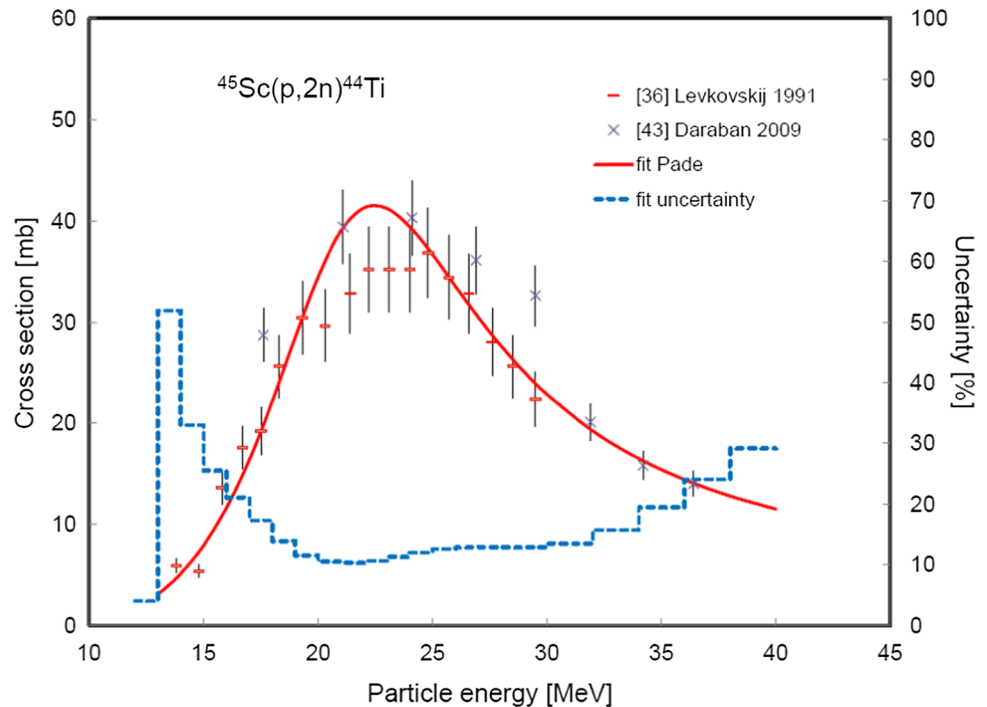


Fig. 8 Two selected experimental datasets for the $^{45}\text{Sc}(p,2n)^{44}\text{Ti}$ reaction [36, 43] with the Padé fit ($L=7$, $N=26$, $\chi^2=1.58$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{45}\text{Sc}(d,3n)^{44}\text{Ti}$

Only one experimental dataset is available in the literature, and is shown in Fig. 9 [44] together with the TENDL calculations. These data and their experimental uncertainties are

shown in Fig. 10 together with the Padé fit ($L=6$, $N=18$, $\chi^2=0.406$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 9 One experimental dataset for the $^{45}\text{Sc}(d,3n)^{44}\text{Ti}$ reaction available in the literature [44], and TENDL calculations

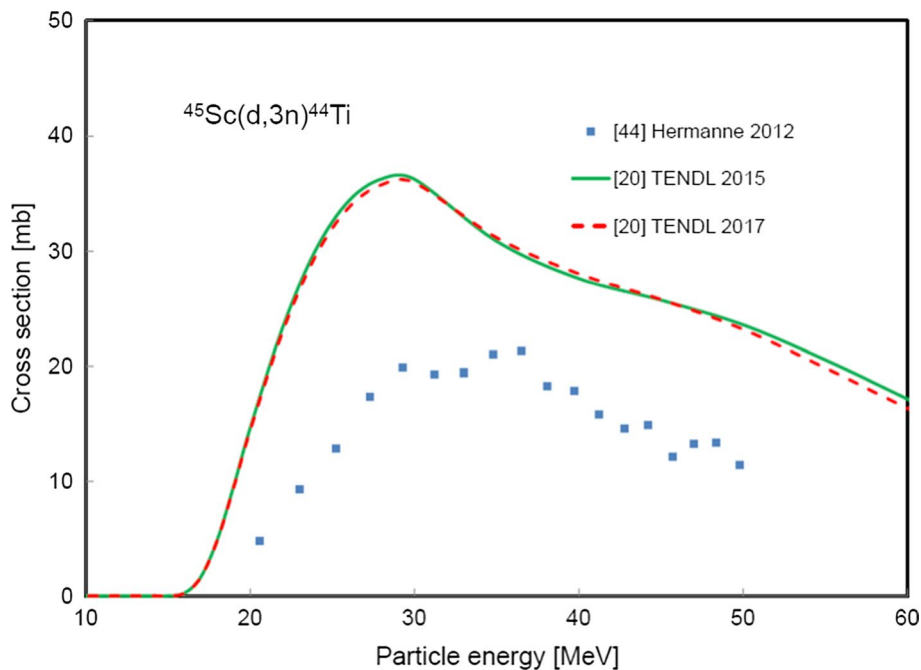
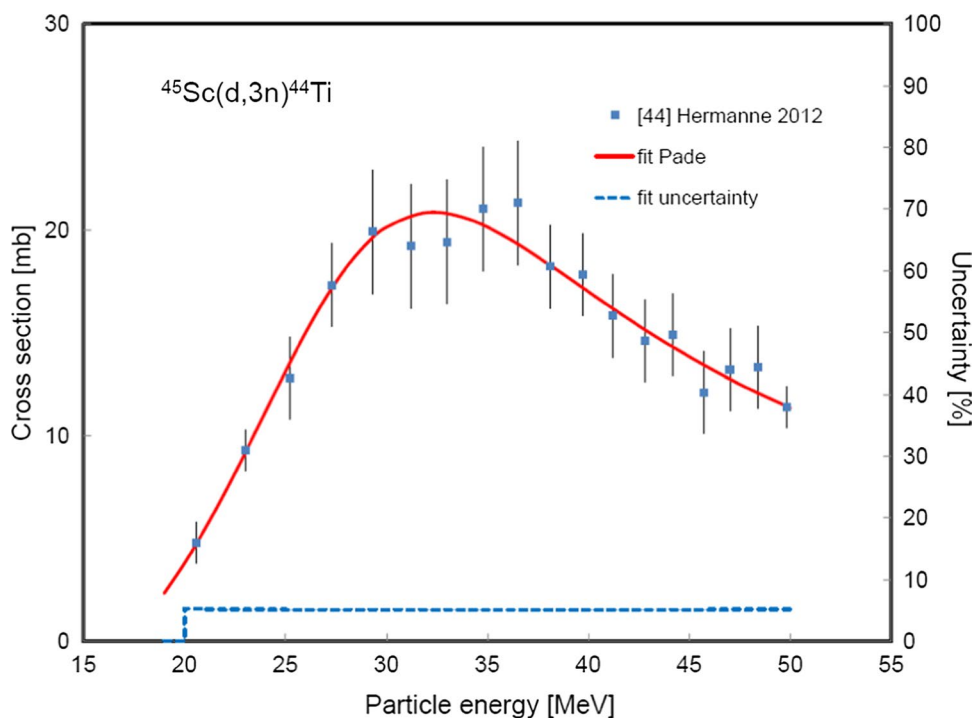


Fig. 10 One experimental dataset for the $^{45}\text{Sc}(d,3n)^{44}\text{Ti}$ reaction [44] with the Padé fit ($L=6$, $N=18$, $\chi^2=0.406$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{44g}Sc , and long-lived ^{44}Ti parent

See Figs. 11 and 12.

Fig. 11 Thick target yields calculated from the recommended cross sections for the $^{44}\text{Ca}(p,n)^{44g}\text{Sc}$, $^{44}\text{Ca}(d,2n)^{44g}\text{Sc}$ and $^{43}\text{Ca}(d,n)^{44g}\text{Sc}$ reactions

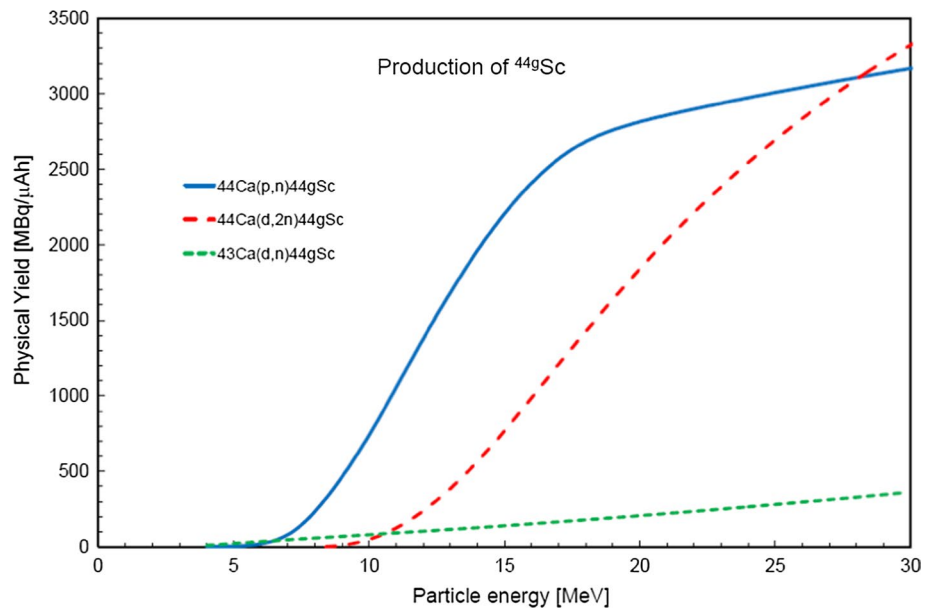
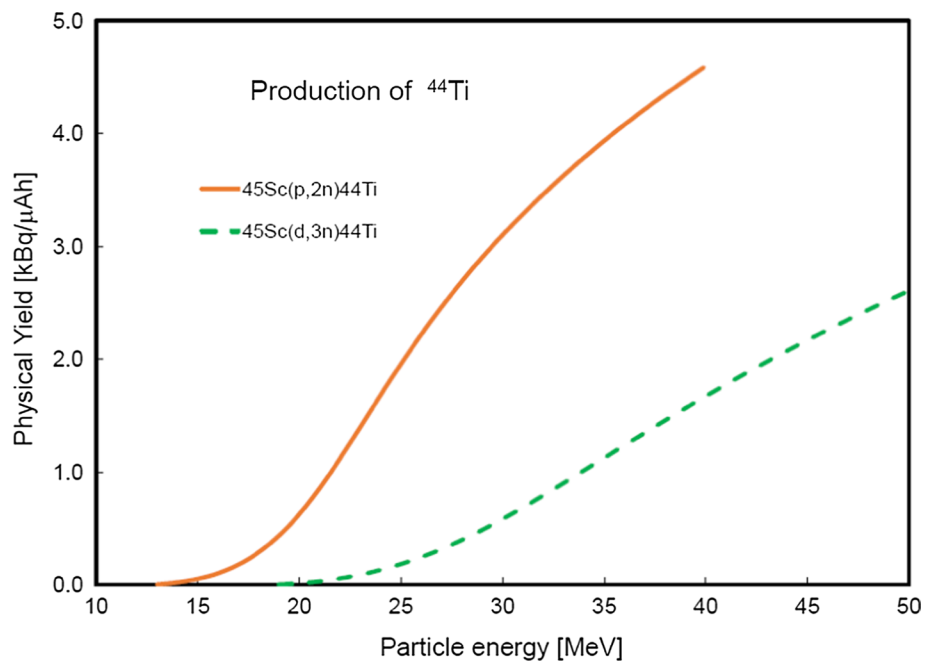


Fig. 12 Thick target yields calculated from the recommended cross sections for the $^{45}\text{Sc}(p,2n)^{44}\text{Ti}$ and $^{45}\text{Sc}(d,3n)^{44}\text{Ti}$ reactions to produce long-lived parent for ^{44}Sc generator



Production of ^{52m}Mn ($T_{1/2} = 21.1$ min) and longer-lived ^{52}Fe parent ($T_{1/2} = 8.275$ h)

Applications: ^{52m}Mn has been suggested for myocardial and cerebral perfusion imaging, more recently for studies similar to Mn-enhanced neuronal MRI, and for diagnosis in other organ systems—bones, spinal cord and the digestive tract.

^{52m}Mn (21.1 min): β^+ (96.6%), and E_γ (keV) (P_γ (%)): 1434.092 (98.2).

^{52}Fe (8.275 h): detected by means of radiation emitted from daughter ^{52m}Mn .

Evaluations have been made of the $^{52}\text{Cr}(p,n)^{52m}\text{Mn}$ and $^{52}\text{Cr}(d,2n)^{52m}\text{Mn}$ direct production routes and $^{nat}\text{Ni}(p,x)^{52}\text{Fe}$,

$^{55}\text{Mn}(p,4n)^{52}\text{Fe}$ and $^{50}\text{Cr}(\alpha,2n)^{52}\text{Fe}$ reactions for indirect production through decay of the longer-lived parent.

$^{nat}\text{Ni}(p,x)^{52}\text{Fe}$

The four experimental datasets available in the literature are shown in Fig. 13 [45–48] together with the TENDL calculations. One set was rejected (Titarenko et al. [47], values too high), and the remaining three datasets were used in the statistical fitting procedure. These selected data and their experimental uncertainties are shown in Fig. 14 together with the Padé fit ($L = 11$, $N = 41$, $\chi^2 = 0.57$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 13 Four experimental datasets for the $^{nat}\text{Ni}(p,x)^{52}\text{Fe}$ reaction available in the literature [45–48], and TENDL calculations

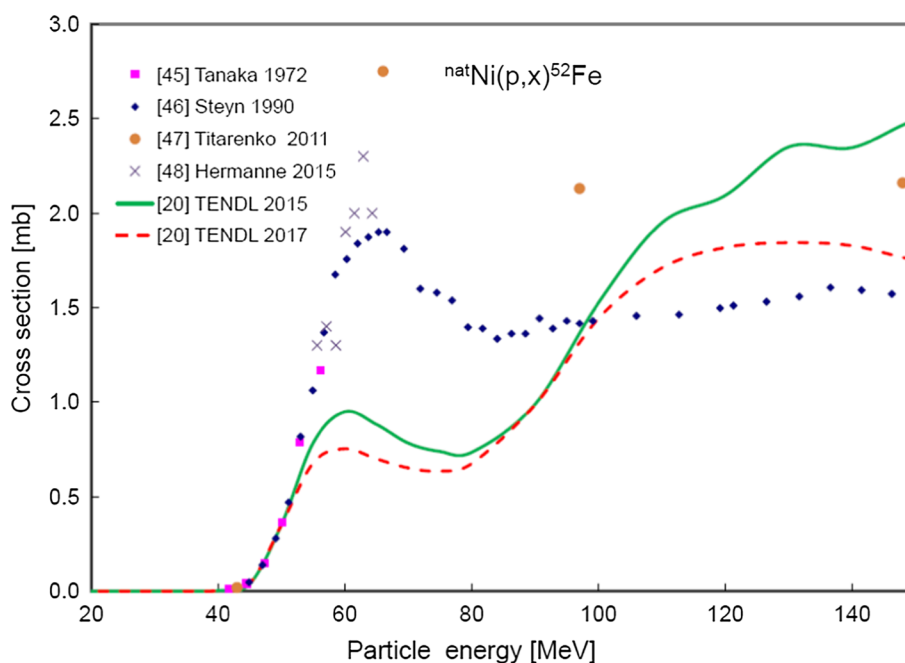
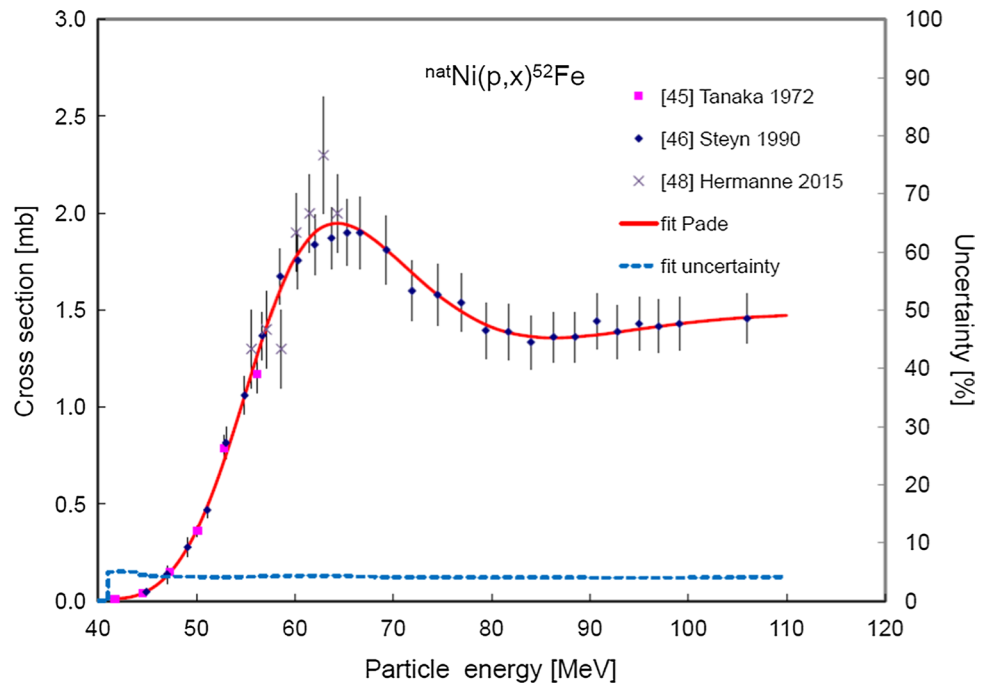


Fig. 14 Three selected experimental datasets for the ${}^{\text{nat}}\text{Ni}(p,x){}^{52}\text{Fe}$ reaction [45, 46, 48] with the Padé fit ($L=11$, $N=41$, $\chi^2=0.57$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{55}\text{Mn}(p,4n)^{52}\text{Fe}$

The four experimental datasets available in the literature are shown in Fig. 15 [46, 49–51] together with the TENDL calculations. All sets were used for the statistical fitting

procedure. These data and their experimental uncertainties are shown in Fig. 16 together with the Padé fit ($L=17$, $N=157$, $\chi^2=1.01$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 15 Four experimental datasets for the $^{55}\text{Mn}(p,4n)^{52}\text{Fe}$ reaction available in the literature [46, 49–51], and TENDL calculations

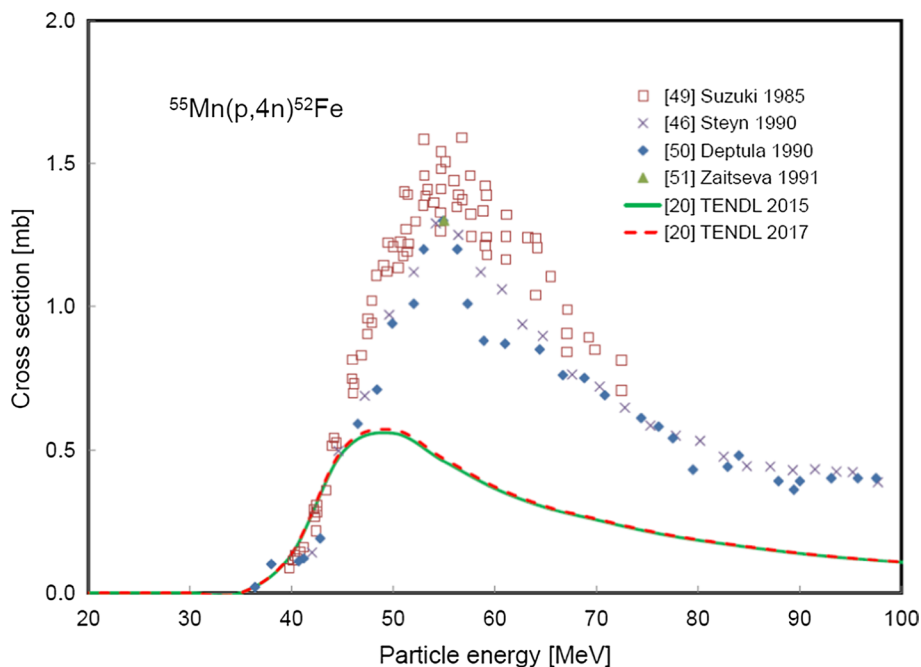
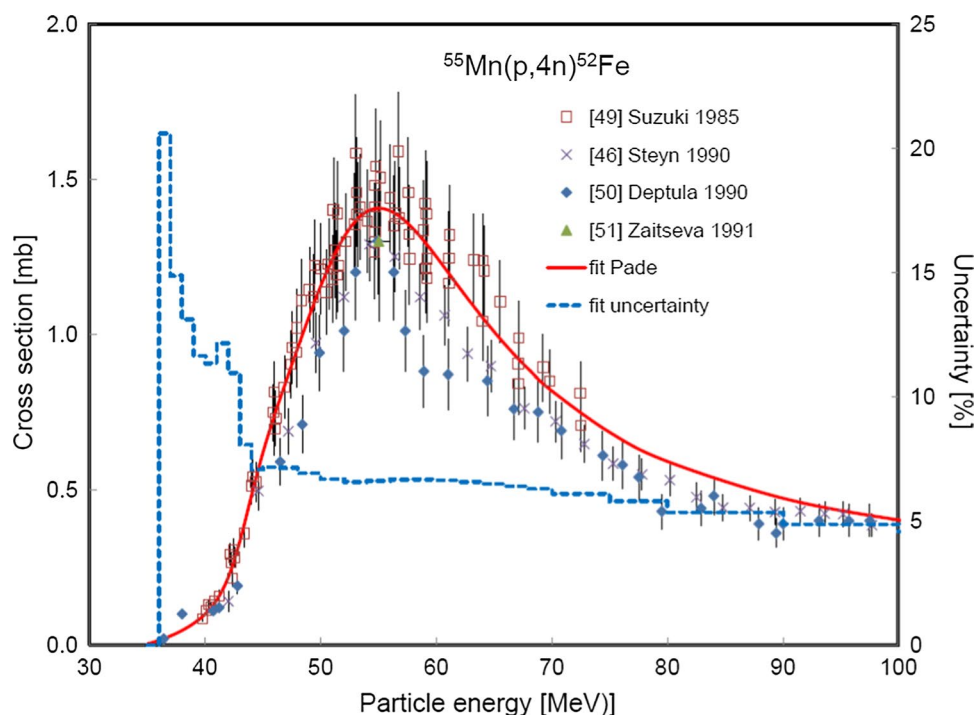


Fig. 16 Four experimental datasets for the $^{55}\text{Mn}(p,4n)^{52}\text{Fe}$ reaction [46, 49–51] with the Padé fit ($L=17$, $N=157$, $\chi^2=1.01$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{50}\text{Cr}(\alpha,2n)^{52}\text{Fe}$

The four experimental datasets available in the literature are shown in Fig. 17 [36, 52–54] together with the TENDL calculations. Two datasets were rejected (Akiha et al. [52], energy shift; Chowdhury et al. [53], unusual shape, with one outlying data point at 27.3 MeV not represented in Fig. 17),

while the remaining two datasets were used in the statistical fitting procedure. Both the selected data and their experimental uncertainties are shown in Fig. 18 together with the Padé fit ($L=9$, $N=52$, $\chi^2=0.616$, solid line) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 17 Four experimental datasets for the $^{50}\text{Cr}(\alpha,2n)^{52}\text{Fe}$ reaction available in the literature [36, 52–54], and TENDL calculations

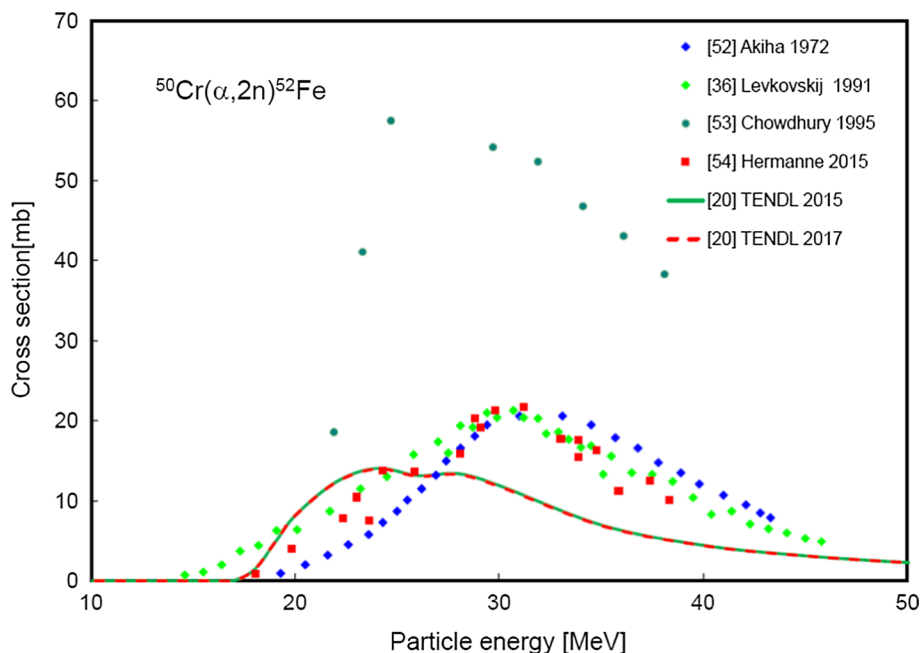
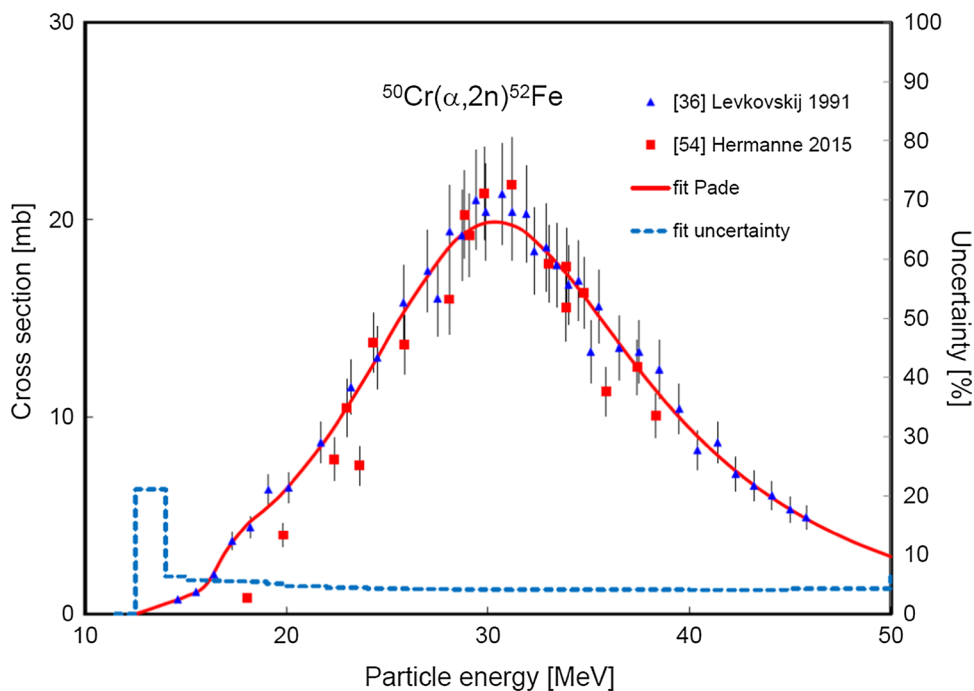


Fig. 18 Two selected experimental datasets for the $^{50}\text{Cr}(\alpha,2n)^{52}\text{Fe}$ reaction [36, 54] with the Padé fit ($L=9$, $N=52$, $\chi^2=0.616$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{52}\text{Cr}(p,n)^{52m}\text{Mn}$

The nine experimental datasets available in the literature are shown in Fig. 19 [36, 55–62] together with the TENDL calculations. Three datasets were rejected (Blosser and Handley [56], Wing and Huizenga [58], and West et al. [62], all

values too high), while the remaining six datasets were used in the statistical fitting procedure. Both the selected data and their experimental uncertainties are shown in Fig. 20 together with the Padé fit ($L=14$, $N=68$, $\chi^2=1.15$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 19 Nine experimental datasets for the $^{52}\text{Cr}(p,n)^{52m}\text{Mn}$ reaction available in the literature [36, 55–62], and TENDL calculations

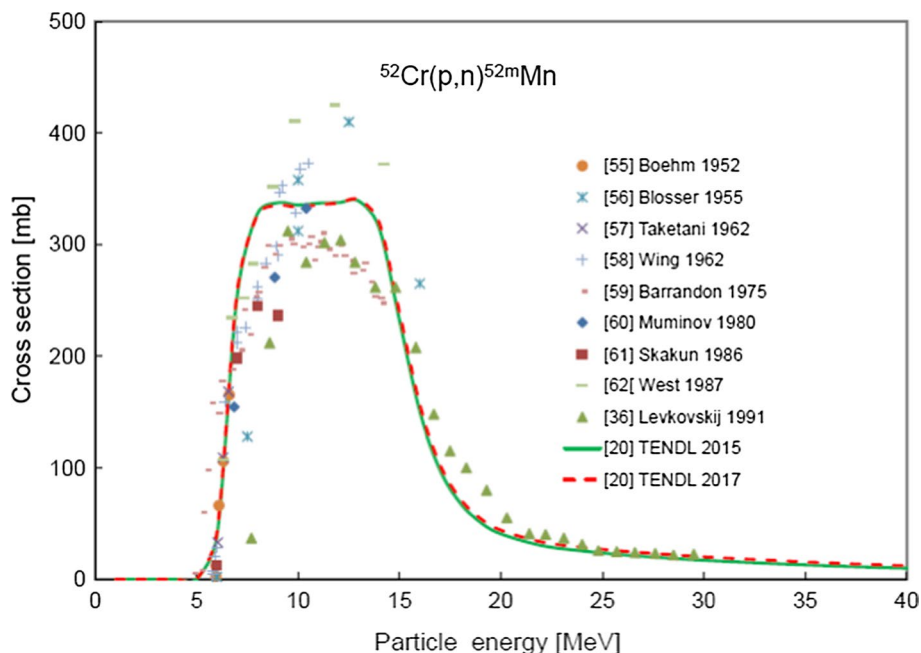
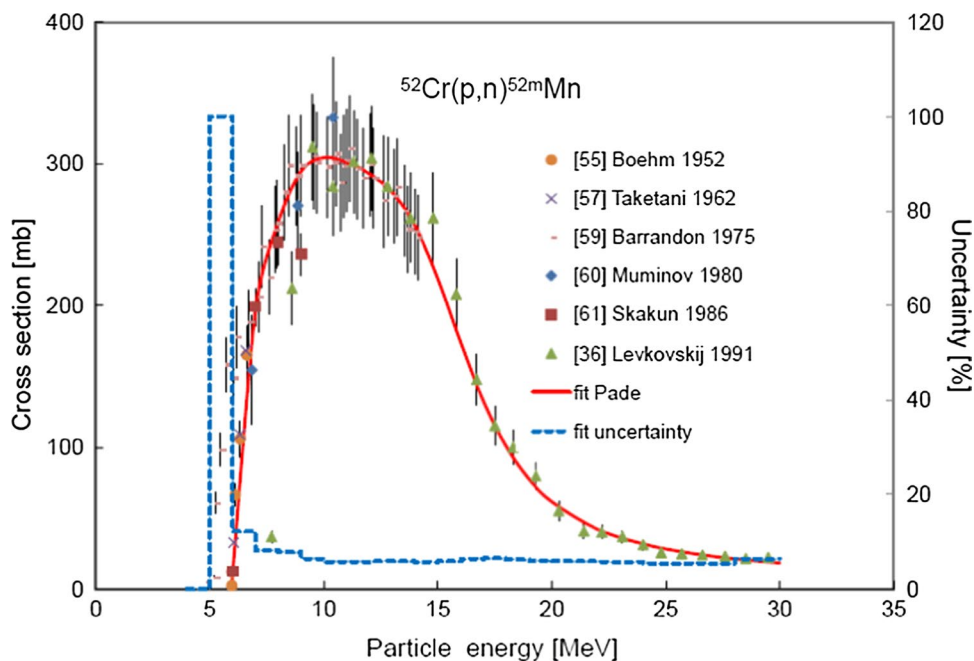


Fig. 20 Six selected experimental datasets for the $^{52}\text{Cr}(p,n)^{52m}\text{Mn}$ reaction [36, 55, 57, 59–61] with the Padé fit ($L=14$, $N=68$, $\chi^2=1.15$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{52}\text{Cr}(d,2n)^{52m}\text{Mn}$

The two experimental datasets available in the literature are shown in Fig. 21 [62, 63] together with the TENDL calculations. Both datasets were used for the statistical fitting

procedure. These data and their experimental uncertainties are shown in Fig. 22 together with the Padé fit ($L=8$, $N=16$, $\chi^2=0.71$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 21 Two experimental datasets for the $^{52}\text{Cr}(d,2n)^{52m}\text{Mn}$ reaction available in the literature [62, 63], and TENDL calculations

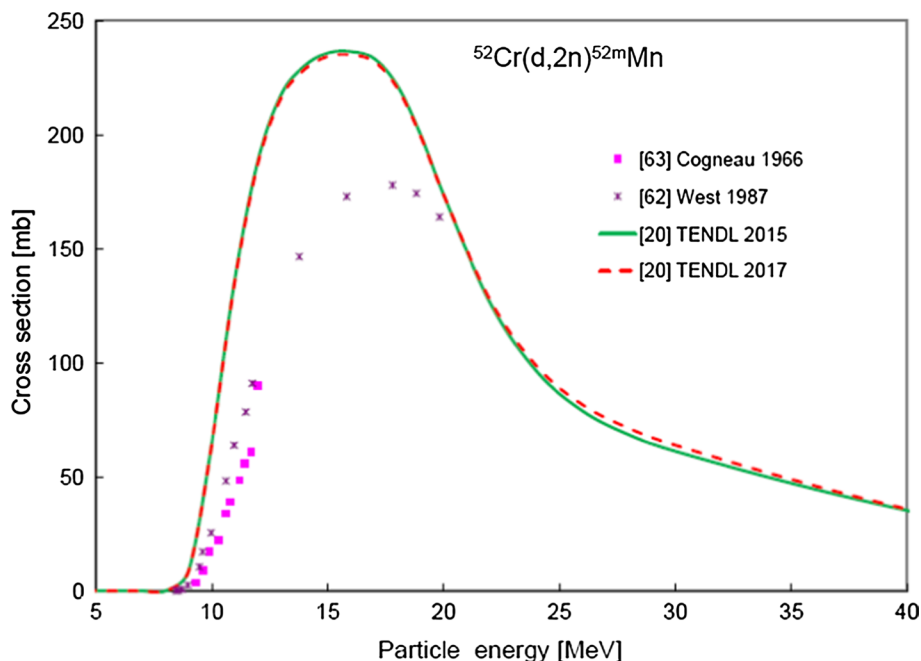
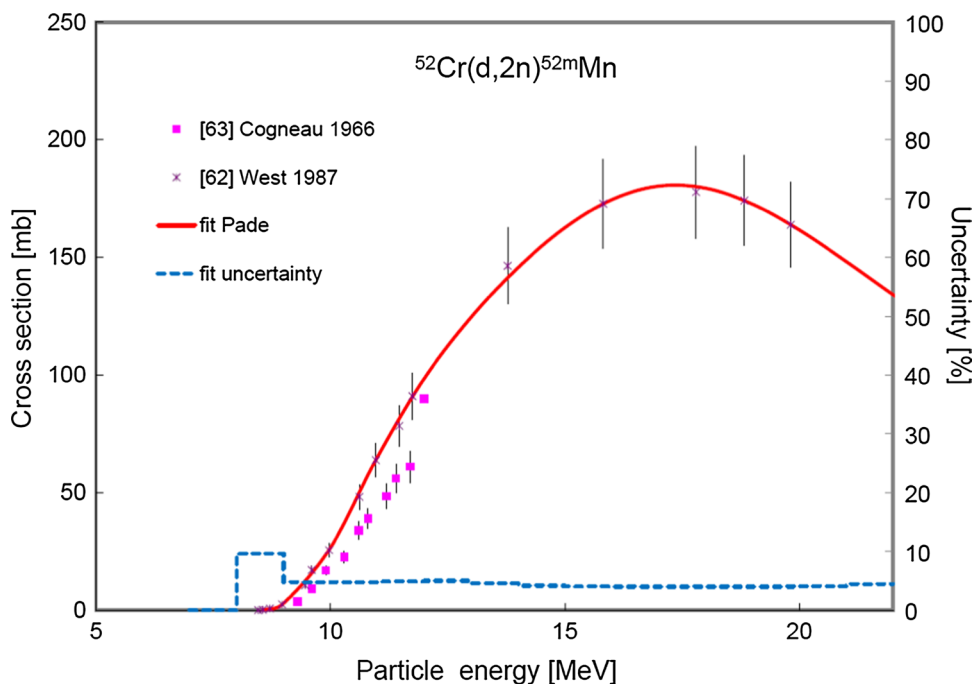


Fig. 22 Two experimental datasets for the $^{52}\text{Cr}(d,2n)^{52m}\text{Mn}$ reaction [62, 63] with the Padé fit ($L=8$, $N=16$, $\chi^2=0.71$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{52m}Mn , and long-lived ^{52}Fe parent

See Figs. 23 and 24.

Fig. 23 Thick target yields calculated from the recommended cross sections for the $^{52}\text{Cr}(p,n)^{52m}\text{Mn}$ and $^{52}\text{Cr}(d,2n)^{52m}\text{Mn}$ reactions

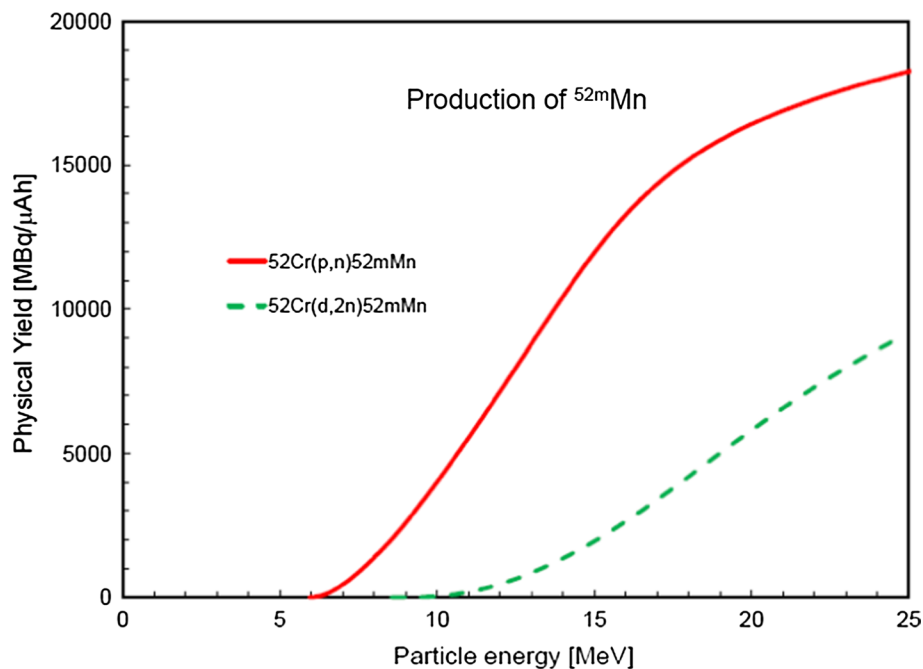
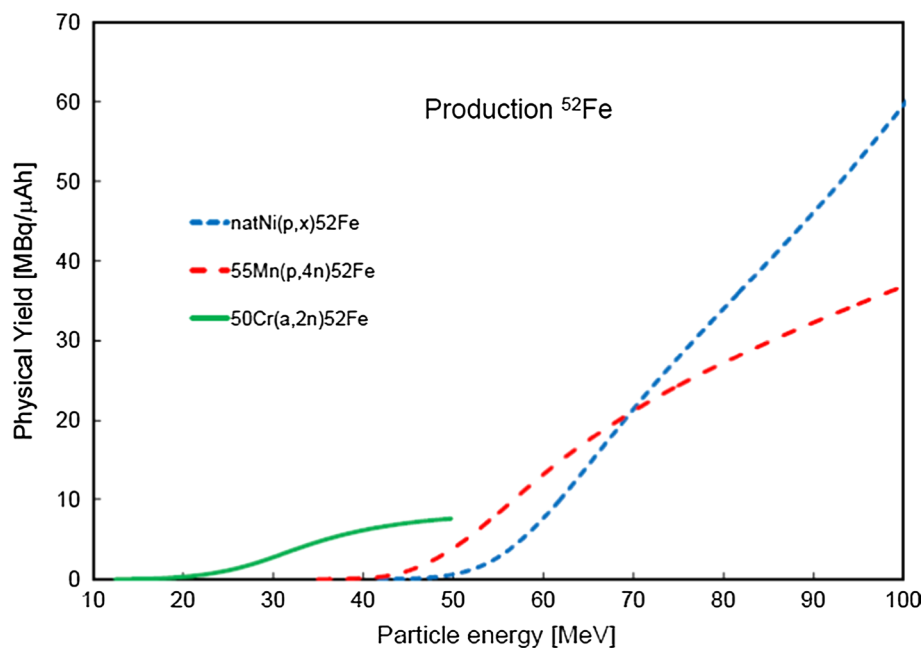


Fig. 24 Thick target yields calculated from the recommended cross sections for the $^{\text{nat}}\text{Ni}(p,x)^{52}\text{Fe}$, $^{55}\text{Mn}(p,4n)^{52}\text{Fe}$ and $^{50}\text{Cr}(\alpha,2n)^{52}\text{Fe}$ parent reactions



Production of ^{52g}Mn ($T_{1/2} = 5.591$ d)

Applications: The longer-lived ^{52}Mn ground state has potential as a PET tracer for preclinical in vivo neuroimaging and other applications such as cell tracking, immuno-PET and functional β -cell mass quantification. Unfortunately, a half-life of 5.591 d coupled with an extremely high radiation burden that arises from the resulting gamma-ray emissions has limited ^{52g}Mn clinical applications.

^{52g}Mn (5.591 d): β^+ (29.4%), and E_γ (keV) (P_γ (%)): 744.233 (90.0), 935.544 (94.5), 1434.092 (100).

Evaluations have been made of the direct $^{52}\text{Cr}(p,n)^{52g}\text{Mn}(m+)$ and $^{52}\text{Cr}(d,2n)^{52g}\text{Mn}(m+)$ production routes, including the partial decay of the simultaneously produced short-lived ^{52m}Mn metastable state ($IT = 1.78\%$, noted as $(m+)$) which has already been assessed and discussed in section “Production of ^{52m}Mn ($T_{1/2} = 21.1$ min) and longer-lived ^{52}Fe parent ($T_{1/2} = 8.275$ h)”.

$^{52}\text{Cr}(p,n)^{52g}\text{Mn}(m+)$

The thirteen experimental datasets available in the literature are shown in Fig. 25 [36, 55, 56, 58, 59, 61, 62, 64–69] together with the TENDL calculations. Six sets of data were rejected (Blosser and Handley [56], Tanaka and Furukawa [64], Lindner and James [65], Antropov et al. [66], Buchholz et al. [67], and Zherebchevsky et al. [69], all disagree significantly with the other datasets), while the remaining seven datasets were used in the statistical fitting procedure. These selected data and their experimental uncertainties are shown in Fig. 26 together with the Padé fit ($L = 9$, $N = 103$, $\chi^2 = 1.84$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 25 Thirteen experimental datasets for the $^{52}\text{Cr}(p,n)^{52g}\text{Mn}(m+)$ reaction available in the literature [36, 55, 56, 58, 59, 61, 62, 64–69], and TENDL calculations

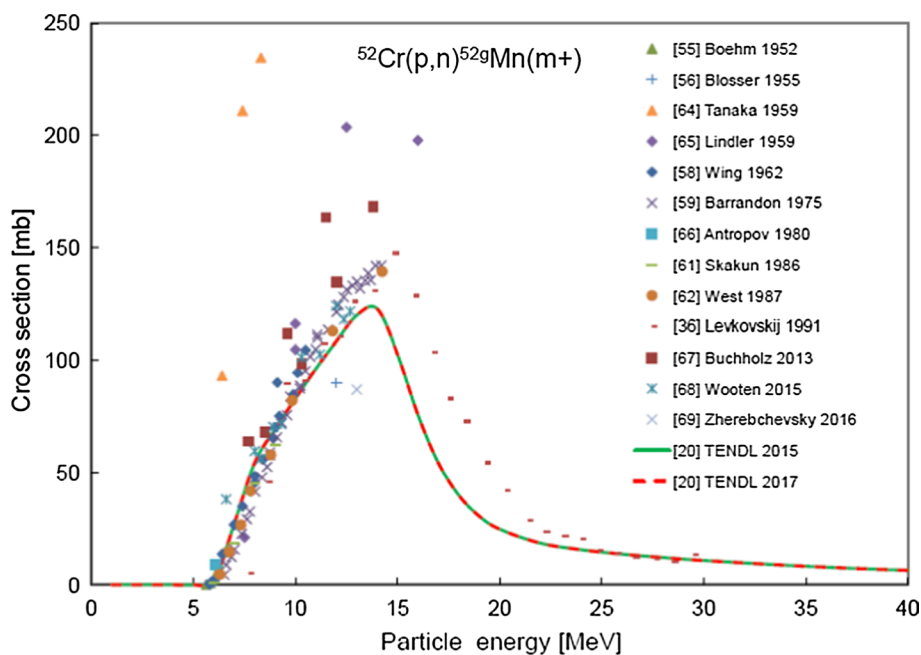
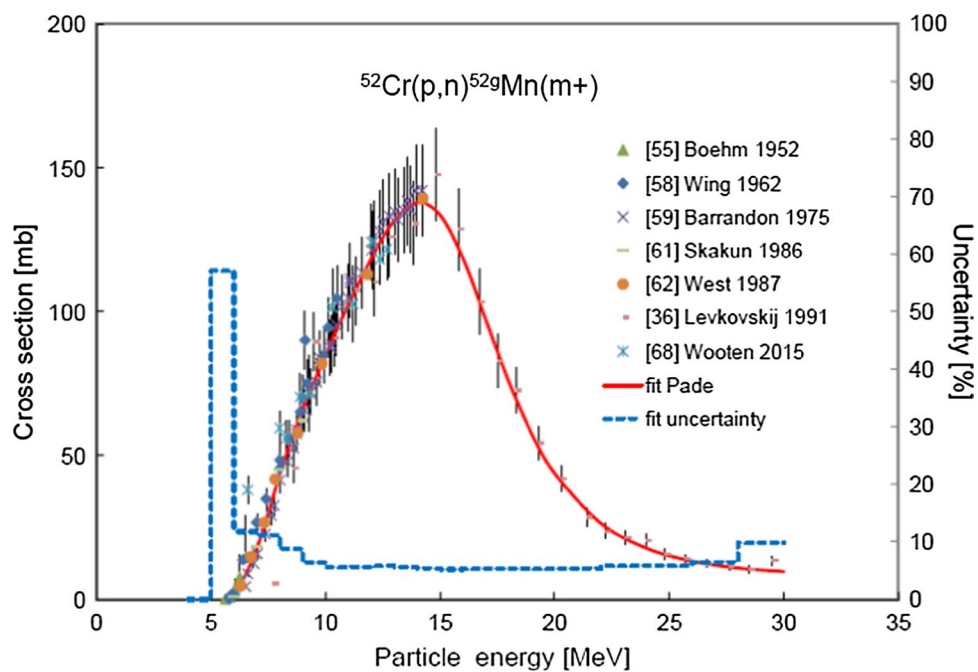


Fig. 26 Seven selected experimental datasets for the $^{52}\text{Cr}(p,n)^{52}\text{gMn}(m+)$ reaction [36, 55, 58, 59, 61, 62, 68] with the Padé fit ($L=9$, $N=103$, $\chi^2=1.84$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{52}\text{Cr}(d,2n)^{52g}\text{Mn}(m+)$

The six experimental datasets available in the literature are shown in Fig. 27 [62, 63, 70–73] together with the TENDL calculations. Two sets were rejected (Cheng Xiaowu et al. [71], values too low and no contribution from decay of meta-stable state marked as “g” in Fig. 27, and Nassiff and Münzel

[72], values too high), and the remaining four datasets were used in the statistical fitting procedure. These selected data and their experimental uncertainties are shown in Fig. 28 together with the Padé fit ($L=8, N=36, \chi^2=0.54$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 27 Six experimental datasets for the $^{52}\text{Cr}(d,2n)^{52g}\text{Mn}(m+)$ reaction available in the literature [62, 63, 70–73], and TENDL calculations

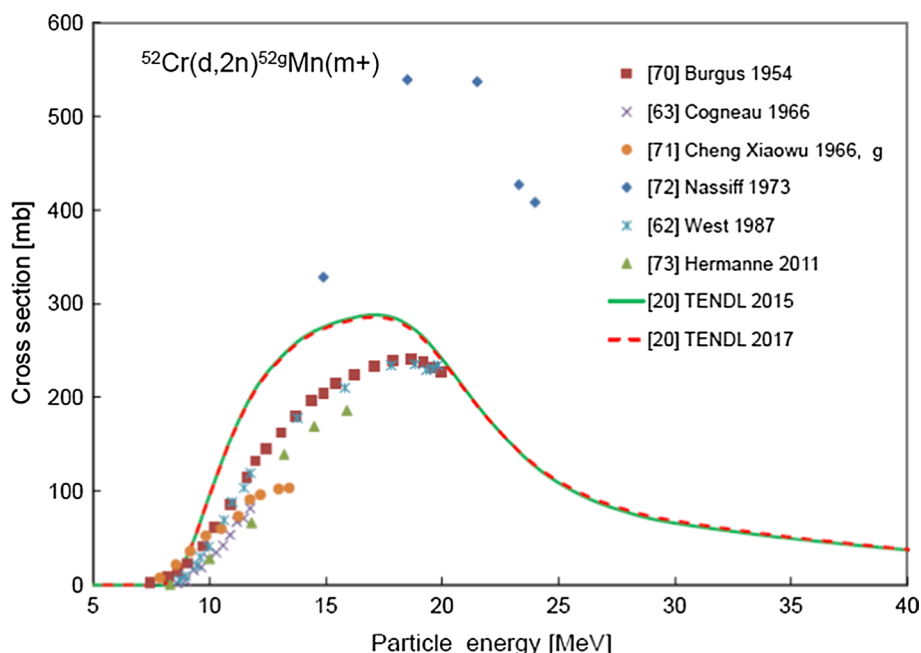
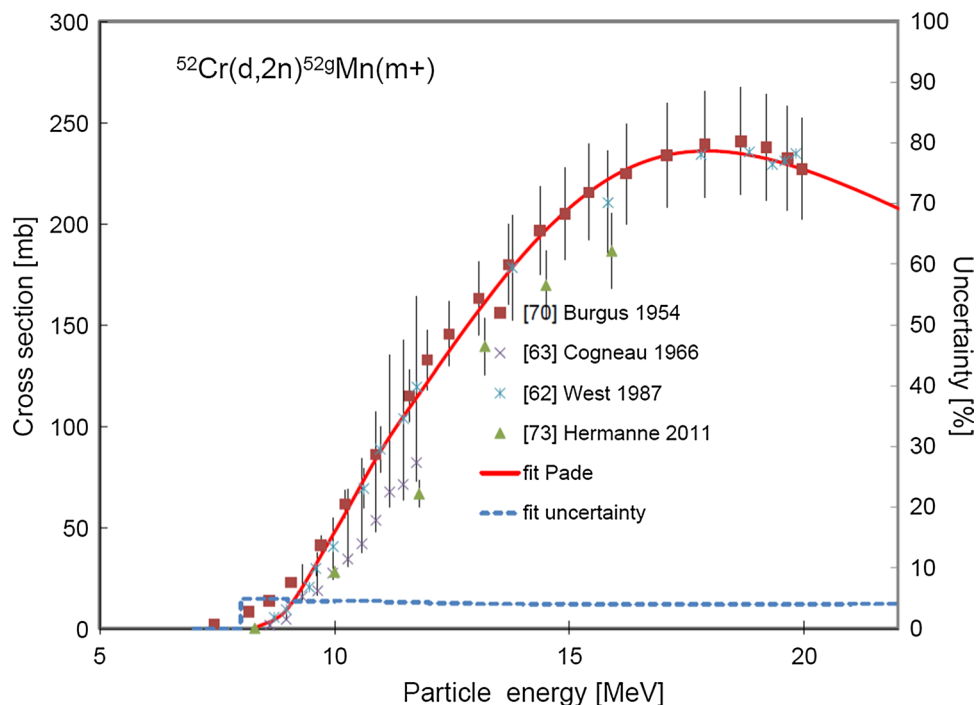


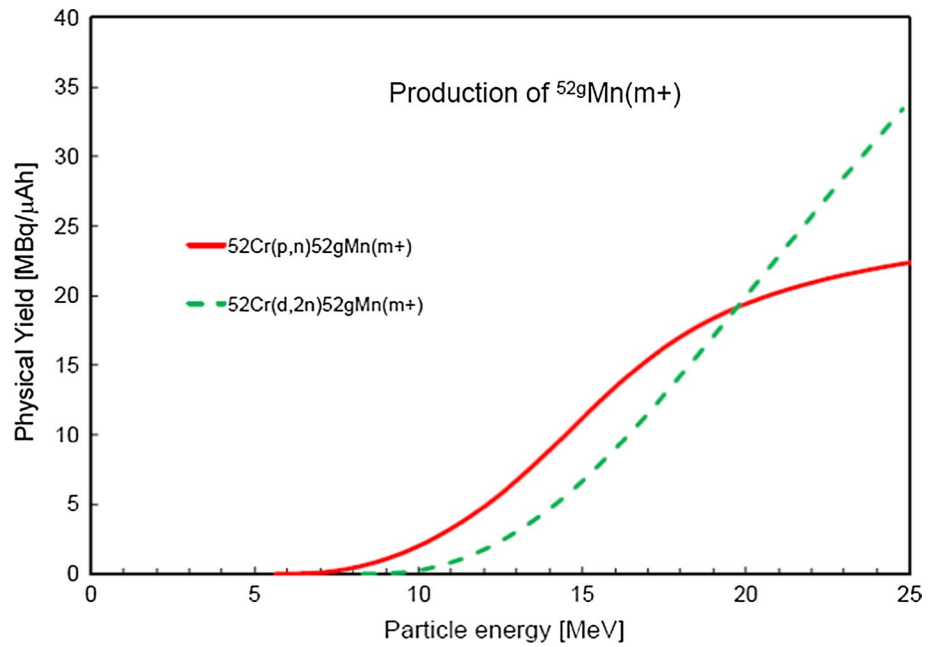
Fig. 28 Four selected experimental datasets for the $^{52}\text{Cr}(d,2n)^{52g}\text{Mn}(m+)$ reaction [62, 63, 70, 73] with the Padé fit ($L=8, N=36, \chi^2=0.54$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of $^{52g}\text{Mn}(m+)$

See Fig. 29.

Fig. 29 Thick target yields calculated from the recommended cross sections for the $^{52}\text{Cr}(p,n)^{52g}\text{Mn}(m+)$ and $^{52}\text{Cr}(d,2n)^{52g}\text{Mn}(m+)$ reactions



Production of ^{55}Co ($T_{1/2} = 17.53\text{ h}$)

Applications: ^{55}Co is a typical example of a positron emitter of sufficient half-life to follow kinetic processes that function over a longer timescale. This radionuclide has been used to target the epidermal growth factor (EGFR) by means of labelled DOTA-conjugated Affibody. Exhibits lower liver and heart uptake for metal-chelate peptide complexes, with improved performance when compared with ^{68}Ga . Also used as a Ca^{2+} analogue in imaging studies of Alzheimer disease, and shows promise in achieving improved imaging of cancer diseases.

^{55}Co (17.53 h): β^+ (76%), and E_γ (keV) ($P_\gamma(\%)$): 931.1 (75), 1316.6 (7.1).

$^{58}\text{Ni}(p,\alpha)^{55}\text{Co}$, $^{54}\text{Fe}(d,n)^{55}\text{Co}$ and $^{56}\text{Fe}(p,2n)^{55}\text{Co}$ production routes have been evaluated.

$^{58}\text{Ni}(p,\alpha)^{55}\text{Co}$

The seventeen experimental datasets available in the literature are shown in Fig. 30 [36, 45, 59, 74–87] together with the TENDL calculations. One dataset was rejected (Haasbroek et al. [76], values too high), while the remaining sixteen datasets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 31 together with the Padé fit ($L = 10$, $N = 352$, $\chi^2 = 1.97$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 30 Seventeen experimental datasets for the $^{58}\text{Ni}(p,\alpha)^{55}\text{Co}$ reaction available in the literature [36, 45, 59, 74–87], and TENDL calculations

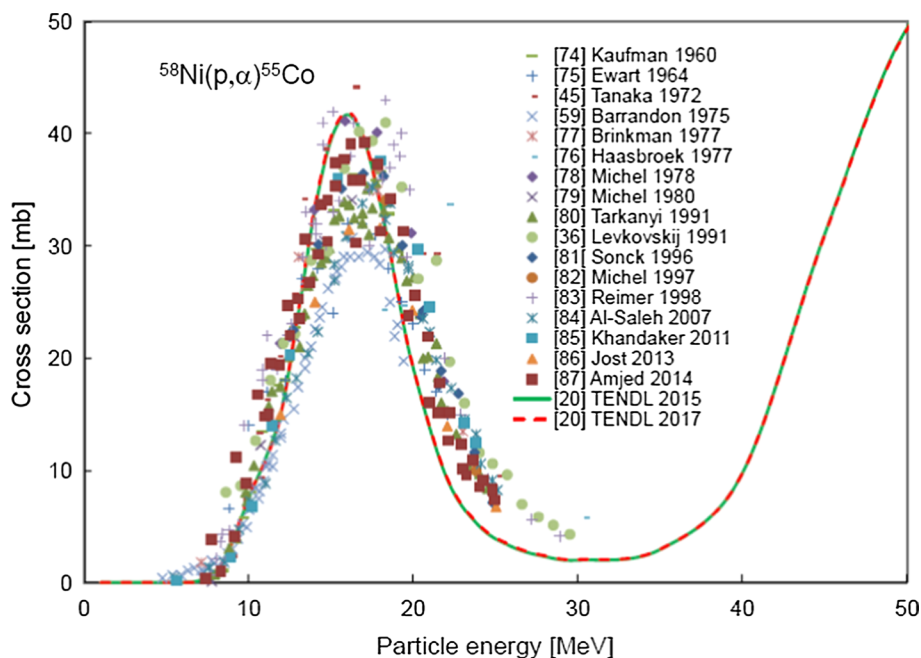
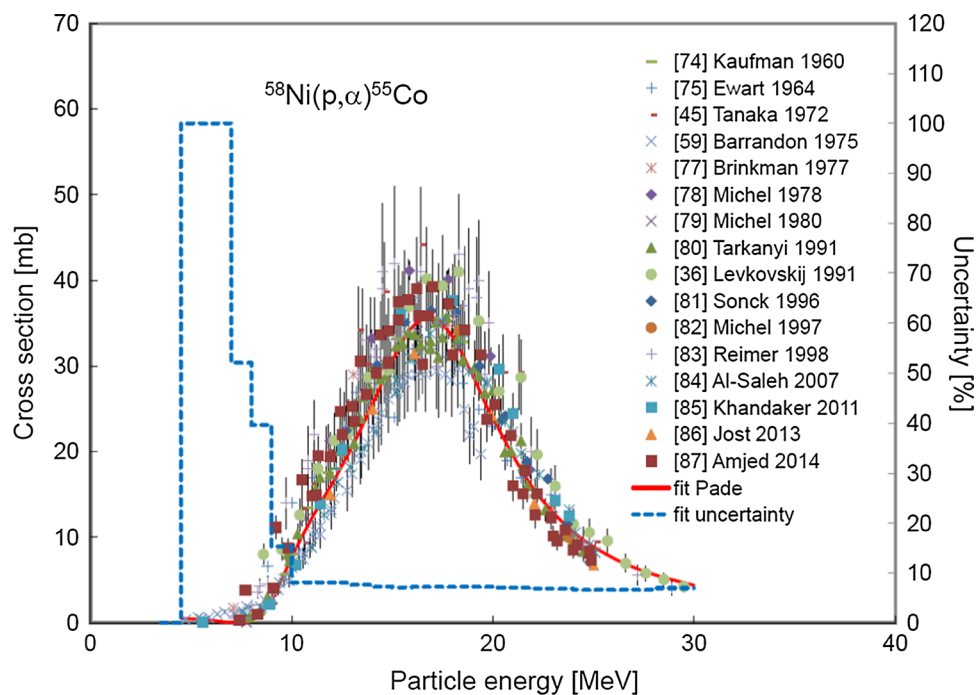


Fig. 31 Sixteen selected experimental datasets for the $^{58}\text{Ni}(p,\alpha)^{55}\text{Co}$ reaction [36, 45, 59, 74, 75, 77–87] with the Padé fit ($L=10$, $N=352$, $\chi^2=1.97$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{54}\text{Fe}(d,n)^{55}\text{Co}$

The ten experimental datasets available in the literature are shown in Fig. 32 [88–97] together with the TENDL calculations. One dataset was rejected (Clark et al. [89], values too high), while the remaining nine datasets were used in the statistical fitting procedure (although some

very discrepant points around 10 MeV from Hermanne [94] and the highest three points from Zhenlan [91] were also discarded). The selected data and their experimental uncertainties are shown in Fig. 33 together with the Padé fit ($L = 13$, $N = 170$, $\chi^2 = 2.14$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 32 Ten experimental datasets for the $^{54}\text{Fe}(d,n)^{55}\text{Co}$ reaction available in the literature [88–97], and TENDL calculations

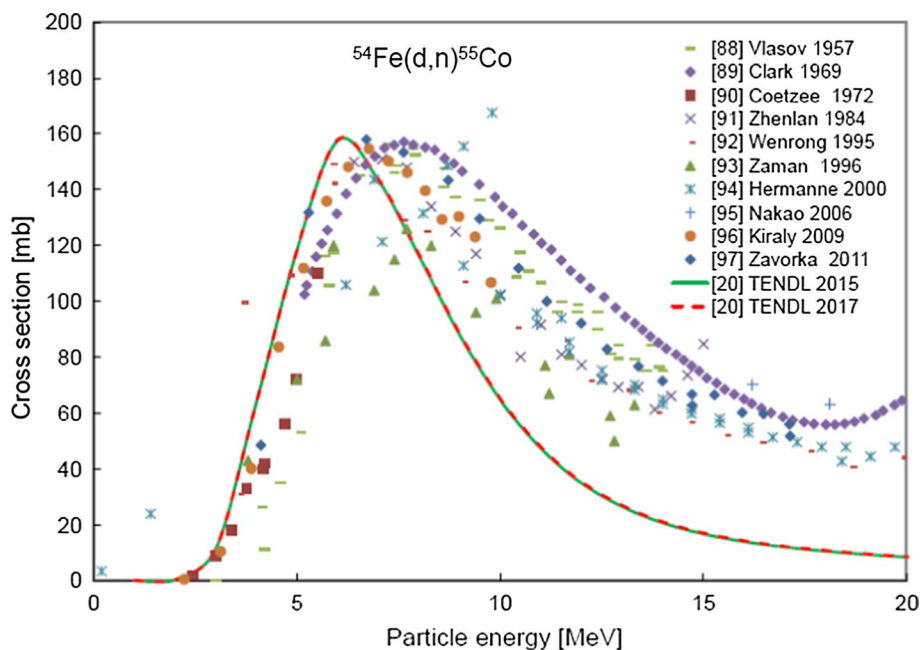
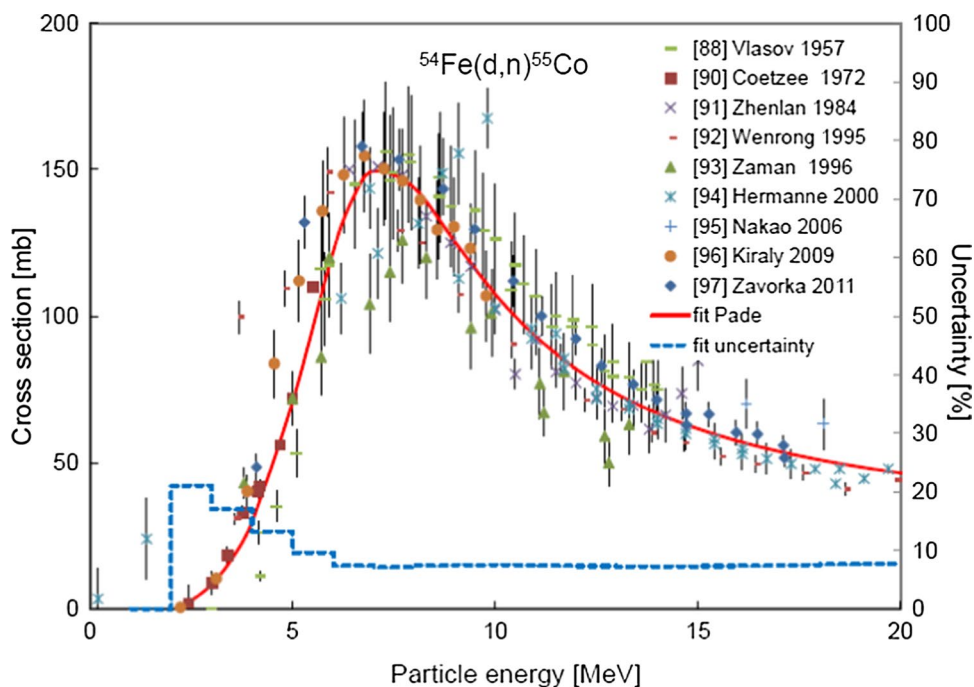


Fig. 33 Nine selected experimental datasets for the $^{54}\text{Fe}(d,n)^{55}\text{Co}$ reaction [88, 90–97] with the Padé fit ($L = 13$, $N = 170$, $\chi^2 = 2.14$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{56}\text{Fe}(p,2n)^{55}\text{Co}$

The fifteen experimental datasets available in the literature are shown in Fig. 34 [36, 59, 82, 98–109] together with the TENDL calculations. Four datasets were rejected (Michel et al. [82], Cohen and Newman [98], Williams and Fulmer [99], and Ditrói et al. [107], all show discrepant values), and

the remaining eleven sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 35 together with the Padé fit ($L=8$, $N=101$, $\chi^2=2.74$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 34 Fifteen experimental datasets for the $^{56}\text{Fe}(p,2n)^{55}\text{Co}$ reaction available in the literature [36, 59, 82, 98–109], and TENDL calculations

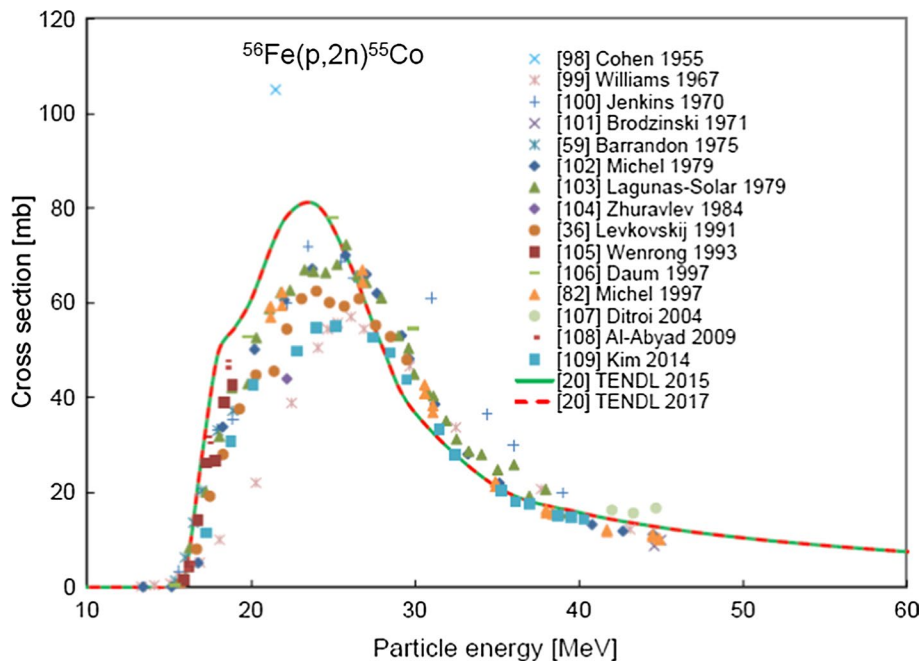
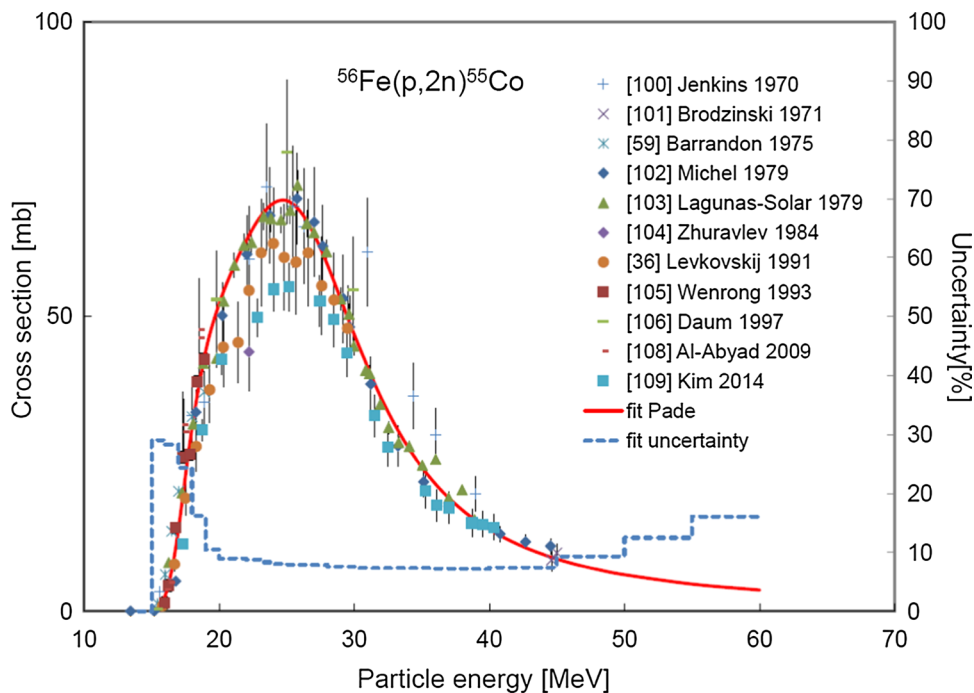


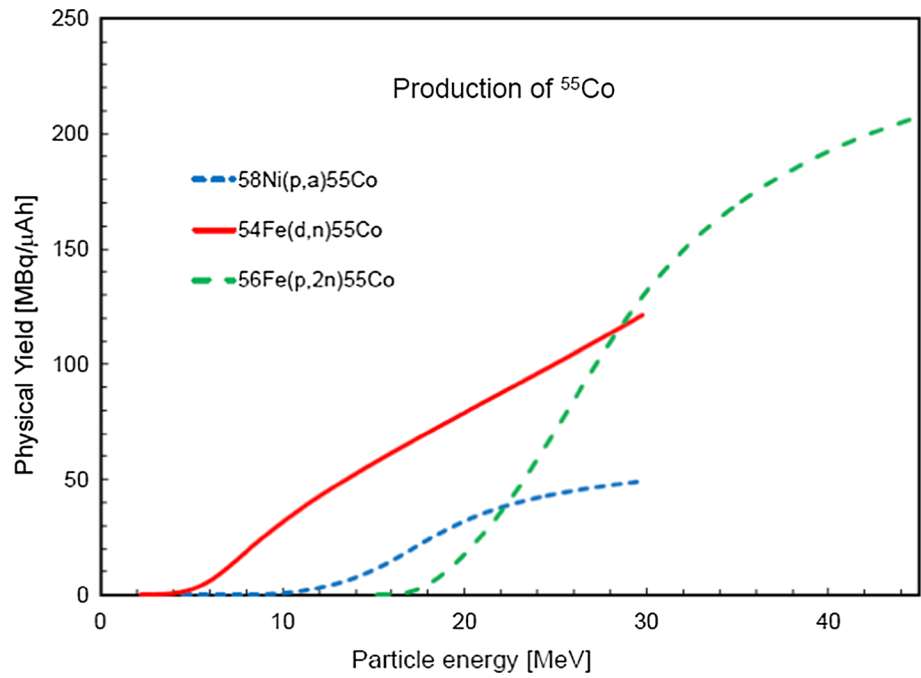
Fig. 35 Eleven selected experimental datasets for the $^{56}\text{Fe}(p,2n)^{55}\text{Co}$ reaction [36, 59, 100–106, 108, 109] with the Padé fit ($L=8$, $N=101$, $\chi^2=2.74$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{55}Co

See Fig. 36.

Fig. 36 Thick target yields calculated from the recommended cross sections for the $^{58}\text{Ni}(p,\alpha)^{55}\text{Co}$, $^{54}\text{Fe}(d,n)^{55}\text{Co}$ and $^{56}\text{Fe}(p,2n)^{55}\text{Co}$ reactions



Production of ^{61}Cu ($T_{1/2} = 3.339\text{ h}$)

Applications: Copper radionuclides form stable complexes with several chelators that can be conjugated to a wide variety of organic molecules for both imaging (^{61}Cu , ^{62}Cu , ^{64}Cu) and radiotherapy (^{64}Cu , ^{67}Cu). Relatively longer-lived ^{61}Cu ($T_{1/2} = 3.339\text{ h}$, 61% β^+ , 39% EC) possesses very good imaging properties that can be used for blood flow studies in a similar manner to ^{51}Cr . Also has been applied to blood pool imaging (DOTA-human serum albumin) and the study of hypoxia in tumours (coupled to ATSM)—useful for following kinetics processes of the order of a few hours.

^{61}Cu (3.339 h): β^+ (61%), and E_γ (keV) ($P_\gamma(\%)$): 282.956 (12.2), 656.008 (10.8), 1185.234 (3.7).

Evaluations have been made of the $^{61}\text{Ni}(p,n)^{61}\text{Cu}$, $^{60}\text{Ni}(d,n)^{61}\text{Cu}$ and $^{64}\text{Zn}(p,\alpha)^{61}\text{Cu}$ direct production routes.

$^{61}\text{Ni}(p,n)^{61}\text{Cu}$

The seventeen experimental datasets available in the literature are shown in Fig. 37 [45, 56, 59, 64, 78, 79, 84, 87, 110–117] together with the TENDL calculations. Ref. [112] contains two datasets, labelled (a) and (b). Five datasets were rejected (Blosser and Handley [56], Tanaka and Furukawa [64], Barrandon et al. [59], Michel et al. [78], and Al-Saleh et al. [84], all of these datasets exhibit maximum values that are too high), and the remaining twelve sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 38 together with the Padé fit ($L = 12$, $N = 192$, $\chi^2 = 2.81$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 37 Seventeen experimental datasets for the $^{61}\text{Ni}(p,n)^{61}\text{Cu}$ reaction available in the literature [45, 56, 59, 64, 78, 79, 84, 87, 110–117], and TENDL calculations

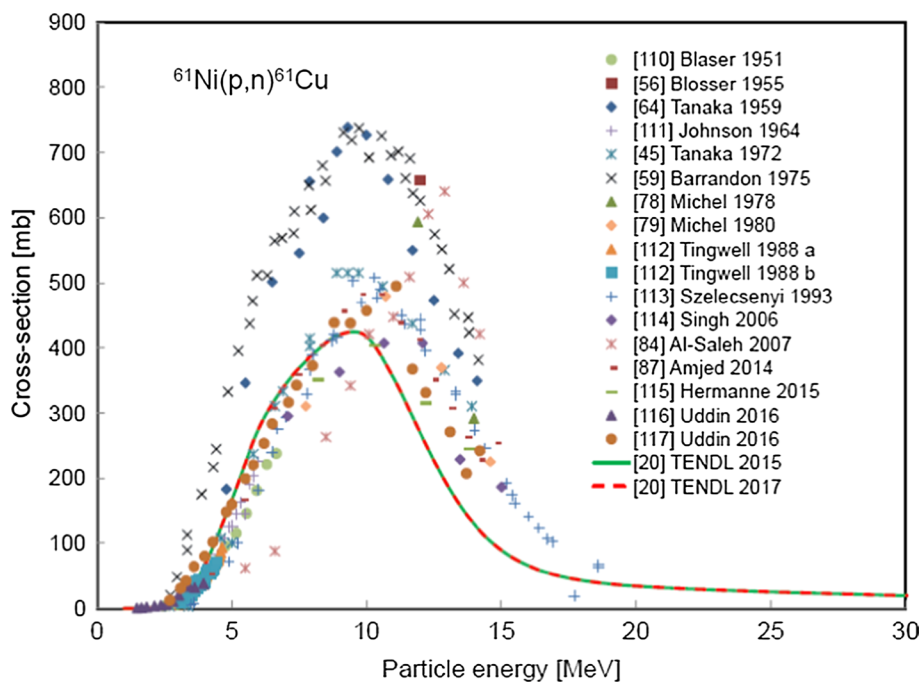
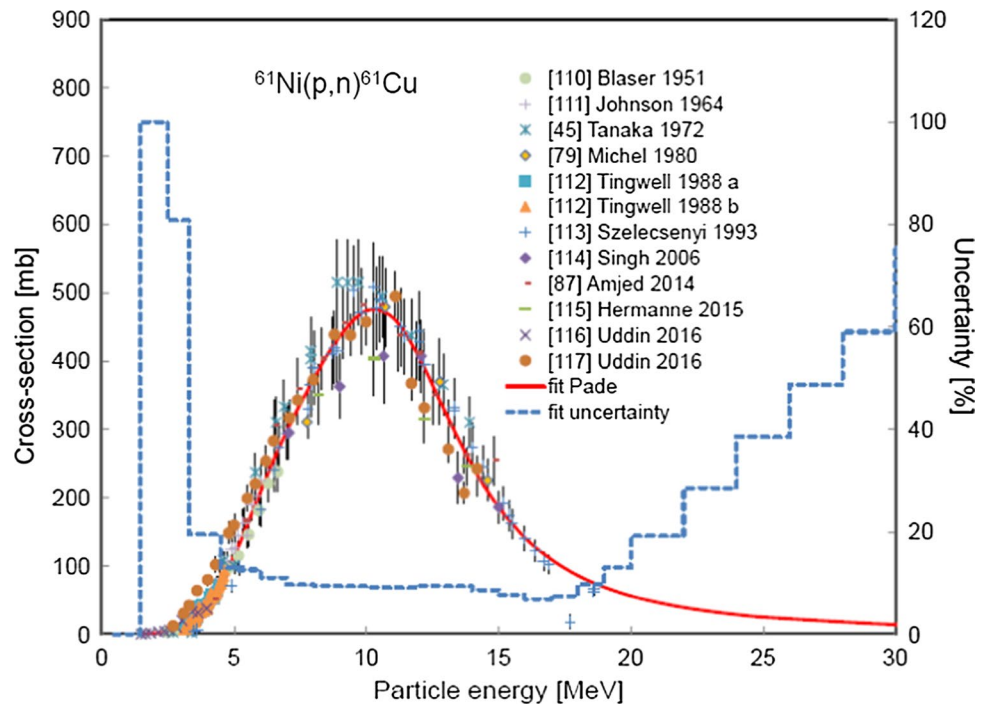


Fig. 38 Twelve selected experimental datasets for the $^{61}\text{Ni}(p,n)^{61}\text{Cu}$ reaction [45, 79, 87, 110–117] with the Padé fit ($L=12$, $N=192$, $\chi^2=2.81$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{60}\text{Ni}(\text{d},\text{n})^{61}\text{Cu}$

The five experimental datasets available in the literature are shown in Fig. 39 [90, 118–121] together with the TENDL calculations. All datasets were used in the statistical fitting procedure (Cogneau et al. [118] data were normalised, and data above 6-MeV particle beam energy discarded

as inconsistent with model calculations). All of the data and their experimental uncertainties are shown in Fig. 40 together with the Padé fit ($L=16$, $N=29$, $\chi^2=1.16$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale). This reaction is the main contributor to the formation of ^{61}Cu on natural Ni by deuterons, adopted as a suitable beam monitor (see Ref. [30], Sect. 3.I).

Fig. 39 Five experimental datasets for the $^{60}\text{Ni}(\text{d},\text{n})^{61}\text{Cu}$ reaction available in the literature [90, 118–121], and TENDL calculations

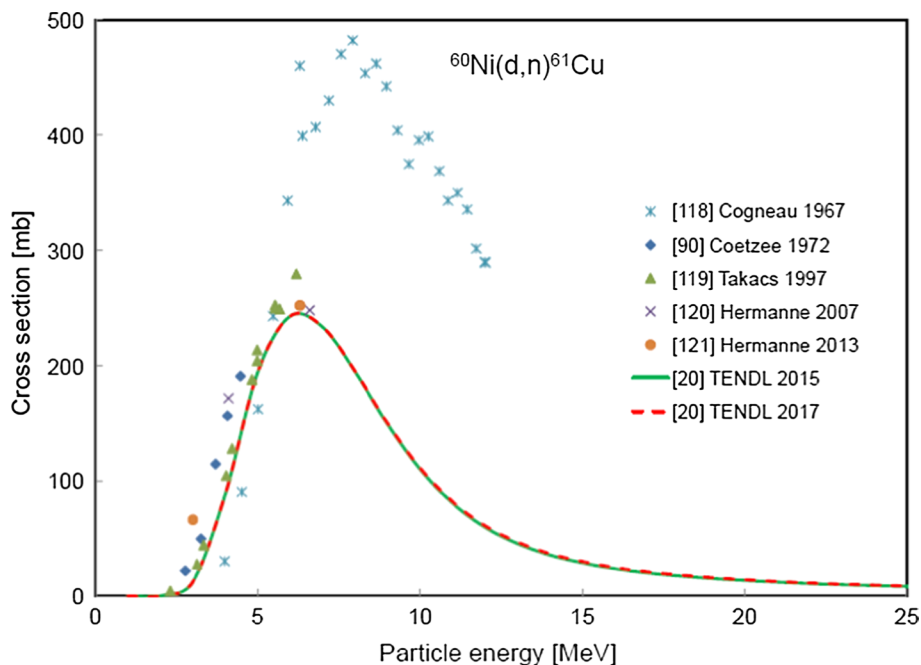
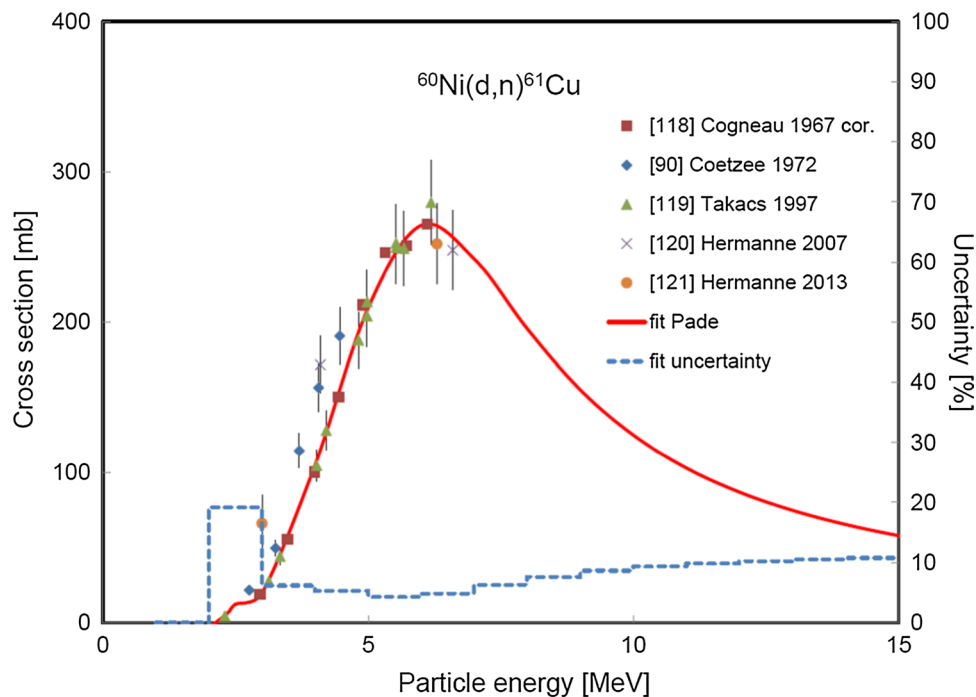


Fig. 40 Five experimental datasets for the $^{60}\text{Ni}(\text{d},\text{n})^{61}\text{Cu}$ reaction [90, 118–121] with the Padé fit ($L=16$, $N=29$, $\chi^2=1.16$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{64}\text{Zn}(p,\alpha)^{61}\text{Cu}$

The seven experimental datasets available in the literature are shown in Fig. 41 [36, 59, 122–126] together with the TENDL calculations. One dataset was rejected (Barrandon et al. [59], discrepant behaviour near maximum), and the

remaining six sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 42 together with the Padé ($L=12$, $N=72$, $\chi^2=0.88$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 41 Seven experimental datasets for the $^{64}\text{Zn}(p,\alpha)^{61}\text{Cu}$ reaction available in the literature [36, 59, 122–126], and TENDL calculations

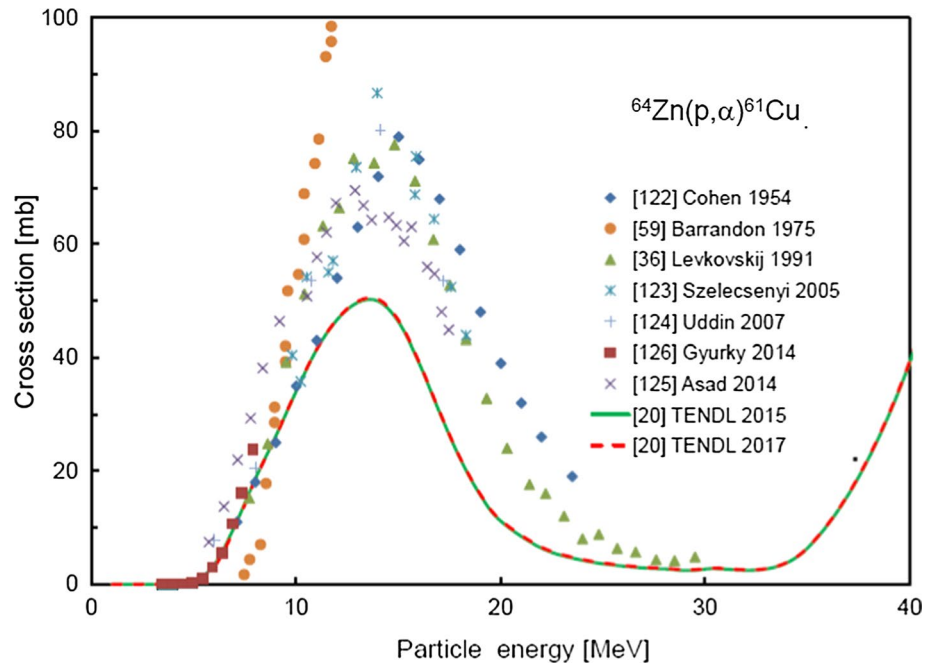
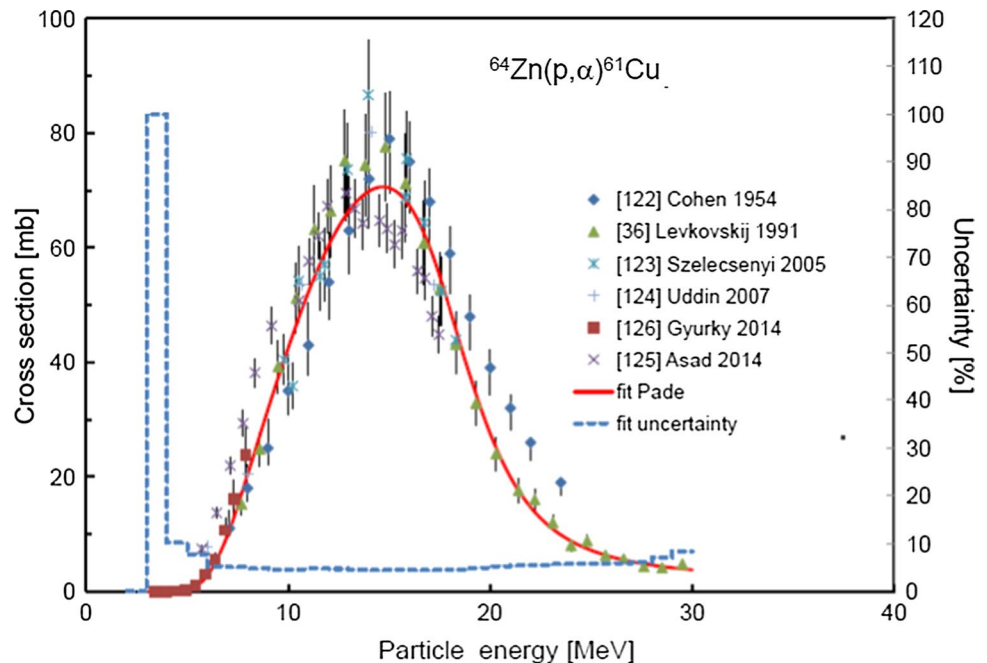


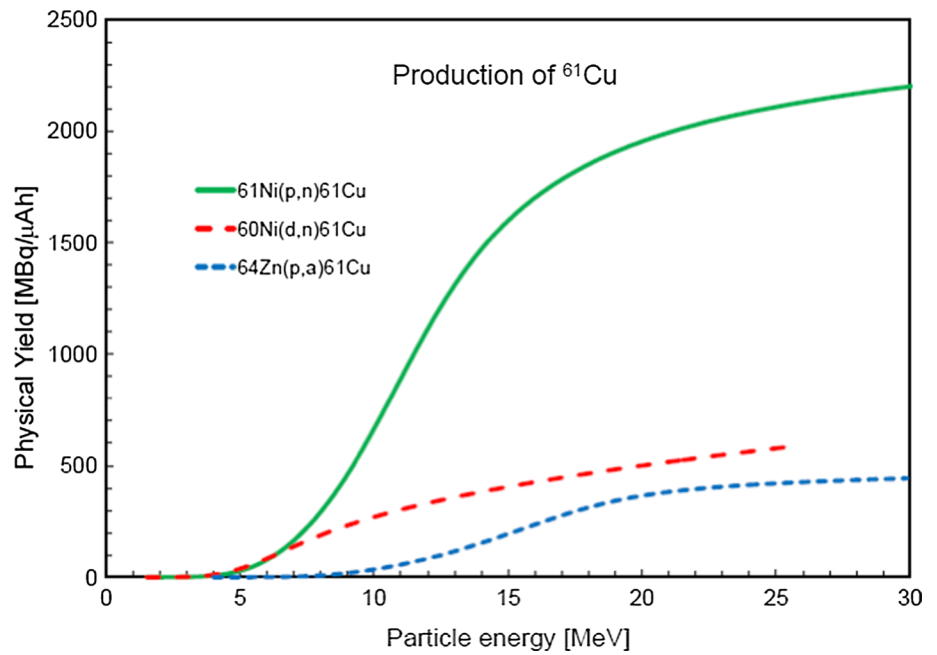
Fig. 42 Six selected experimental datasets [36, 122–126] for the $^{64}\text{Zn}(p,\alpha)^{61}\text{Cu}$ reaction with the Padé fit ($L=12$, $N=72$, $\chi^2=0.88$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{61}Cu

See Fig. 43.

Fig. 43 Thick target yields calculated from the recommended cross sections for the $^{61}\text{Ni}(p,n)^{61}\text{Cu}$, $^{60}\text{Ni}(d,n)^{61}\text{Cu}$ and $^{64}\text{Zn}(p,\alpha)^{61}\text{Cu}$ reactions



Production of ^{62}Cu ($T_{1/2} = 9.67$ min) and longer-lived ^{62}Zn parent ($T_{1/2} = 9.193$ h)

Applications: As stated earlier, copper isotopes form stable complexes with several chelators that can be conjugated to a wide variety of organic molecules for both imaging (^{61}Cu , ^{62}Cu , ^{64}Cu) and therapy (^{64}Cu , ^{67}Cu). Short-lived ^{62}Cu has been proposed for the labelling of PTSM (pyruvaldehyde bis) to undertake myocardial and brain blood flow studies. ^{62}Cu (9.67 min): β^+ (97.83%), and E_γ (keV) ($P_\gamma(\%)$): 875.66 (0.147), 1172.97 (0.342).

^{62}Zn (9.193 h): β^+ (8.2%), and E_γ (keV) ($P_\gamma(\%)$): 548.35 (15.3), 596.56 (26).

Evaluations have been made of the $^{63}\text{Cu}(p,2n)^{62}\text{Zn}$, $^{63}\text{Cu}(d,3n)^{62}\text{Zn}$ and $^{nat}\text{Ni}(\alpha,xn)^{62}\text{Zn}$ indirect, and $^{62}\text{Ni}(p,n)^{62}\text{Cu}$ and $^{62}\text{Ni}(d,2n)^{62}\text{Cu}$ direct production routes.

$^{63}\text{Cu}(p,2n)^{62}\text{Zn}$

Twenty-four experimental datasets available in the literature are shown in Fig. 44 [36, 82, 98, 99, 127–146] together with the TENDL calculations. Seven datasets were rejected (Ghoshal [127], Williams and Fulmer [99], Greene and Lebowitz [128], Greenwood and Smither [130], Aleksandrov et al. [132], Levkovskij [36], and Tárkányi et al. [142], all disagree significantly with the other datasets), and the remaining seventeen sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 45 together with the Padé fit ($L = 16$, $N = 213$, $\chi^2 = 1.89$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale). As the only reaction known to contribute to the formation of ^{62}Zn on ^{nat}Cu for protons below 30 MeV, the fitted data have been adopted as a beam monitor in this energy region (see Ref. [30], Sect. 2.6).

Fig. 44 Twenty-four experimental datasets for the $^{63}\text{Cu}(p,2n)^{62}\text{Zn}$ reaction available in the literature [36, 82, 98, 99, 127–146], and TENDL calculations

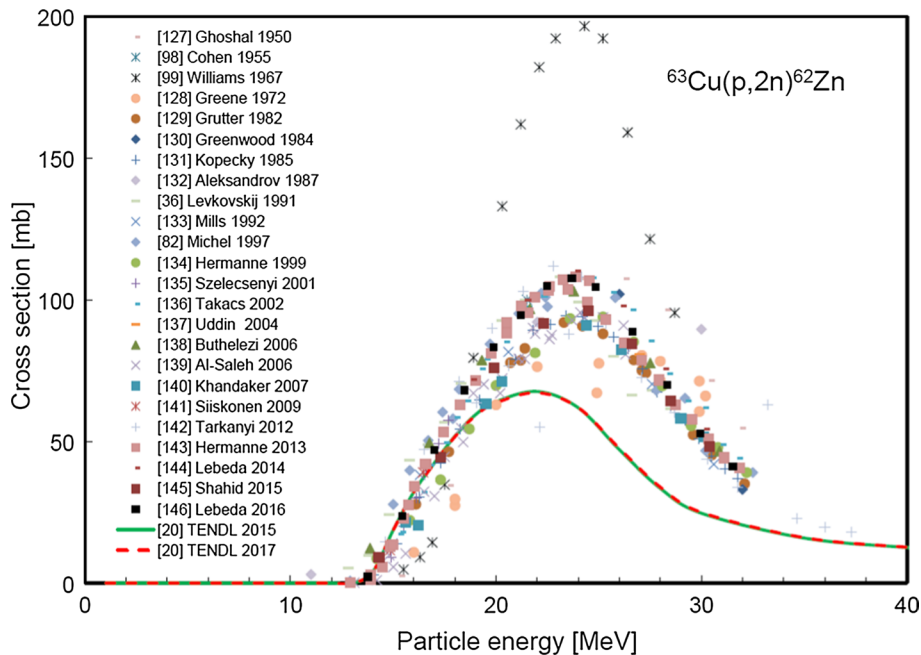
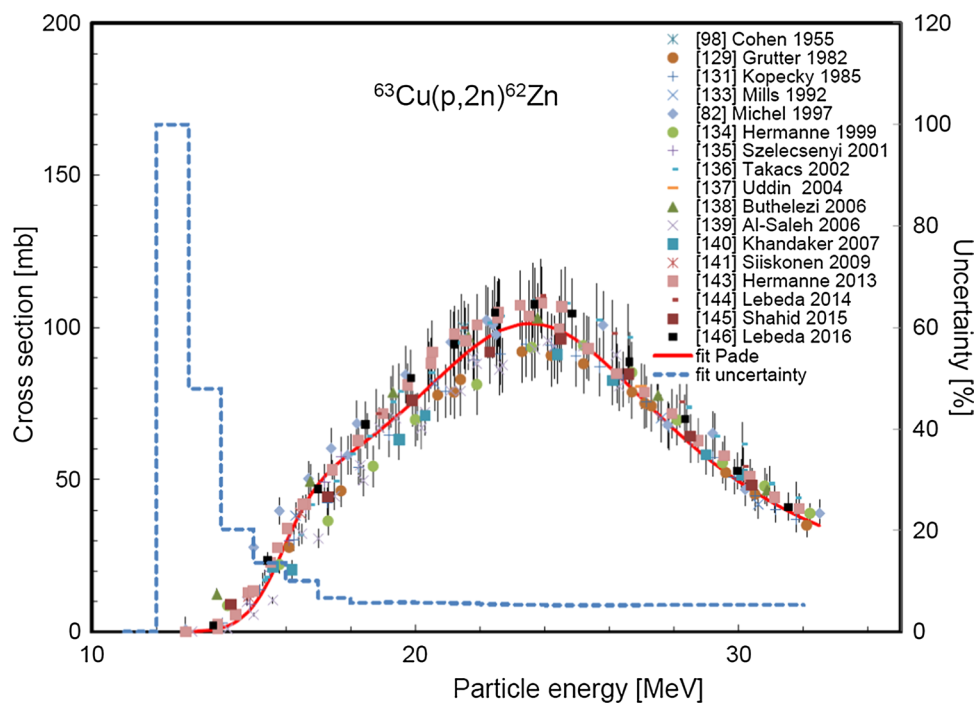


Fig. 45 Seventeen selected experimental datasets for the $^{63}\text{Cu}(p,2n)^{62}\text{Zn}$ reaction [82, 98, 129, 131, 133–141, 143–146] with the Padé fit ($L=16$, $N=213$, $\chi^2=1.89$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{63}\text{Cu}(d,3n)^{62}\text{Zn}$

While a known dataset by Bartell et al. [147] is not represented in Fig. 46 because the values are totally discrepant even after arbitrary normalisation, eight other experimental datasets available in the literature are shown [73, 95, 148–153] together with the TENDL calculations. The data by Fulmer and Williams [148] were subsequently rejected because they disagree significantly with the other datasets (attributed to the normalisation of inadequately

defined low-intensity decay data). All of the remaining seven datasets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 47 together with the Padé fit ($L=12$, $N=82$, $\chi^2=1.89$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale). As the only reaction known to contribute to the formation of ^{62}Zn on ^{nat}Cu for deuterons below 35 MeV, the fitted data have been adopted as a beam monitor in this energy region (see Ref. [30], Section III E).

Fig. 46 Eight experimental datasets for the $^{63}\text{Cu}(d,3n)^{62}\text{Zn}$ reaction available in the literature [73, 95, 148–153], and TENDL calculations

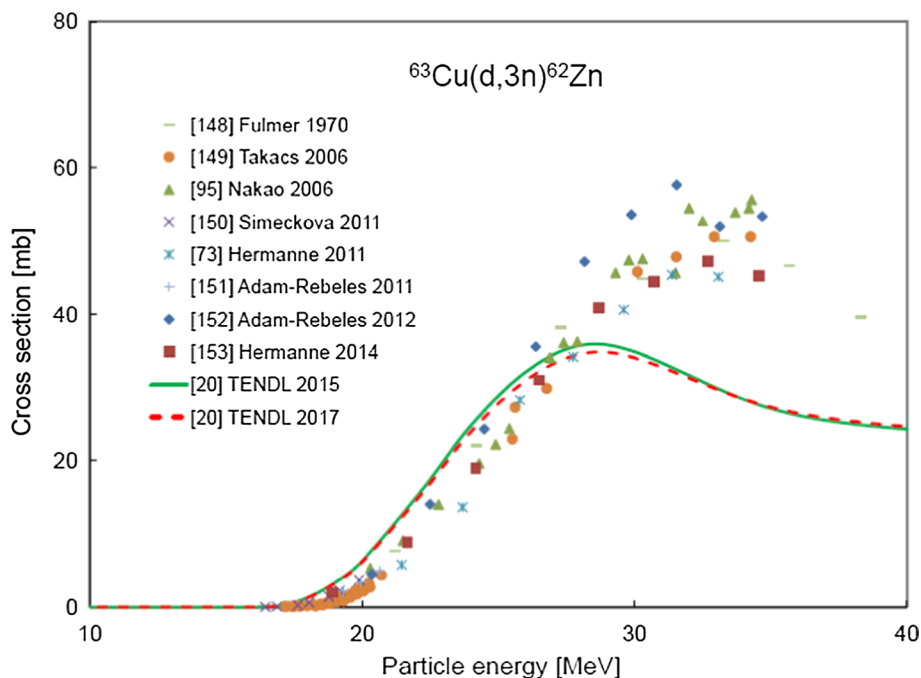
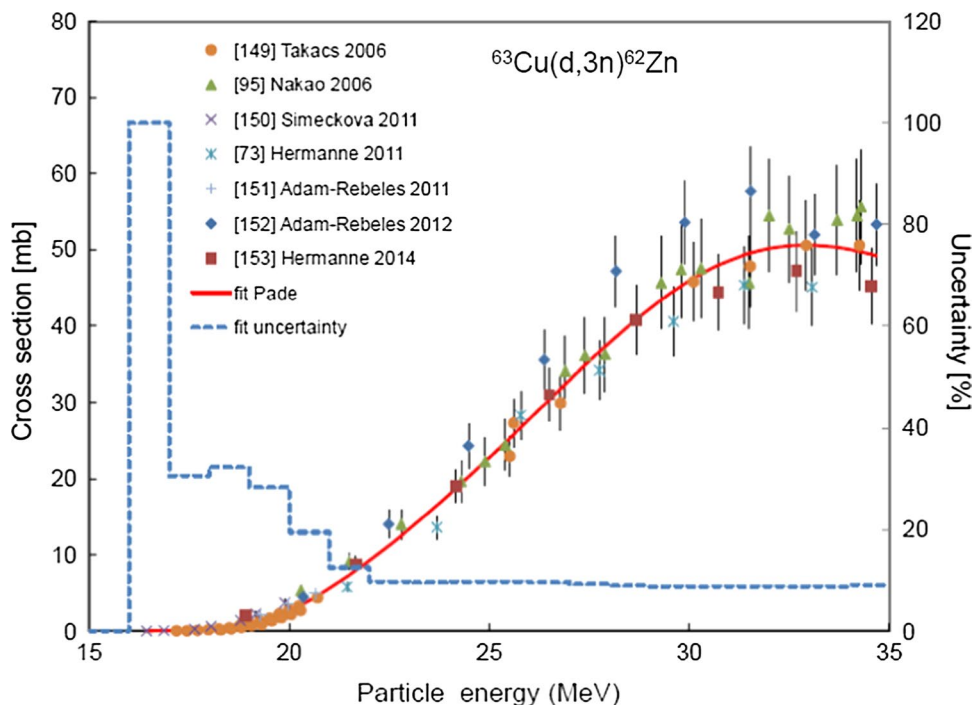


Fig. 47 Seven selected experimental datasets for the $^{63}\text{Cu}(d,3n)^{62}\text{Zn}$ reaction [73, 95, 149–153] with the Padé fit ($L=12$, $N=82$, $\chi^2=1.89$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



${}^{\text{nat}}\text{Ni}(\alpha, \text{xn}){}^{62}\text{Zn}$

The nine experimental datasets available in the literature are shown in Fig. 48 [36, 127, 154–160] together with the TENDL calculations. Three datasets were rejected (Neirinckx [155] (energy shift near threshold), Singh et al. [159] (discrepant values at energies below 35 MeV), and Yadav

et al. [160] (value too low)), and the remaining six sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 49 together with the Padé fit ($L=21$, $N=45$, $\chi^2=1.72$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 48 Nine experimental datasets for the ${}^{\text{nat}}\text{Ni}(\alpha, \text{xn}){}^{62}\text{Zn}$ reaction available in the literature [36, 127, 154–160], and TENDL calculations

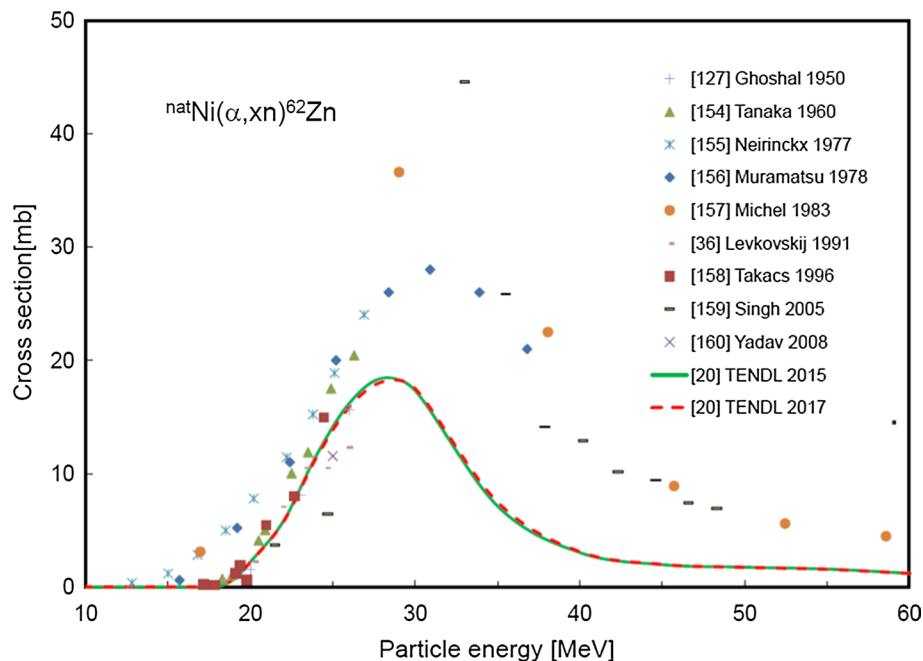
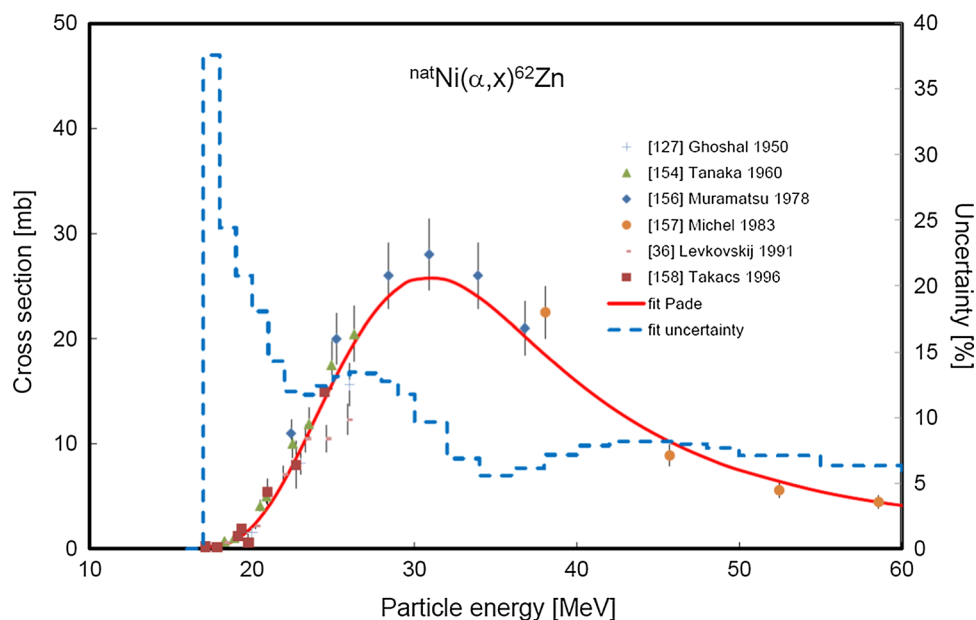


Fig. 49 Six selected experimental datasets for the ${}^{\text{nat}}\text{Ni}(\alpha, \text{xn}){}^{62}\text{Zn}$ reaction [36, 127, 154, 156–158] with the Padé fit ($L=10$, $N=45$, $\chi^2=1.74$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{62}\text{Ni}(p,n)^{62}\text{Cu}$

The seven experimental datasets available in the literature are shown in Fig. 50 [36, 45, 66, 110, 161–163] together with the TENDL calculations. All datasets were used in the

statistical fitting procedure. The data and their experimental uncertainties are shown in Fig. 51 together with the Padé fit ($L=12$, $N=77$, $\chi^2=1.33$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 50 Seven experimental datasets for the $^{62}\text{Ni}(p,n)^{62}\text{Cu}$ reaction available in the literature [36, 45, 66, 110, 161–163], and TENDL calculations

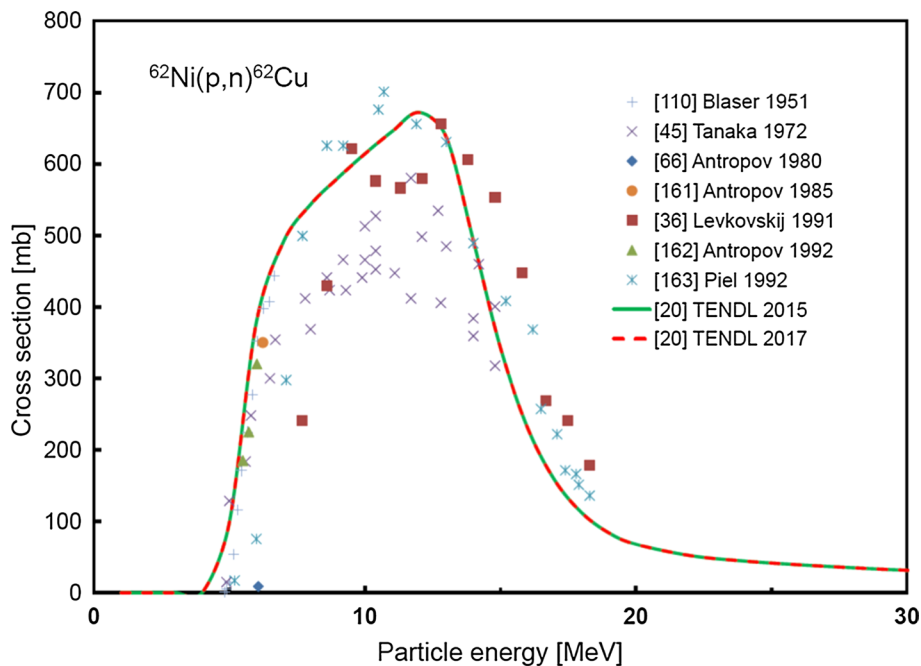
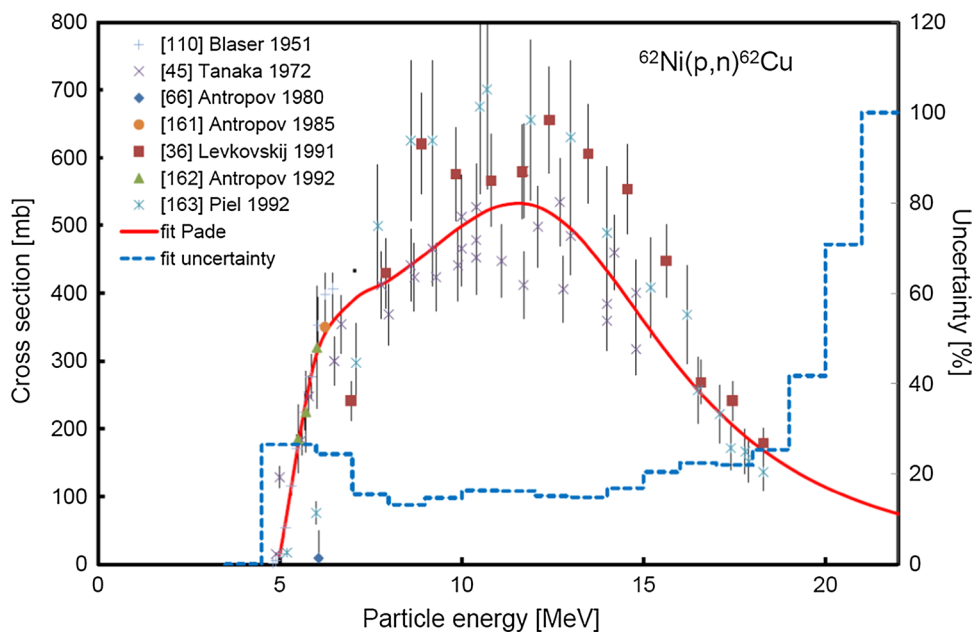


Fig. 51 Seven experimental datasets [36, 45, 66, 110, 161–163] for the $^{62}\text{Ni}(p,n)^{62}\text{Cu}$ reaction with the Padé fit ($L=12$, $N=77$, $\chi^2=1.33$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{62}\text{Ni}(d,2n)^{62}\text{Cu}$

The single dataset available in the literature is shown in Fig. 52 [118] together with the TENDL calculations. This dataset was used in the statistical fitting procedure. The data

and their experimental uncertainties are shown in Fig. 53 together with the Padé fit ($L=5$, $N=16$, $\chi^2=0.83$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 52 Experimental dataset for the $^{62}\text{Ni}(d,2n)^{62}\text{Cu}$ reaction available in the literature [118], and TENDL calculations

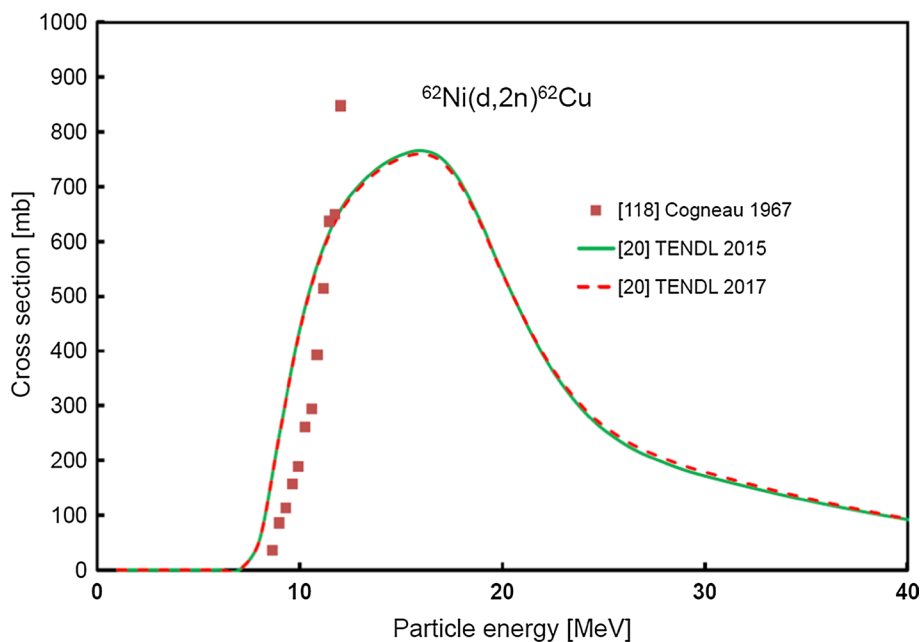
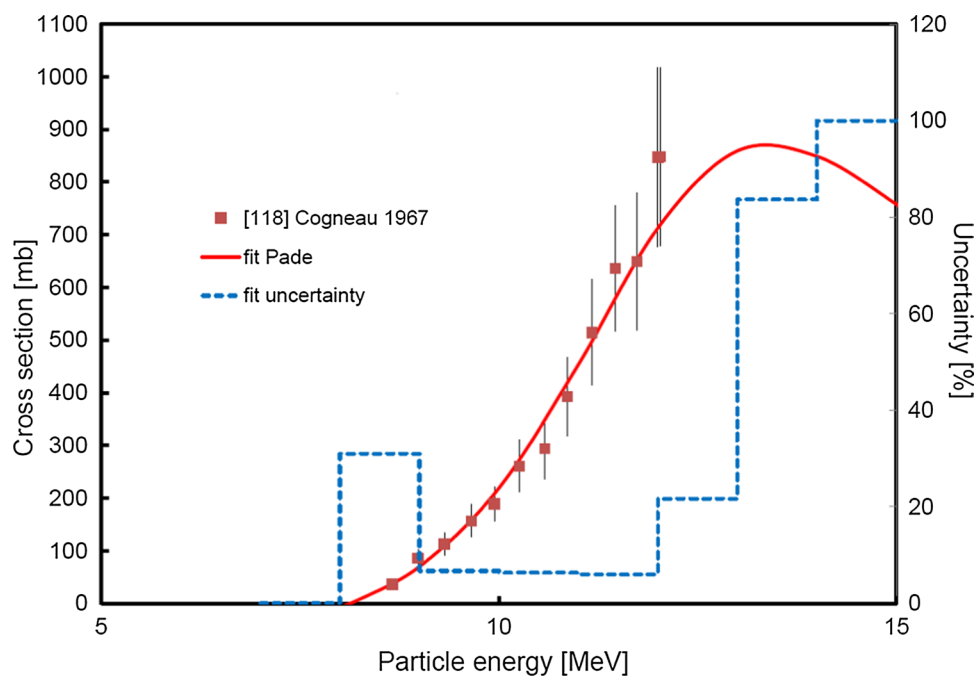


Fig. 53 Experimental dataset for the $^{62}\text{Ni}(d,2n)^{62}\text{Cu}$ reaction [118] with the Padé fit ($L=5$, $N=16$, $\chi^2=0.83$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{62}Cu , and ^{62}Zn parent

See Figs. 54 and 55.

Fig. 54 Thick target yields calculated from the recommended cross sections for the $^{62}\text{Ni}(p,n)^{62}\text{Cu}$ and $^{62}\text{Ni}(d,2n)^{62}\text{Cu}$ reactions

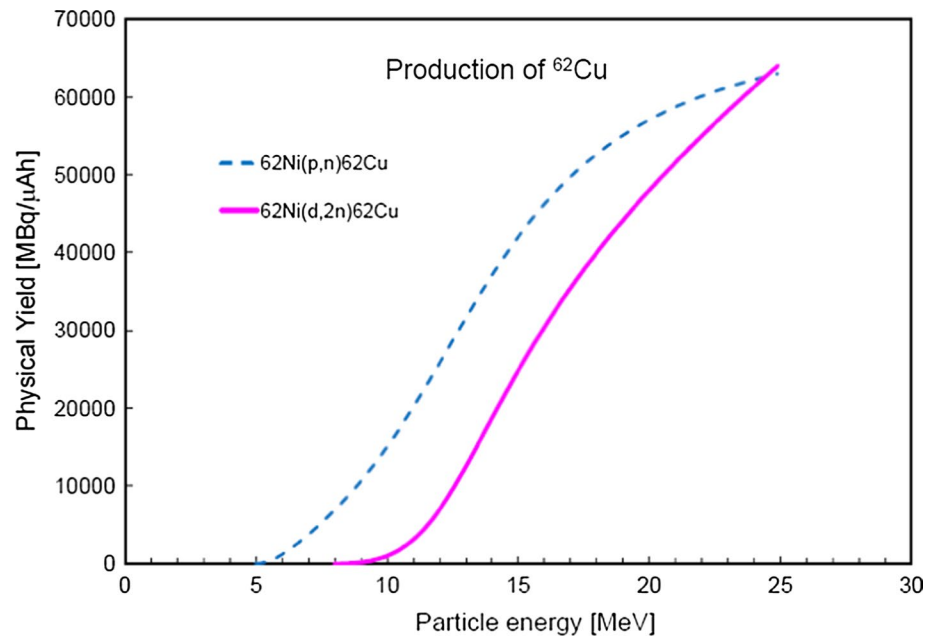
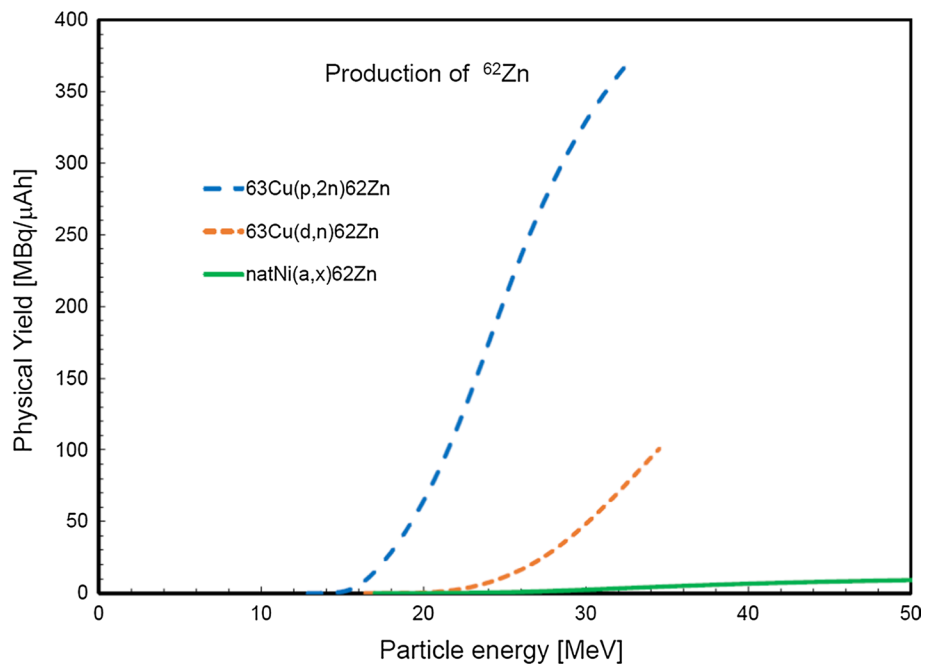


Fig. 55 Thick target yields calculated from the recommended cross sections for the $^{63}\text{Cu}(p,2n)^{62}\text{Zn}$, $^{63}\text{Cu}(d,n)^{62}\text{Zn}$ and $^{\text{nat}}\text{Ni}(\alpha,xn)^{62}\text{Zn}$ reactions



Production of ^{66}Ga ($T_{1/2} = 9.49\text{ h}$)

Applications: Both ^{66}Ga and ^{68}Ga are positron-emitting radionuclides that can be used in PET imaging. Longer-lived ^{66}Ga has been coupled to monoclonal antibodies (e.g., for tumour angiogenesis studies) and to nanoparticles. This radionuclide has also been proposed in hadron therapy as an in situ marker for the incorporation of Zn in tumours. Obvious disadvantages are the rather high radiation burden and inferior imaging properties caused by the many gamma rays that accompany decay.

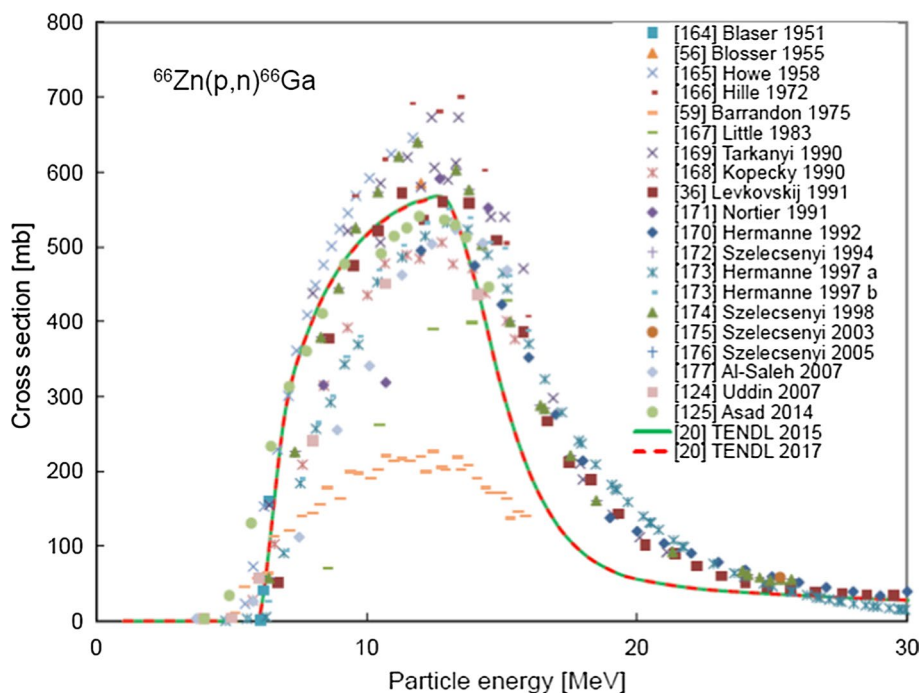
^{66}Ga (9.49 h): β^+ (57%), and E_γ (keV) ($P_\gamma(\%)$): 833.5324 (5.9), 1039.220 (37.0).

Evaluations have been made of the $^{66}\text{Zn}(p,n)^{66}\text{Ga}$ and $^{63}\text{Cu}(\alpha,n)^{66}\text{Ga}$ direct production routes.

$^{66}\text{Zn}(p,n)^{66}\text{Ga}$

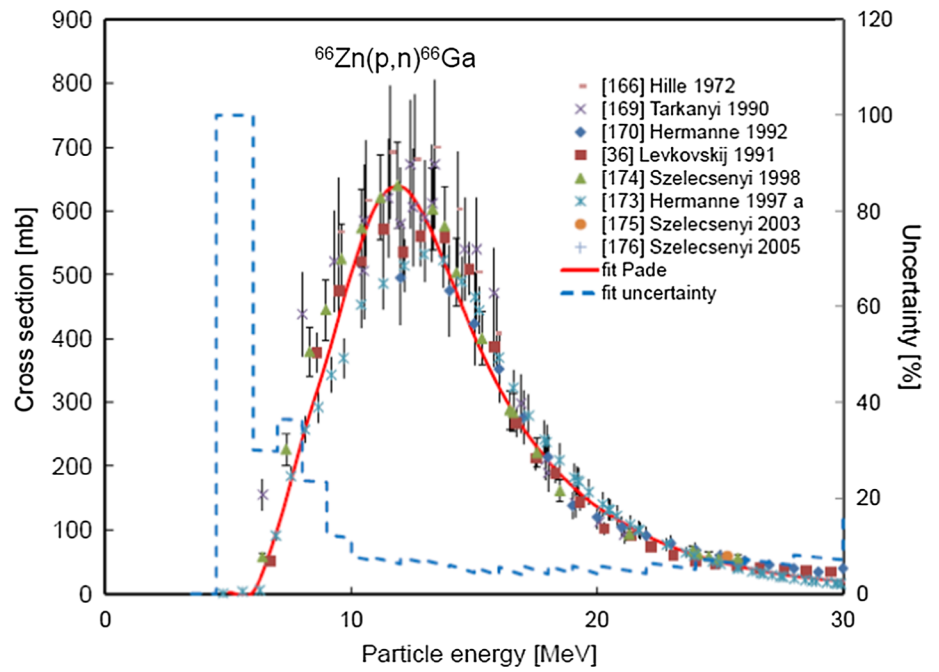
The twenty experimental datasets available in the literature are shown in Fig. 56 [36, 56, 59, 124, 125, 164–177]

Fig. 56 Twenty experimental datasets (for the $^{66}\text{Zn}(p,n)^{66}\text{Ga}$ reaction available in the literature [36, 56, 59, 124, 125, 164–177], and TENDL calculations. Ref. [173] contains two datasets labelled (a) and (b)



together with the TENDL-2015 and TENDL-2017 calculations. Hermanne [173] contains two datasets labelled (a) and (b). Twelve datasets were rejected (Little and Lagunas-Solar [167] (values too low), Nortier et al. [171] (energy shift), Blosser and Handley [56] (only one data point that can not be checked), Howe [165] (energy shift), Kopecký [168] (values too low), Asad et al. [125] (values too low), Szelecsényi et al. [172] (preliminary results), Hermanne [173] set b (discrepant data points), Barrandon et al. [59] (values too low), Al-Saleh et al. [177] (values too low), Uddin et al. [124] (values too low), and Blaser et al. [164] (discrepant data points)), while the remaining eight sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 57 together with the Padé ($L = 13$, $N = 188$, $\chi^2 = 1.87$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 57 Eight selected experimental datasets for the $^{66}\text{Zn}(p,n)^{66}\text{Ga}$ reaction [36, 166, 169, 170, 173–176] with the Padé fit ($L=13$, $N=188$, $\chi^2=1.87$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{63}\text{Cu}(\alpha, n)^{66}\text{Ga}$

The twenty-three experimental datasets available in the literature are shown in Fig. 58 [36, 54, 81, 166, 178–196] together with the TENDL calculations. Seven datasets were rejected (Porges [178] (values too low), Bonesso et al. [188] (values too low), Zhukova et al. [182] (values too low), Singh et al. [190] (values too low), Rizvi et al. [184] (values too low), Porile and Morrison [179] (values too low),

and Nassiff and Nassiff [183] (discrepant data points)), and the remaining sixteen sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 59 together with the Padé ($L = 13$, $N = 252$, $\chi^2 = 1.34$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale). This reaction is also used to monitor α -particle beams (see Ref. [30], Section V D).

Fig. 58 Twenty-three experimental datasets for the $^{63}\text{Cu}(\alpha, n)^{66}\text{Ga}$ reaction available in the literature [36, 54, 81, 166, 178–196], and TENDL calculations

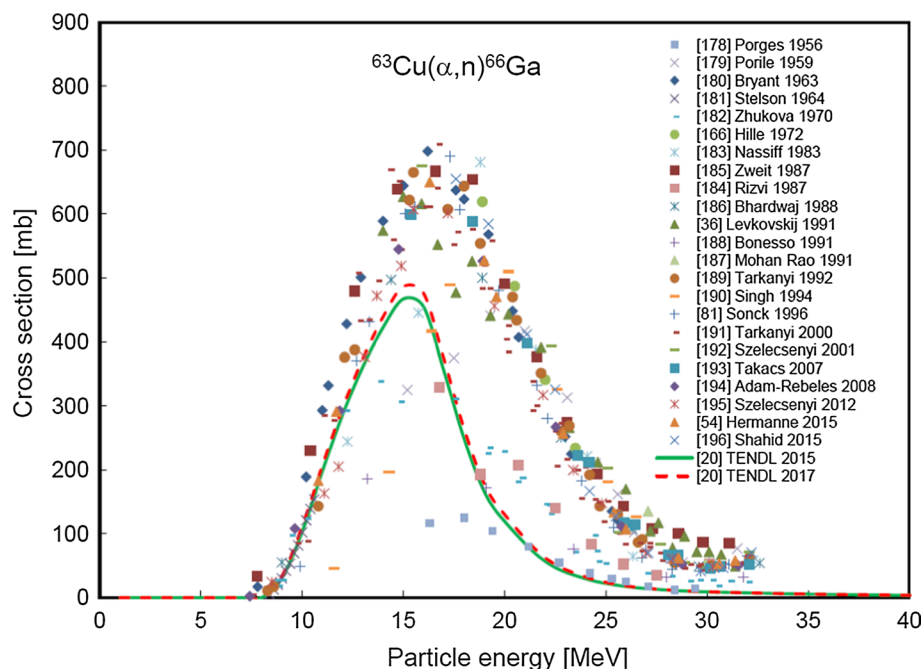
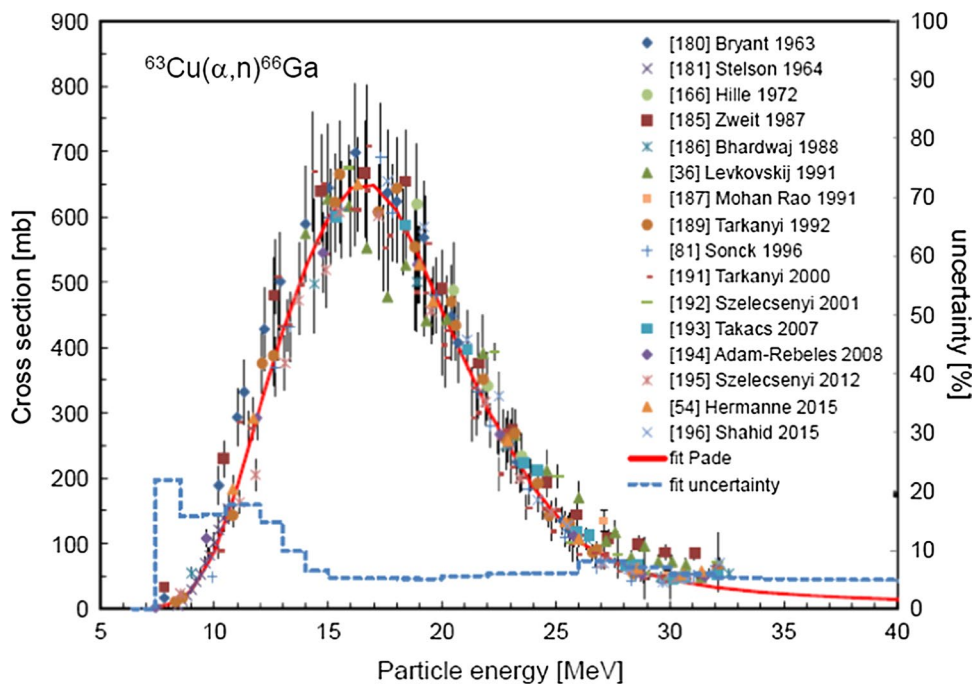


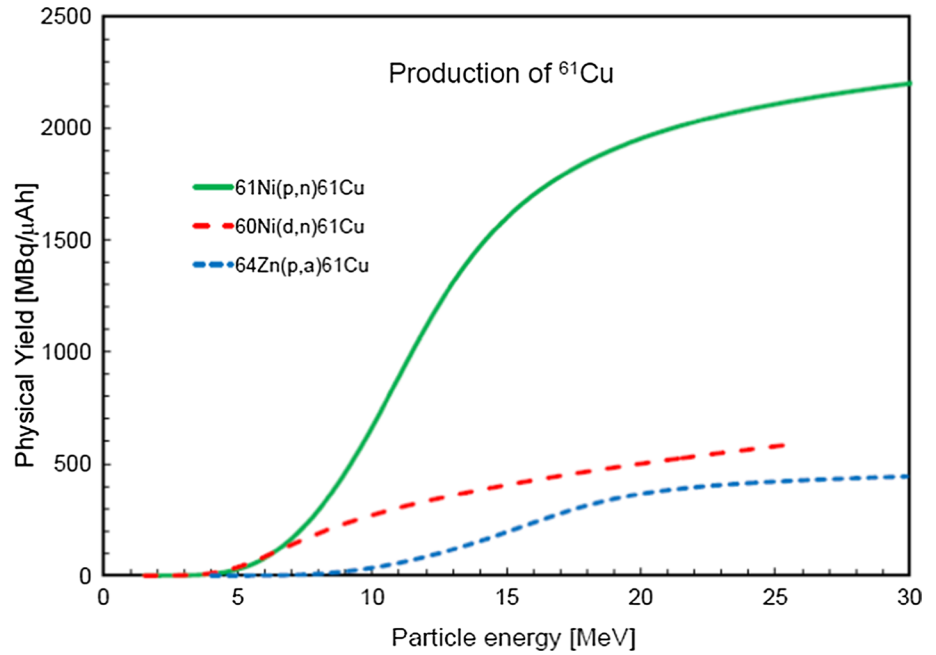
Fig. 59 Sixteen selected experimental datasets for the $^{63}\text{Cu}(\alpha, n)^{66}\text{Ga}$ reaction [36, 54, 81, 166, 180, 181, 185–187, 189, 191–196] with the Padé fit ($L = 13$, $N = 252$, $\chi^2 = 1.34$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{66}Ga

See Fig. 60.

Fig. 60 Thick target yields calculated from the recommended cross sections for the $^{66}\text{Zn}(p,n)^{66}\text{Ga}$ and $^{63}\text{Cu}(\alpha,n)^{66}\text{Ga}$ reactions



Production of ^{68}Ga ($T_{1/2} = 67.71$ min) and long-lived ^{68}Ge parent ($T_{1/2} = 270.95$ d)

Applications: Rather short-lived ^{68}Ga became the first widespread generator-produced positron emitter, thereby competing somewhat with ^{18}F for preferred adoption in PET imaging. First introduced for the imaging of neuroendocrine tumours (^{68}Ga -labelled DOTA-TOC), more recent significant success has been achieved in the form of very efficient imaging agents for prostate cancer diagnosis and staging (^{68}Ga -DOTA-PSMA and derivatives).

^{68}Ga (67.71 min): β^+ (88.91%), and E_γ (keV) ($P_\gamma(\%)$): 1077.34 (3.22).

^{68}Ge (270.95 d): detected by means of radiation from daughter ^{68}Ga .

Evaluations have been undertaken of the $^{68}\text{Zn}(p,n)^{68}\text{Ga}$ and $^{65}\text{Cu}(\alpha,n)^{68}\text{Ga}$ direct routes and $^{nat}\text{Ga}(p,x)^{68}\text{Ge}$ and $^{69}\text{Ga}(p,2n)^{68}\text{Ge}$ generator production.

$^{68}\text{Zn}(p,n)^{68}\text{Ga}$

The eighteen experimental datasets available in the literature are shown in Fig. 61 [36, 41, 56, 59, 111, 162, 164–166, 169, 170, 173, 177, 195, 197–200] together with the TENDL calculations. Five datasets were rejected (Hermanne et al. [170] (energy shift), Blosser and Handley [56] (value too high), McGee et al. [41] (value too low), Hermanne [173] (energy shift), and Barrandon et al. [59] (values too low)), and the remaining thirteen sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 62 together with the Padé ($L = 20$, $N = 282$, $\chi^2 = 1.97$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 61 Eighteen experimental datasets for the $^{68}\text{Zn}(p,n)^{68}\text{Ga}$ reaction available in the literature [36, 41, 56, 59, 111, 162, 164–166, 169, 170, 173, 177, 195, 197–200], and TENDL calculations

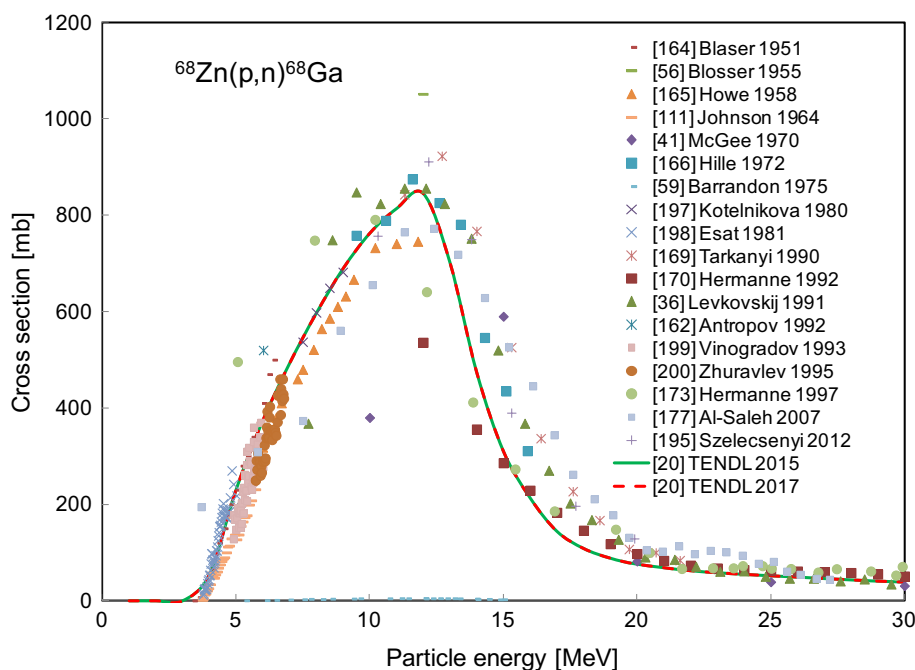
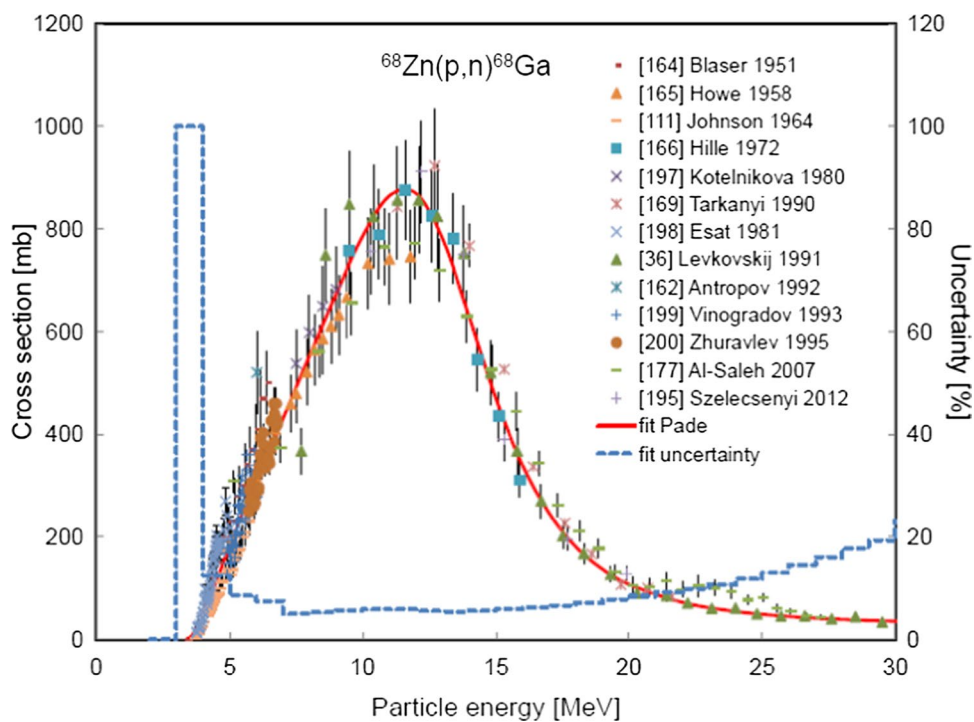


Fig. 62 Thirteen selected experimental datasets for the $^{68}\text{Zn}(p,n)^{68}\text{Ga}$ reaction [36, 111, 162, 164–166, 169, 177, 195, 197–200] with the Padé fit ($L=20$, $N=282$, $\chi^2=1.97$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{65}\text{Cu}(\alpha, n)^{68}\text{Ga}$

The fourteen experimental datasets available in the literature are shown in Fig. 63 [36, 54, 166, 178–180, 184, 186, 188, 190, 195, 196, 201, 202] together with the TENDL calculations. Four datasets were rejected (Porile and Morrison [179] (energy shift), Rizvi et al. [184] (energy shift), Bonesso et al.

[188] (values too high), and Porges [178] (values too low)), and the remaining ten sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 64 together with the Padé ($L=10$, $N=92$, $\chi^2=1.21$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 63 Fourteen experimental datasets for the $^{65}\text{Cu}(\alpha, n)^{68}\text{Ga}$ reaction available in the literature [36, 54, 166, 178–180, 184, 186, 188, 190, 195, 196, 201, 202], and TENDL calculations

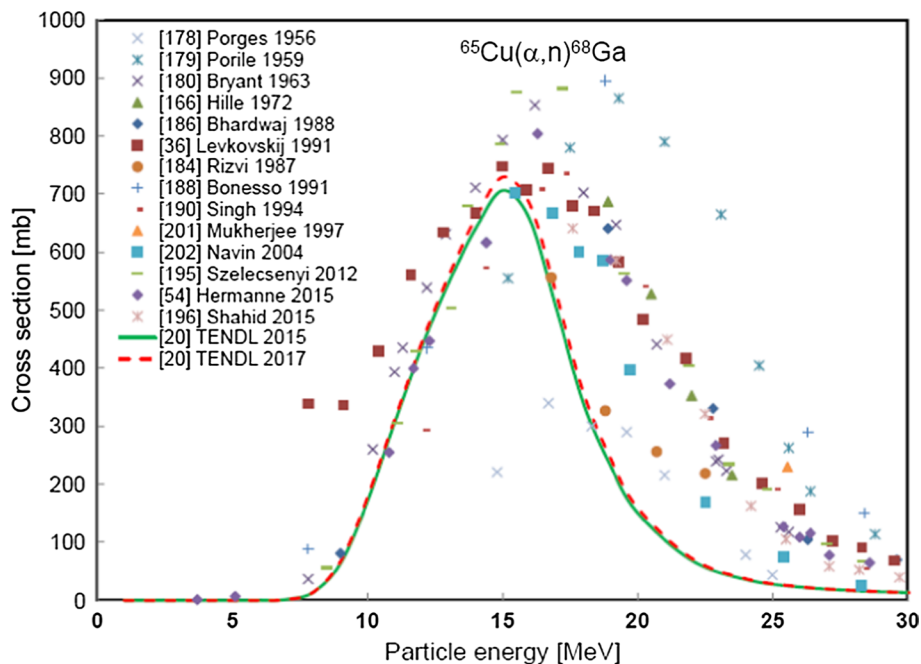
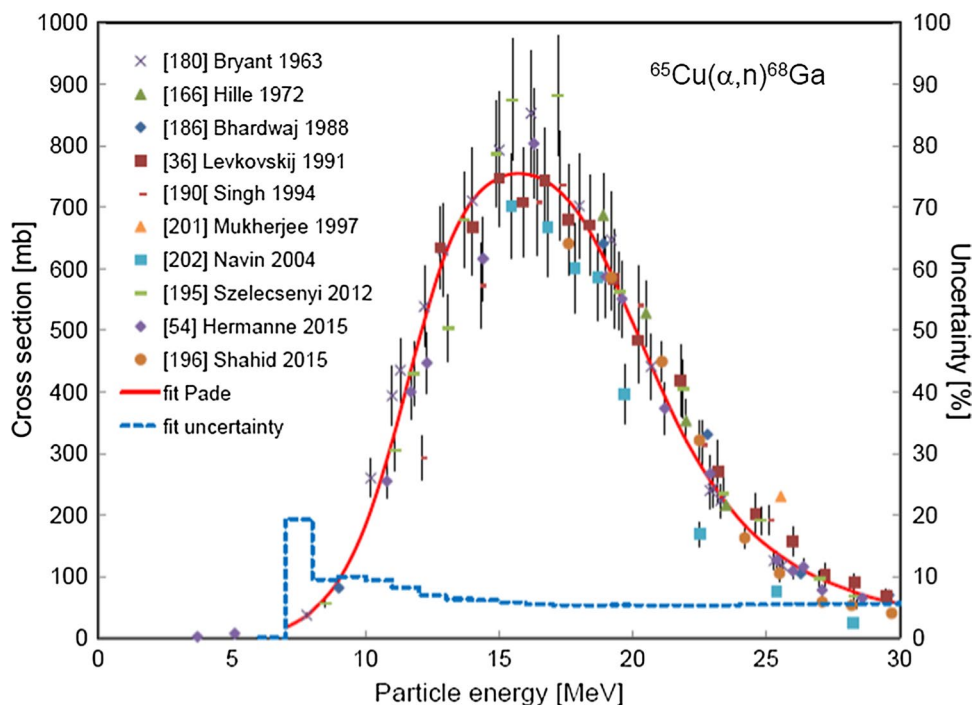


Fig. 64 Ten selected experimental datasets for the $^{65}\text{Cu}(\alpha, n)^{68}\text{Ga}$ reaction [36, 54, 166, 180, 186, 190, 195, 196, 201, 202] with the Padé fit ($L=10$, $N=92$, $\chi^2=1.21$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{nat}\text{Ga}(p,xn)^{68}\text{Ge}$

The six experimental datasets available in the literature are shown in Fig. 65 [36, 48, 98, 203, 204] together with the TENDL calculations. Hermanne et al. [48] contains two datasets labelled (a) and (b). One dataset was rejected

(Cohen and Newman [98], single data point too low), and the remaining five sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 66 together with the Padé ($L=11$, $N=101$, $\chi^2=1.42$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 65 Six experimental datasets for the $^{nat}\text{Ga}(p,xn)^{68}\text{Ge}$ reaction available in the literature [36, 48, 98, 203, 204], and TENDL calculations. Hermanne et al. [48] contains two sets of data labelled (a) and (b)

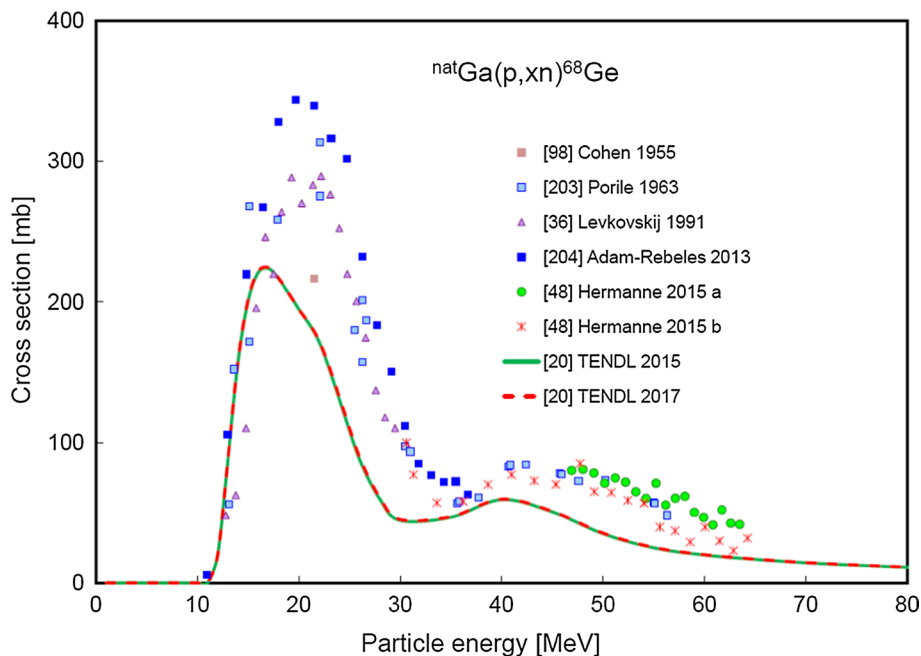
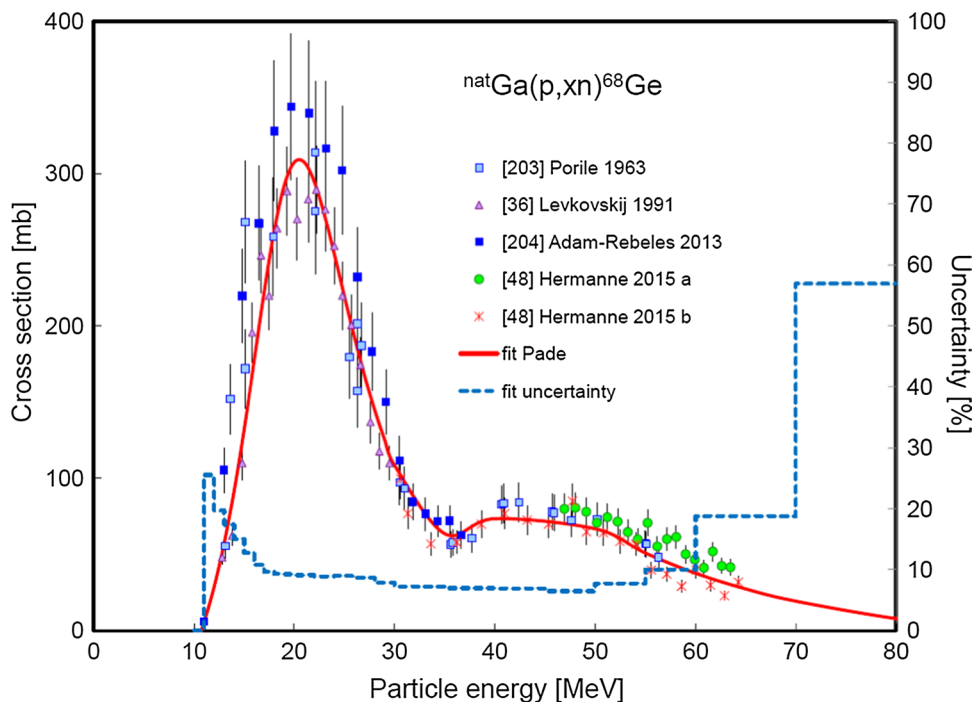


Fig. 66 Five selected experimental datasets for the $^{nat}\text{Ga}(p,xn)^{68}\text{Ge}$ reaction [36, 48, 203, 204] with the Padé fit ($L=11$, $N=101$, $\chi^2=1.42$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{69}\text{Ga}(p,2n)^{68}\text{Ge}$

The four experimental datasets available in the literature are shown in Fig. 67 [36, 48, 203, 204] together with the TENDL calculations. All sets were used in the statistical

fitting procedure. The data and their experimental uncertainties are shown in Fig. 68 together with the Padé ($L=8$, $N=53$, $\chi^2=1.56$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 67 Four experimental datasets for the $^{69}\text{Ga}(p,2n)^{68}\text{Ge}$ reaction available in the literature [36, 48, 203, 204], and TENDL calculations

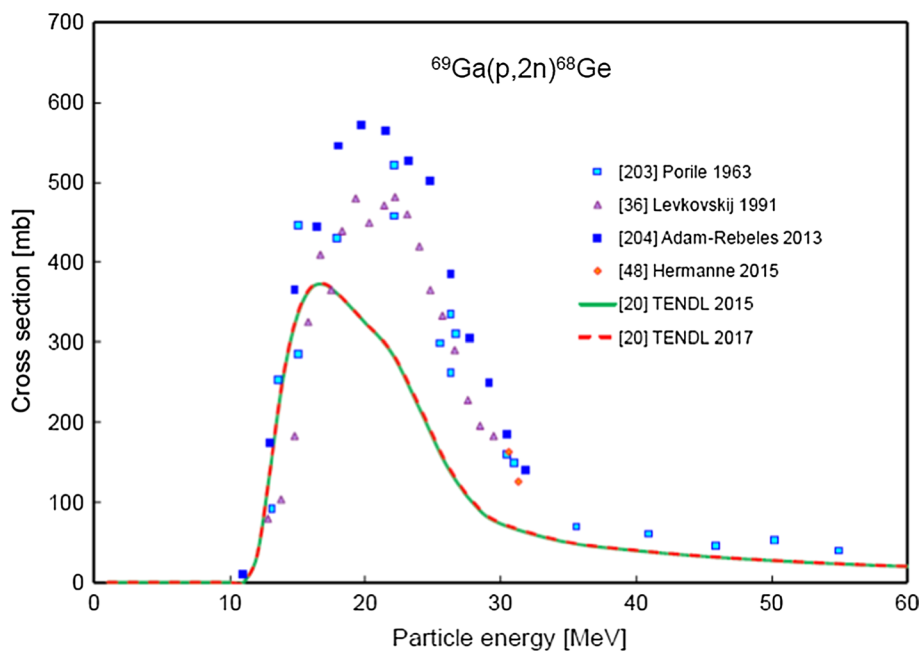
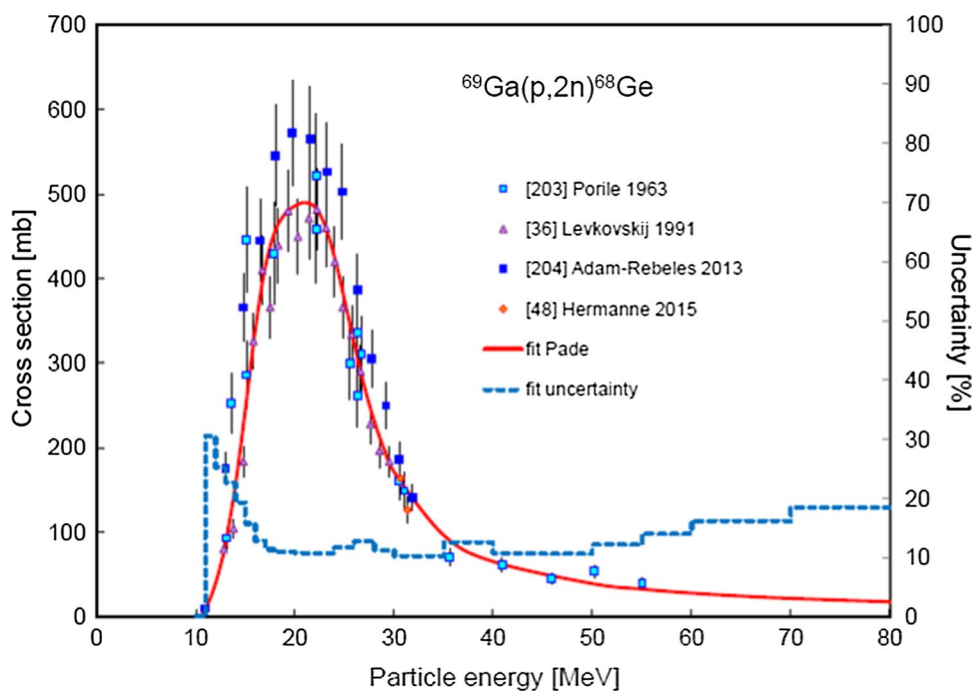


Fig. 68 Four experimental datasets for the $^{69}\text{Ga}(p,2n)^{68}\text{Ge}$ reaction [36, 48, 203, 204] with the Padé fit ($L=8$, $N=53$, $\chi^2=1.56$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for ^{68}Ga , and long-lived ^{68}Ge parent for generator

See Figs. 69 and 70.

Fig. 69 Thick target yields calculated from the recommended cross sections for the $^{68}\text{Zn}(p,n)^{68}\text{Ga}$ and $^{65}\text{Cu}(\alpha,n)^{68}\text{Ga}$ direct reactions

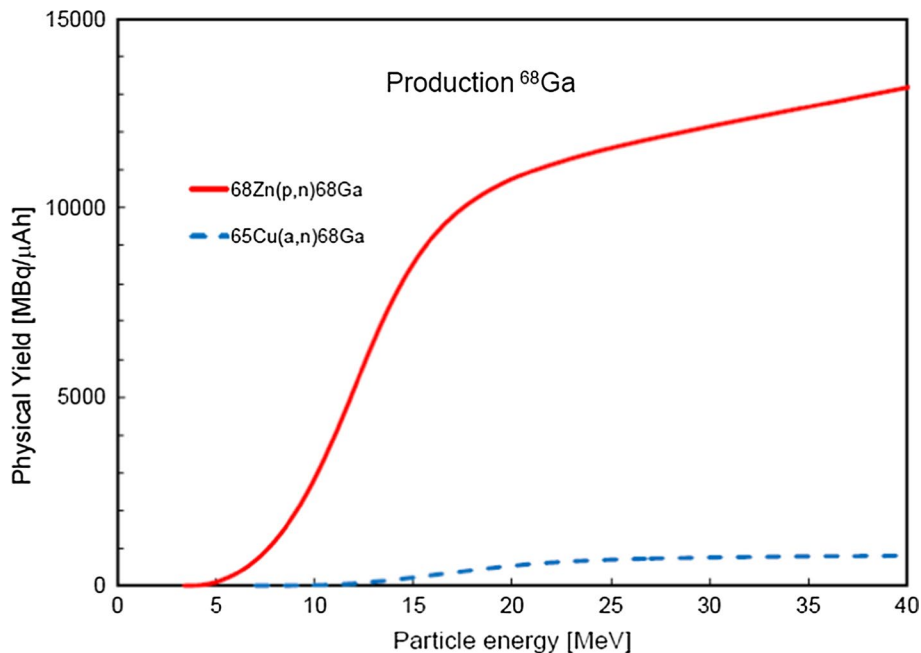
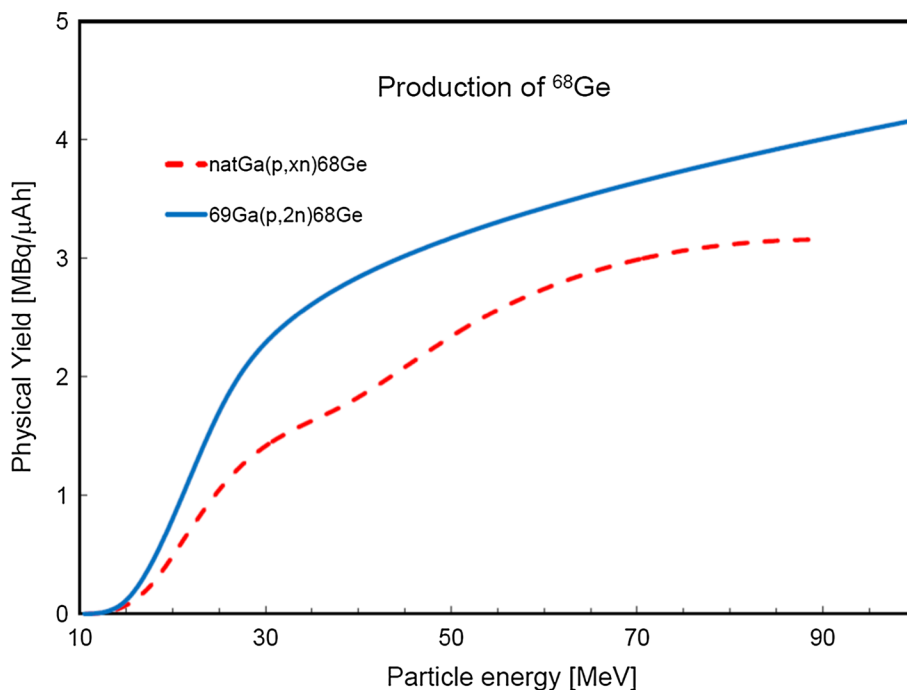


Fig. 70 Thick target yields calculated from the recommended cross sections for the $^{nat}\text{Ga}(p,xn)^{68}\text{Ge}$ and $^{69}\text{Ga}(p,2n)^{68}\text{Ge}$ reactions to produce long-lived parent for ^{68}Ga generator



Production of ^{72}As ($T_{1/2} = 26.0$ h) and longer-lived ^{72}Se parent ($T_{1/2} = 8.40$ d)

Applications: ^{72}As is a long-lived positron-emitting radionuclide suitable for imaging the bio-distribution of monoclonal antibodies with long biological half-lives that are promising in PET oncological research. Chemical properties offer the possibility of covalent bonding to thiol groups.

^{72}As (26.0 h): β^+ (87.8%), and E_γ (keV) (P_γ (%)): 629.92 (8.07), 833.99 (81).

^{72}Se (8.40 d): detected by means of radiation emitted by daughter ^{72}As .

Evaluations have been undertaken of the $^{75}\text{As}(p,4n)^{72}\text{Se}$ and $^{nat}\text{Br}(p,x)^{72}\text{Se}$ routes for parent production, and the

$^{nat}\text{Ge}(p,xn)^{72}\text{As}$ and $^{nat}\text{Ge}(d,xn)^{72}\text{As}$ direct production routes.

$^{75}\text{As}(p,4n)^{72}\text{Se}$

The two experimental datasets available in the literature for the energy domain considered are shown in Fig. 71 [205, 206] together with the TENDL calculations. Both datasets were used in the statistical fitting procedure. The data and their experimental uncertainties are shown in Fig. 72 together with the Padé fit ($L=8$, $N=33$, $\chi^2=1.30$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 71 Two experimental datasets for the $^{75}\text{As}(p,4n)^{72}\text{Se}$ reaction available in the literature [205, 206], and TENDL calculations

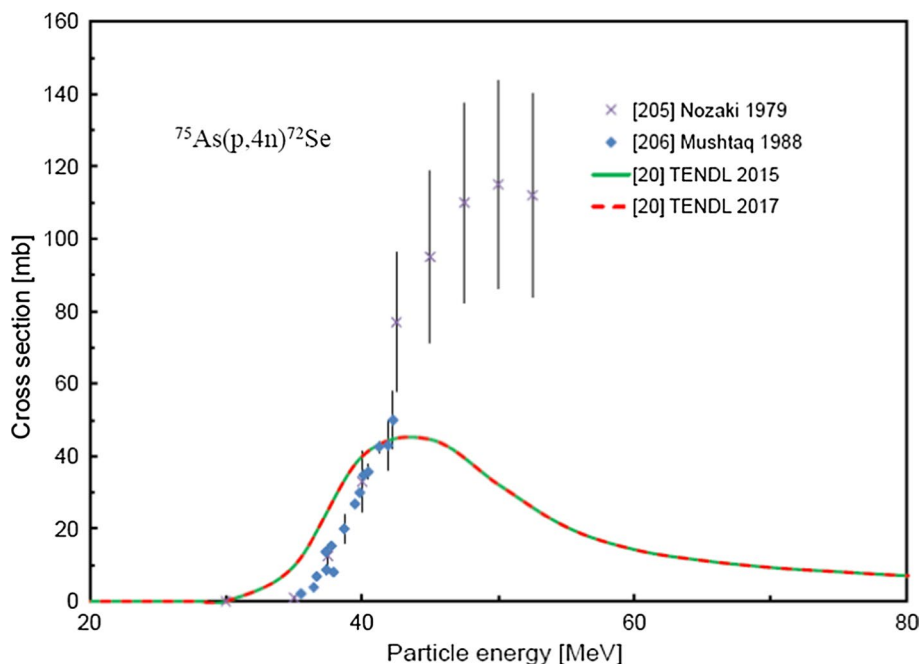
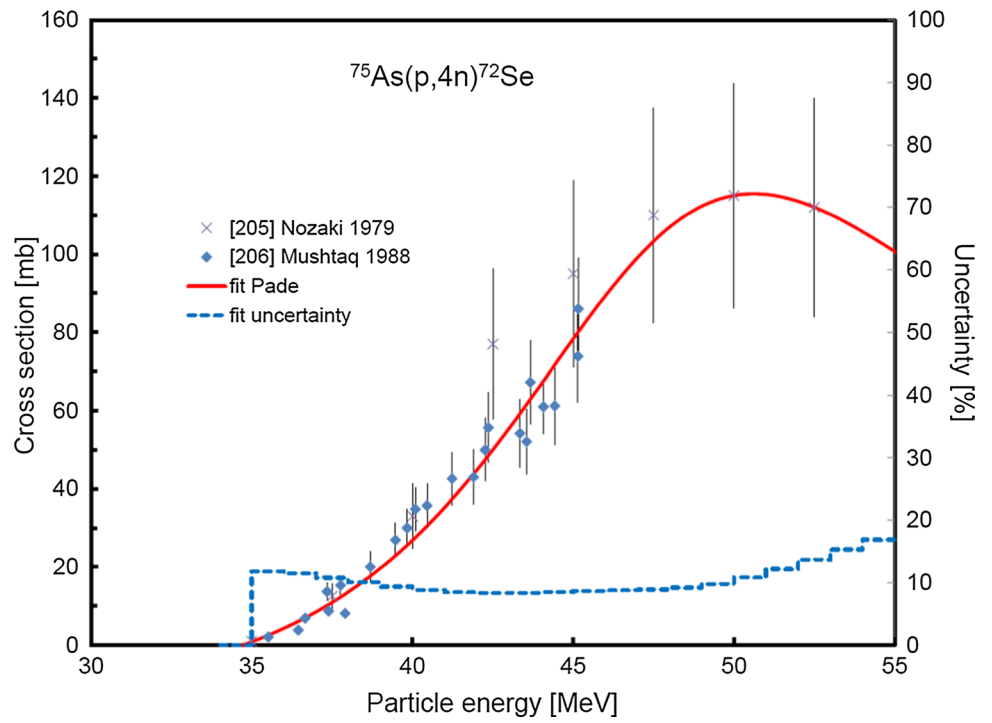


Fig. 72 Two experimental datasets for the $^{75}\text{As}(p,4n)^{72}\text{Se}$ reaction [205, 206] with the Padé fit ($L=8$, $N=33$, $\chi^2=1.30$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{nat}\text{Br}(p,x)^{72}\text{Se}$

The two experimental datasets available in the literature are shown in Fig. 73 [207, 208] together with the TENDL calculations. Both sets of measurements by Fassbender et al. [207] and de Villiers et al. [208] originate from the same experimental study, and should be identical. Therefore, the data of de Villiers et al. [208] were set aside, while only the

other dataset was used in the statistical fitting procedure. These selected data and their experimental uncertainties are shown in Fig. 74 together with the Padé fit ($L=10$, $N=14$, $\chi^2=0.35$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale). The contributions of the similar (p,2pxn) reactions on the two stable isotopes of Br can be clearly distinguished (^{79}Br : 50.69%; ^{81}Br : 49.31%).

Fig. 73 Two experimental datasets for the $^{nat}\text{Br}(p,x)^{72}\text{Se}$ reaction available in the literature [207, 208], and TENDL calculations

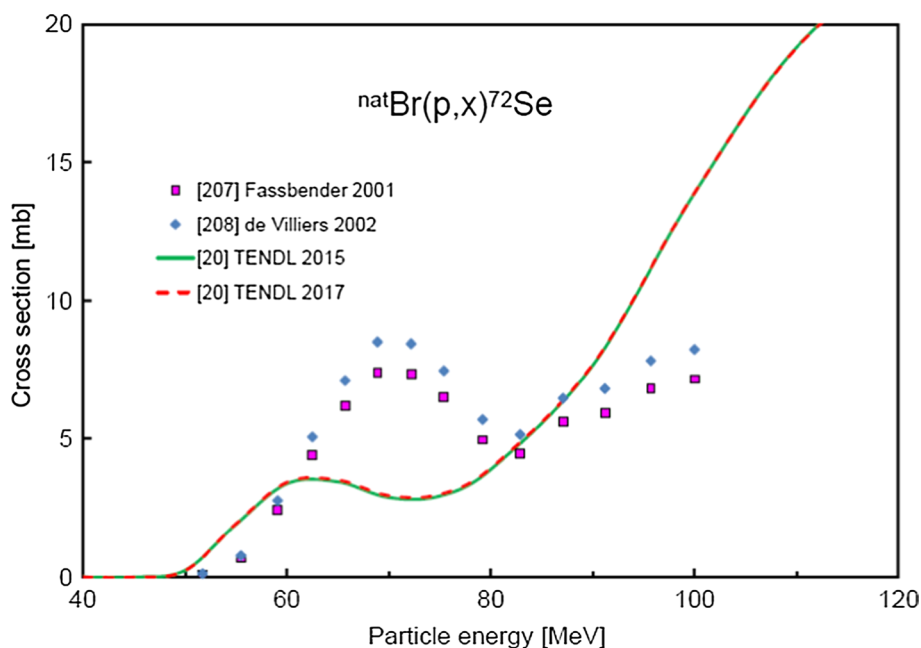
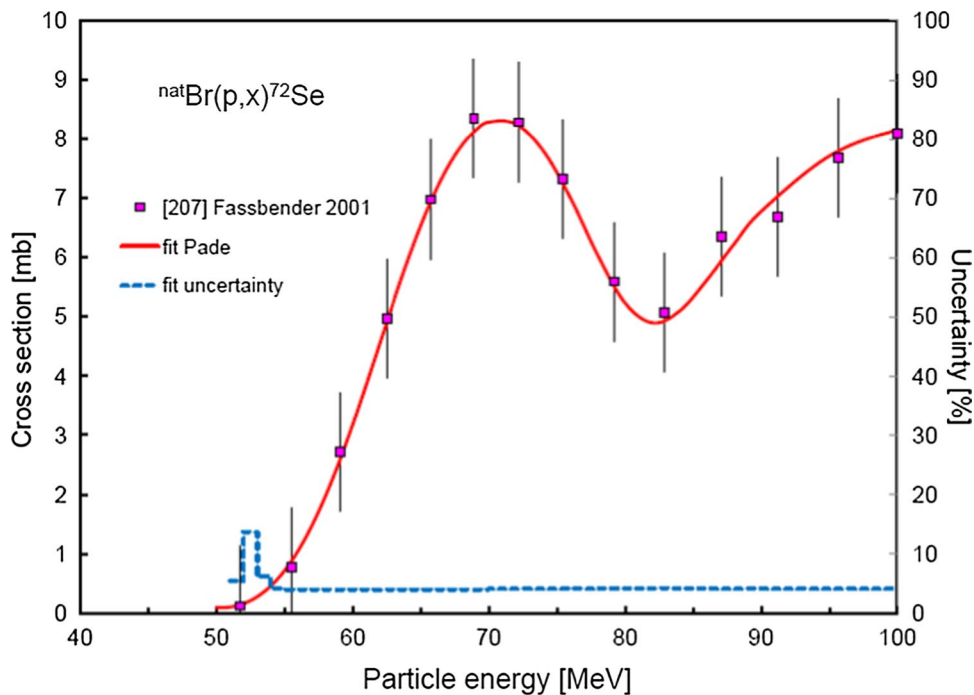


Fig. 74 One selected experimental dataset for the $^{nat}\text{Br}(p,x)^{72}\text{Se}$ reaction [207] with the Padé fit ($L=10$, $N=14$, $\chi^2=0.35$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



${}^{\text{nat}}\text{Ge}(p,xn){}^{72}\text{As}$

The four experimental datasets available in the literature are shown in Fig. 75 [36, 209–211] together with the TENDL calculations. All datasets were used in the statistical fitting procedure. The data and their experimental uncertainties are

shown in Fig. 76 together with the Padé ($L=18$, $N=123$, $\chi^2=1.97$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale). Contributions of similar (p,xn) reactions with increasing thresholds can be clearly distinguished for the higher abundance ${}^{72}\text{Ge}$, ${}^{74}\text{Ge}$ and ${}^{76}\text{Ge}$.

Fig. 75 Four experimental datasets for the ${}^{\text{nat}}\text{Ge}(p,xn){}^{72}\text{As}$ reaction available in the literature [36, 209–211], and TENDL calculations

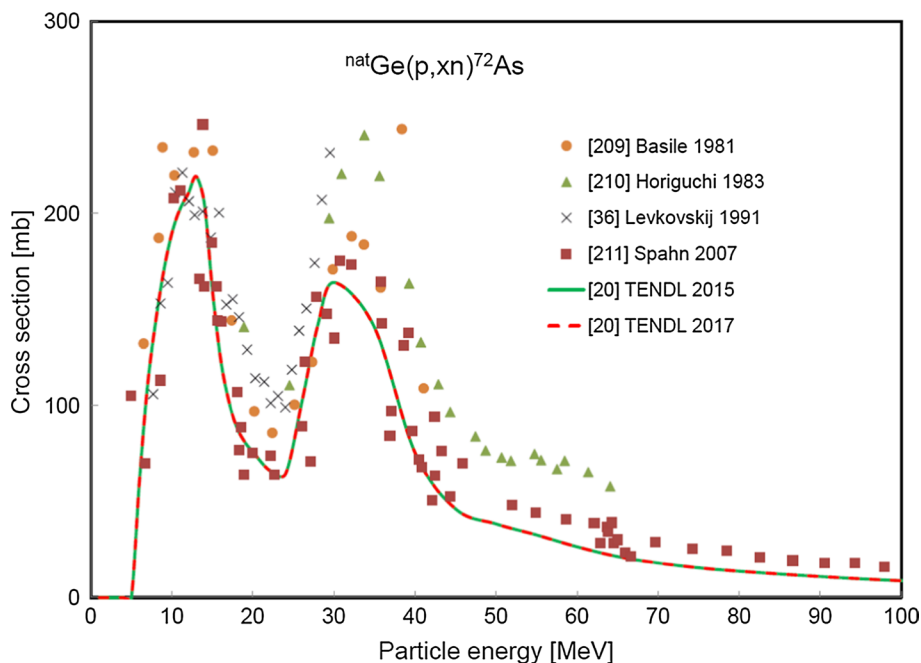
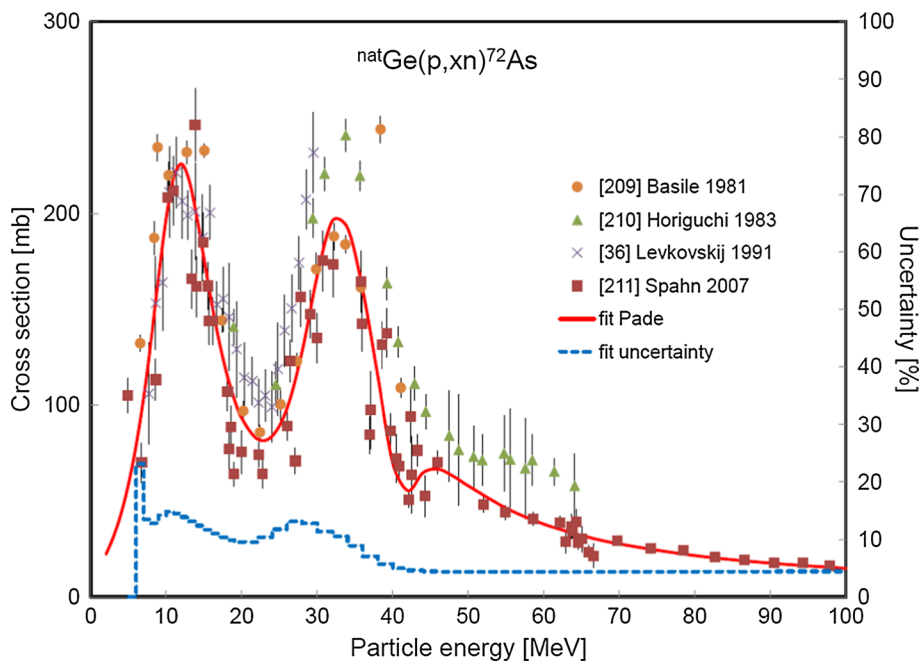


Fig. 76 Four experimental datasets for the ${}^{\text{nat}}\text{Ge}(p,xn){}^{72}\text{As}$ reaction [36, 209–211] with the Padé fit ($L=18$, $N=123$, $\chi^2=1.97$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{nat}\text{Ge}(d,xn)^{72}\text{As}$

The single experimental dataset available in the literature is shown in Fig. 77 [212] together with the TENDL calculations. All data points and their experimental uncertainties are shown in Fig. 78 together with the Padé fit ($L=10$,

$N=25$, $\chi^2=1.13$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale). The contributions of the $^{72}\text{Ge}(d,2n)$ and $^{74}\text{Ge}(d,4n)$ reactions on high natural abundance Ge isotopes can be seen in both figures.

Fig. 77 One experimental dataset for the $^{nat}\text{Ge}(d,xn)^{72}\text{As}$ reaction available in the literature [212], and TENDL calculations

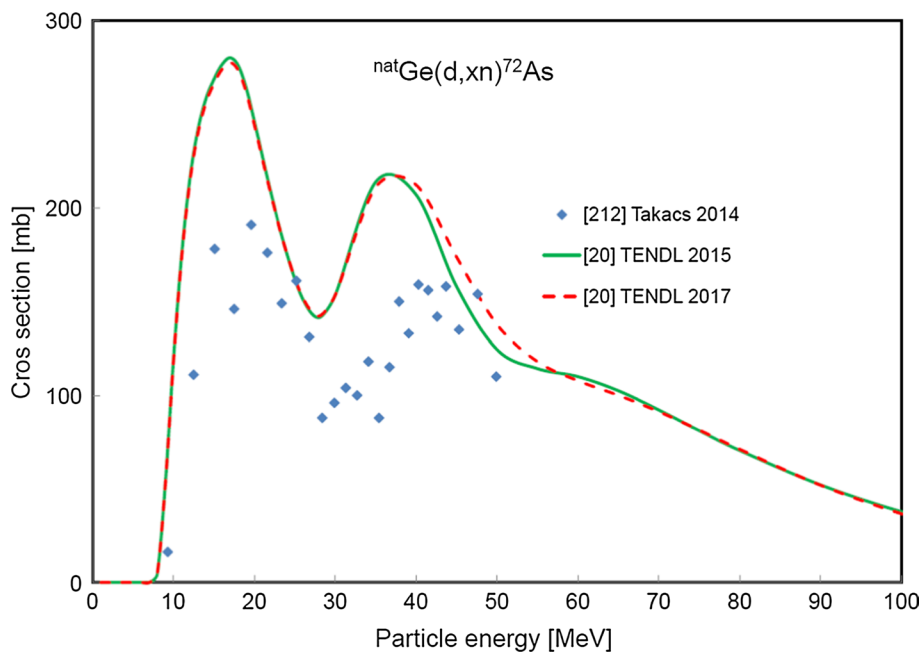
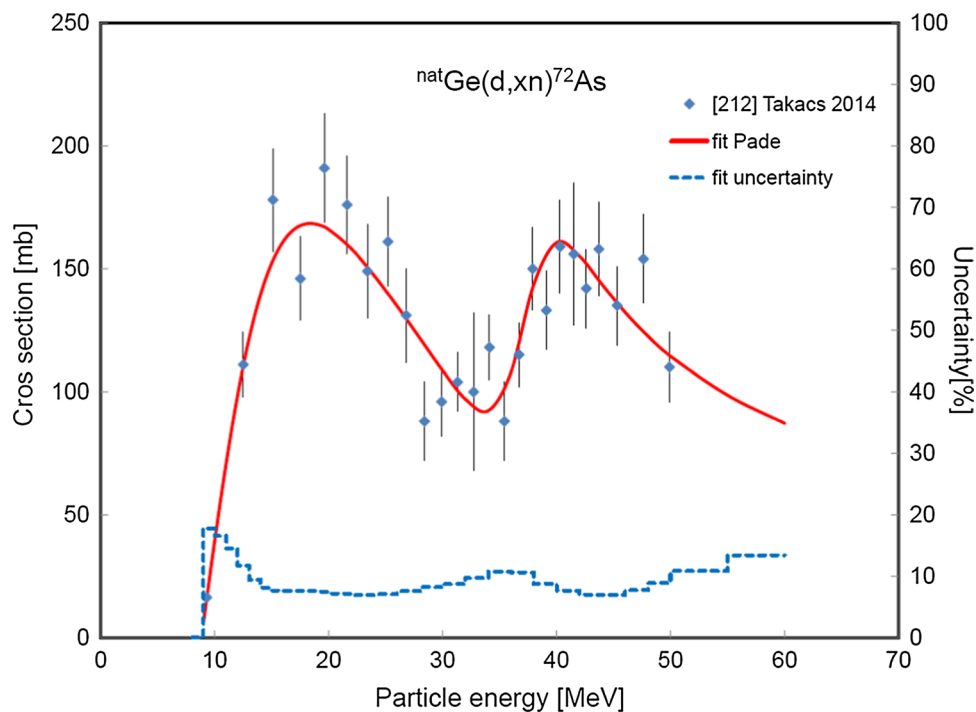


Fig. 78 One experimental dataset for the $^{nat}\text{Ge}(d,xn)^{72}\text{As}$ reaction [212] with the Padé fit ($L=10$, $N=25$, $\chi^2=1.13$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{72}As , and ^{72}Se parent

See Figs. 79 and 80.

Fig. 79 Thick target yields calculated from the recommended cross sections for the $^{nat}\text{Ge}(p,xn)^{72}\text{As}$ and $^{nat}\text{Ge}(d,xn)^{72}\text{As}$ reactions

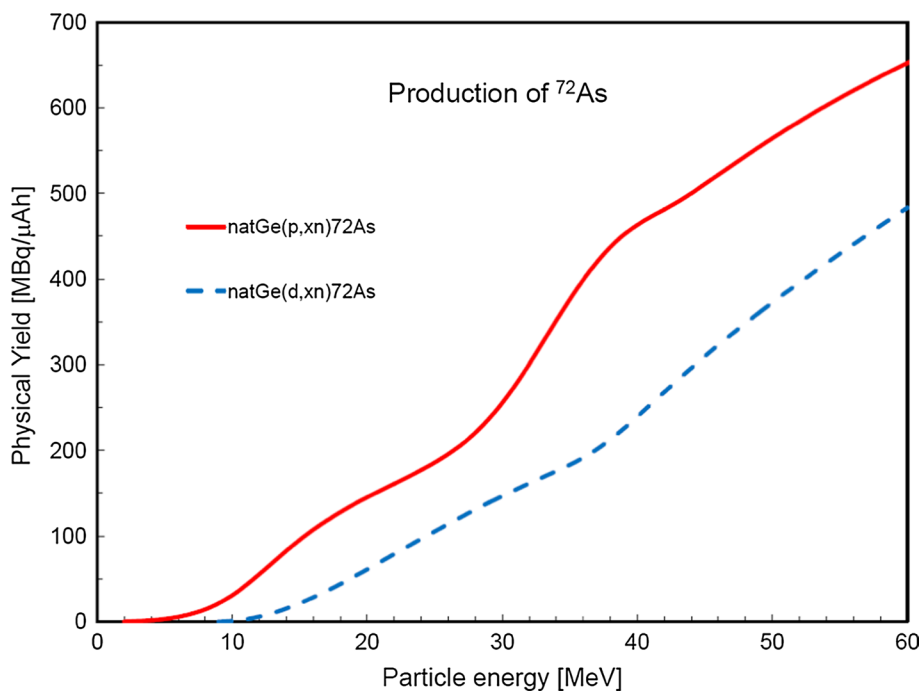
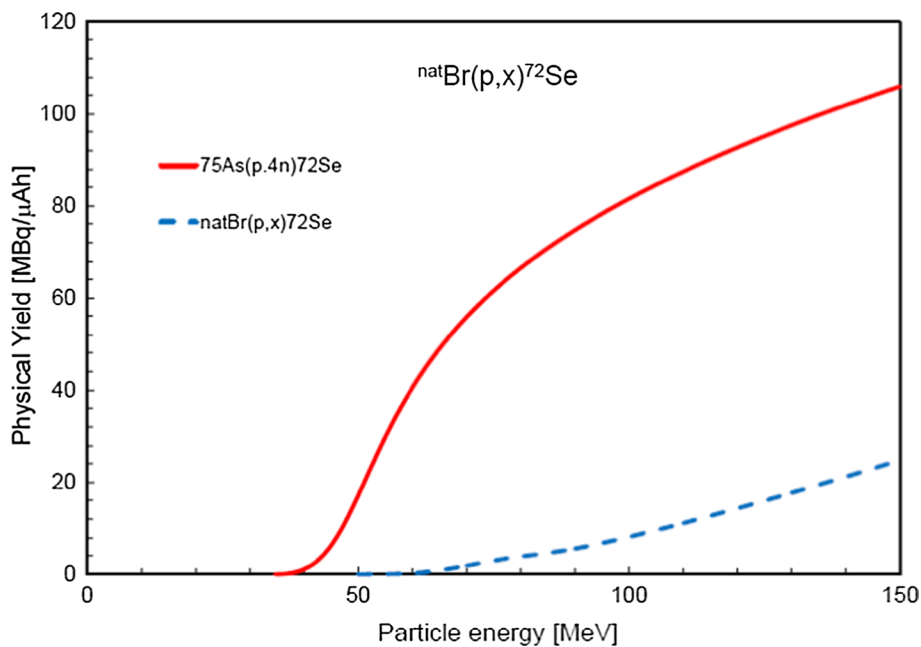


Fig. 80 Thick target yields calculated from the recommended cross sections for the $^{75}\text{As}(p,4n)^{72}\text{Se}$ and $^{nat}\text{Br}(p,x)^{72}\text{Se}$ reactions



Production of ^{73}Se ($T_{1/2} = 7.15\text{ h}$)

Applications: ^{73}Se ($T_{1/2} = 7.15\text{ h}$; $\text{EC} = 34.6\%$, $\beta^+ = 65.4\%$; $E_{\beta^+}(\text{max}) = 1.65\text{ MeV}$) is an interesting β^+ -emitting analogue of sulphur suitable for the imaging of enzymatic systems or sulphur-containing amino acids.

$^{73}\text{Se}(7.15\text{ h})$: β^+ (65.4%), and E_γ (keV) ($P_\gamma(\%)$): 67.07 (70), 361.2 (97.0).

Evaluations have been made of the $^{75}\text{As}(p,3n)^{73}\text{Se}$ and $^{72}\text{Ge}(\alpha,3n)^{73}\text{Se}$ direct production routes.

$^{75}\text{As}(p,3n)^{73}\text{Se}$

The four experimental datasets available in the literature are shown in Fig. 81 [36, 206, 213, 214] together with the TENDL calculations. One dataset was rejected (Mushtaq et al. [206] (values too low near maximum)), and the remaining three sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 82 together with the Padé ($L = 9$, $N = 64$,

Fig. 81 Four experimental datasets for the $^{75}\text{As}(p,3n)^{73}\text{Se}$ reaction available in the literature [36, 206, 213, 214], and TENDL calculations

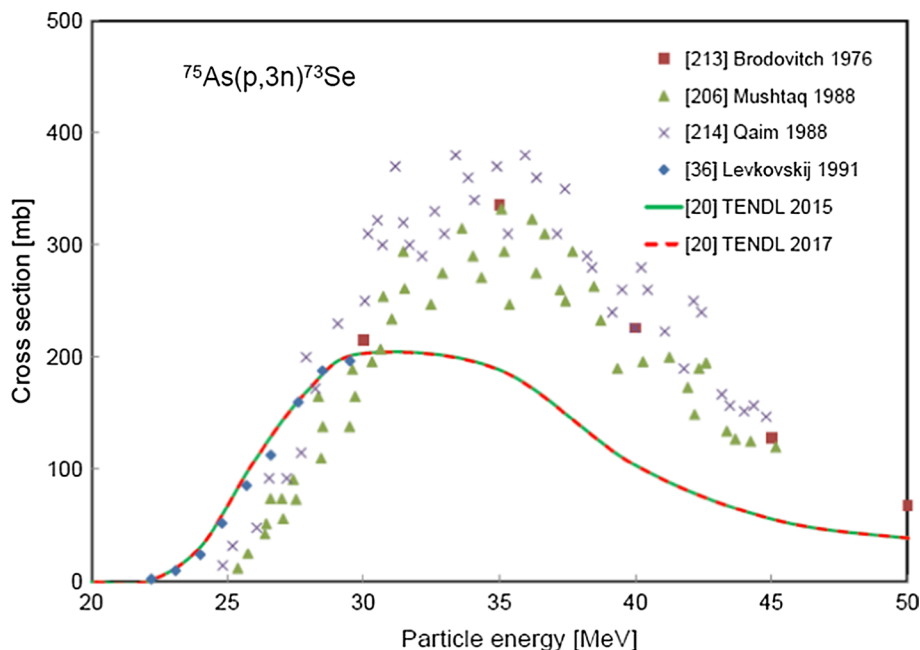
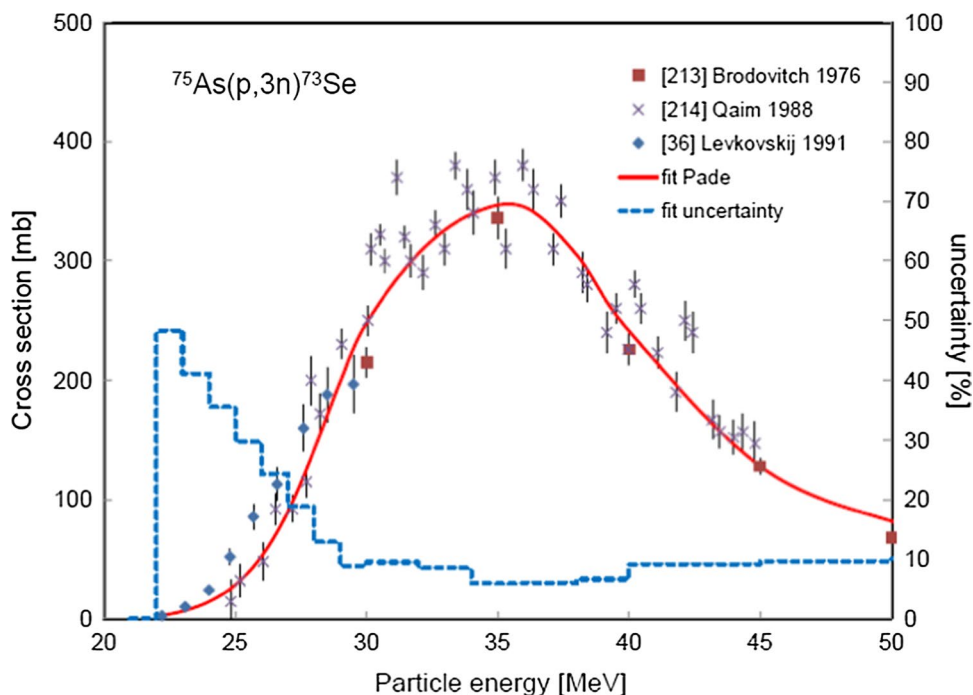


Fig. 82 Three selected experimental datasets for the $^{75}\text{As}(p,3n)^{73}\text{Se}$ reaction [36, 213, 214] with the Padé fit ($L = 9$, $N = 64$, $\chi^2 = 1.52$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$\chi^2 = 1.52$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

$^{72}\text{Ge}(\alpha,3n)^{73}\text{Se}$

The two experimental datasets available in the literature are shown in Fig. 83 [36, 215] together with the TENDL

calculations. Both datasets were used in the statistical fitting procedure. The data and their experimental uncertainties are shown in Fig. 84 together with the Padé fit ($L=8, N=27$, $\chi^2 = 3.81$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 83 Two experimental datasets for the $^{72}\text{Ge}(\alpha,3n)^{73}\text{Se}$ reaction available in the literature [36, 215], and TENDL calculations

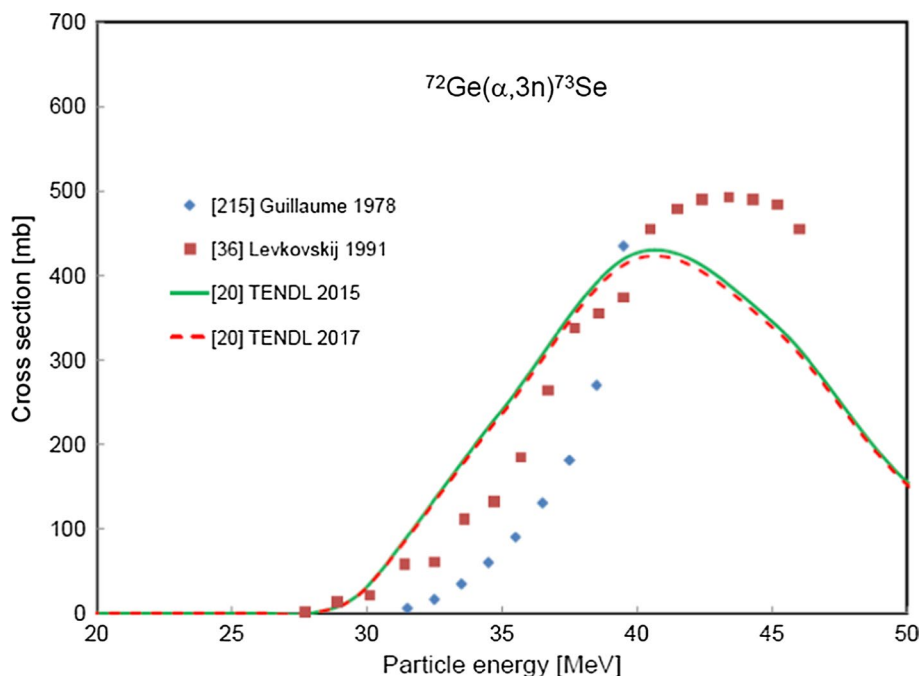
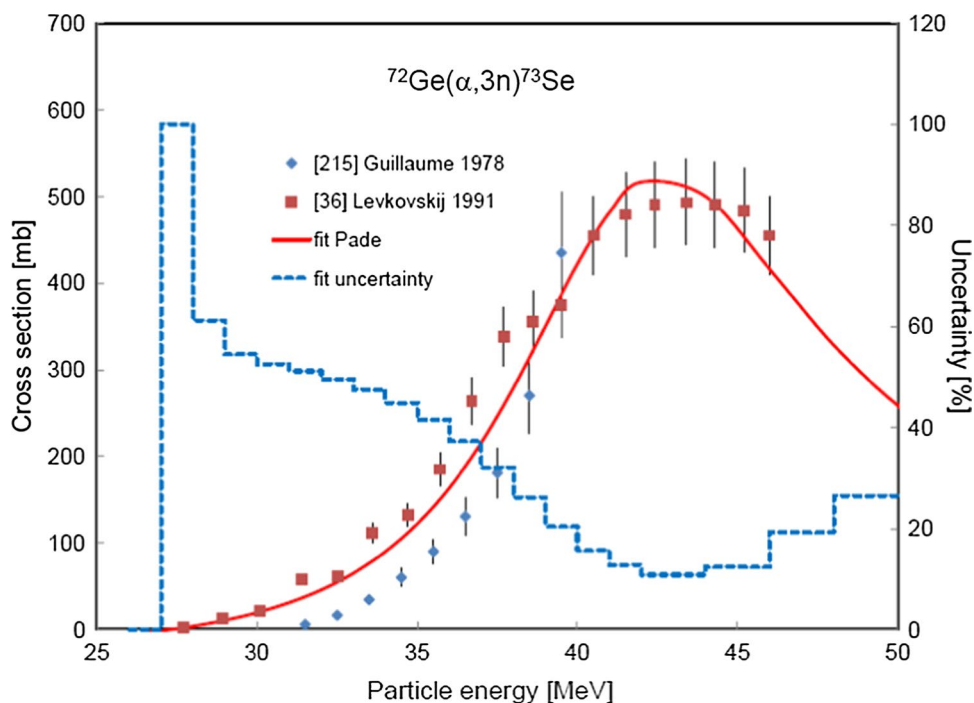


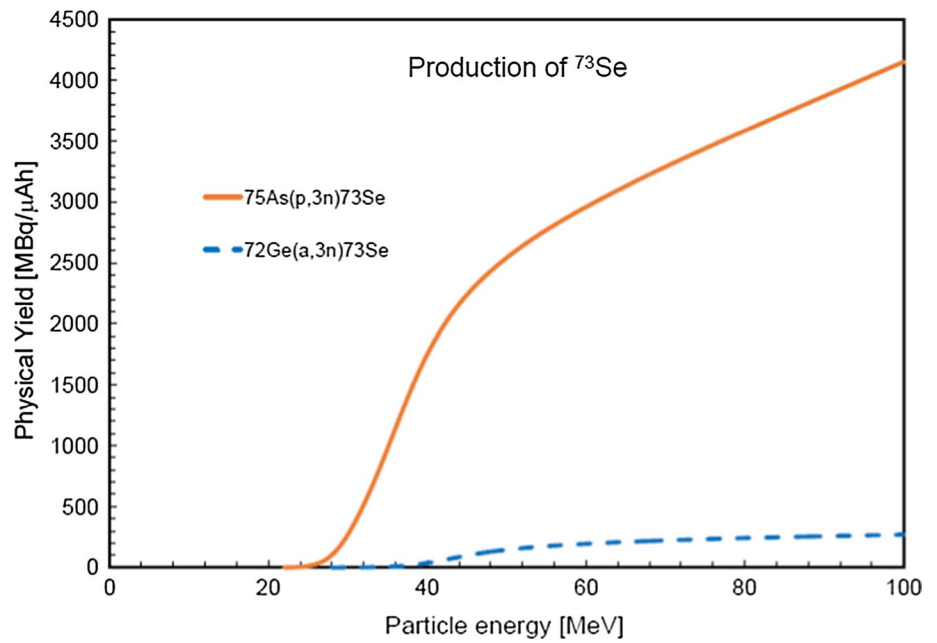
Fig. 84 Two experimental datasets for the $^{72}\text{Ge}(\alpha,3n)^{73}\text{Se}$ reaction [36, 215] with the Padé fit ($L=8, N=27$, $\chi^2 = 3.81$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{73}Se

See Fig. 85.

Fig. 85 Thick target yields calculated from the recommended cross sections for the $^{75}\text{As}(p,3n)^{73}\text{Se}$ and $^{72}\text{Ge}(\alpha,3n)^{73}\text{Se}$ reactions



Production of ^{76}Br ($T_{1/2} = 16.2\text{ h}$)

Applications: Longer-lived positron-emitting radiohalogens were some of the first radionuclides studied to follow processes with kinetics inappropriate for ^{18}F application. ^{76}Br was used in several studies to label monoclonal antibodies, although the large number of accompanying gamma rays that result in a relatively high radiation burden and poor imaging properties has seen a subsequent decline of interest in this radionuclide.

^{76}Br (16.2 h): β^+ (55%) and E_γ (keV) (P_γ (%)): 559.09 (74), 657.02 (15.9), 1853.67 (14.7).

Evaluations have been made of the $^{76}\text{Se}(p,n)^{76}\text{Br}$, $^{77}\text{Se}(p,2n)^{76}\text{Br}$ and $^{75}\text{As}(\alpha,3n)^{76}\text{Br}$ production routes.

$^{76}\text{Se}(p,n)^{76}\text{Br}$

The five experimental datasets available in the literature are shown in Fig. 86 [36, 216–219] together with the TENDL calculations. Two datasets were rejected (Kovács et al. [218] (values too low near maximum), and Hassan et al. [219] (discrepant data near maximum)), and the remaining three sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 87 together with the Padé fit ($L=8$, $N=39$, $\chi^2=1.05$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 86 Five experimental datasets for the $^{76}\text{Se}(p,n)^{76}\text{Br}$ reaction available in the literature [36, 216–219], and TENDL calculations

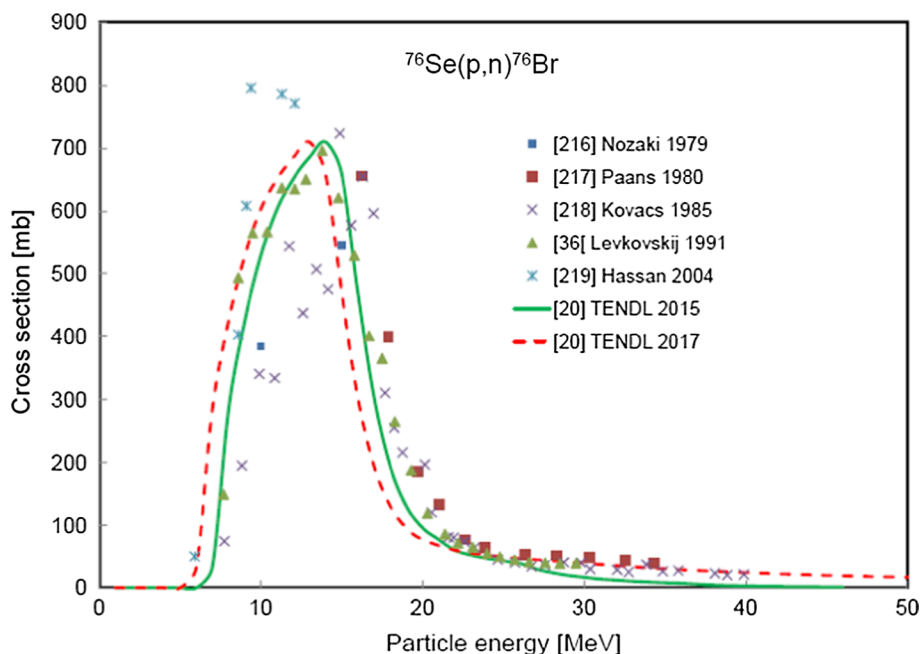
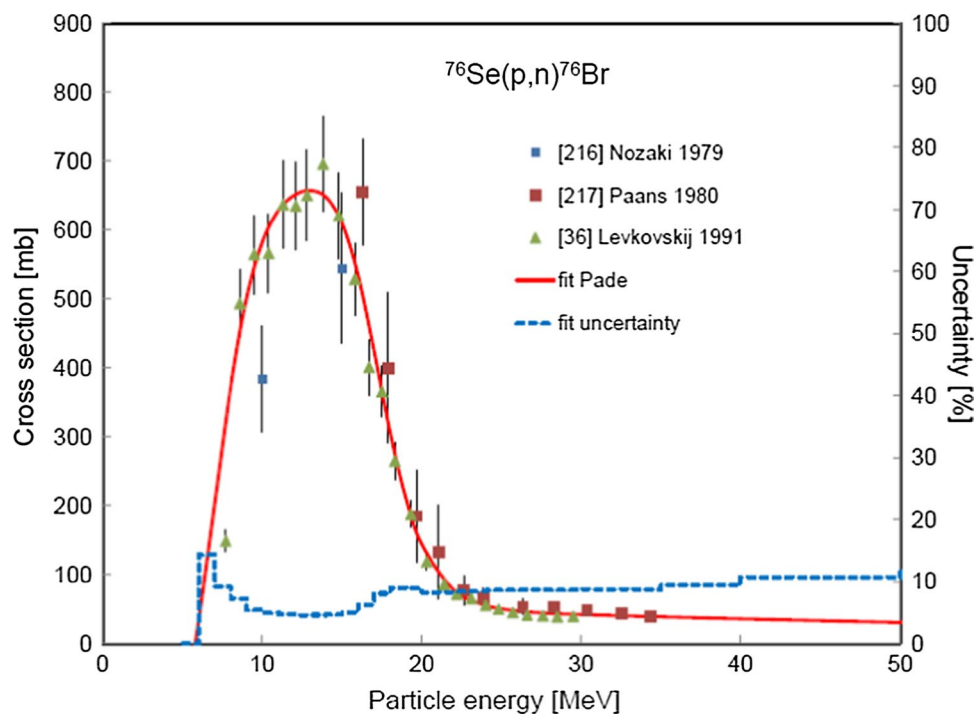


Fig. 87 Three selected experimental datasets for the $^{76}\text{Se}(p,n)^{76}\text{Br}$ reaction [36, 216, 217] with the Padé fit ($L=8$, $N=39$, $\chi^2=1.05$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{77}\text{Se}(p,2n)^{76}\text{Br}$

The four experimental datasets available in the literature are shown in Fig. 88 [36, 219–221] together with the TENDL calculations. Two datasets were rejected (Janssen et al. [220] (values too low), and Hassan et al. [219] (values too high)),

and the remaining two sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 89 together with the Padé fit ($L=9$, $N=52$, $\chi^2=1.34$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 88 Four experimental datasets for the $^{77}\text{Se}(p,2n)^{76}\text{Br}$ reaction available in the literature [36, 219–221], and TENDL calculations

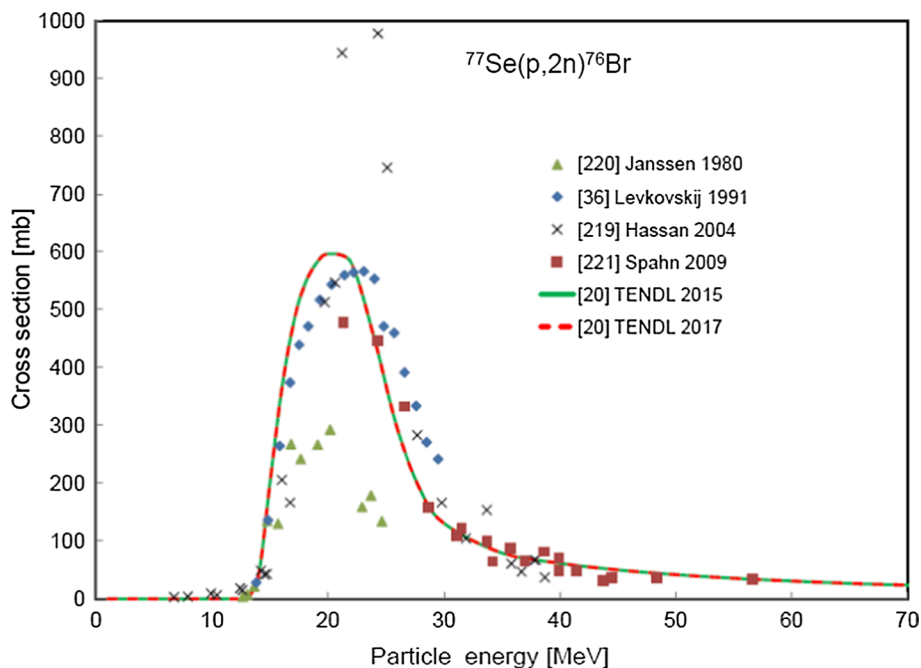
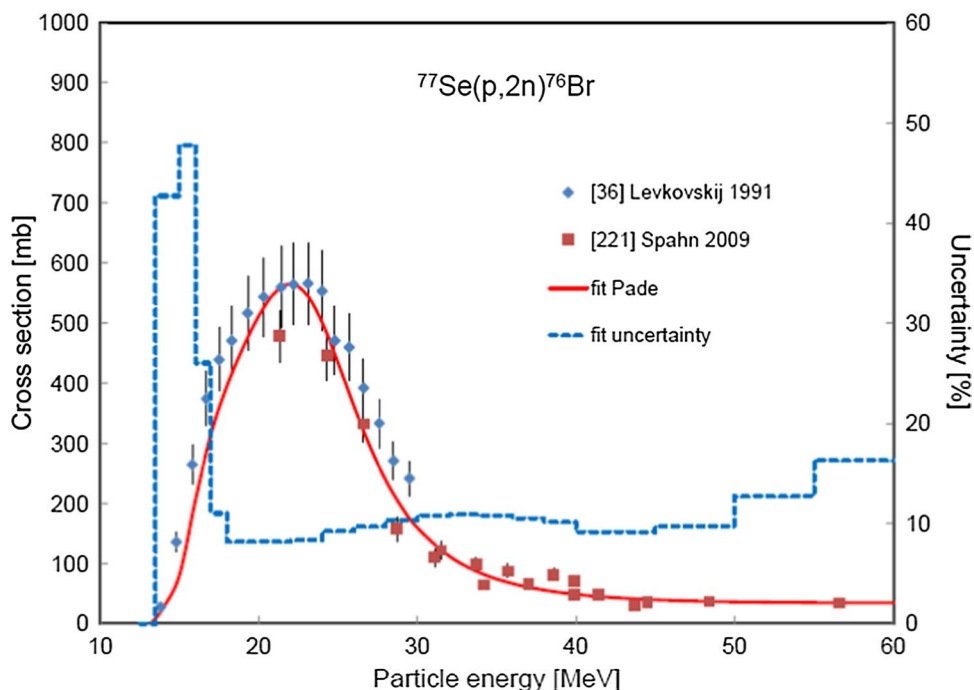


Fig. 89 Two selected experimental datasets for the $^{77}\text{Se}(p,2n)^{76}\text{Br}$ reaction [36, 221] with the Padé fit ($L=9$, $N=52$, $\chi^2=1.34$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{75}\text{As}(\alpha,3n)^{76}\text{Br}$

The five experimental datasets available in the literature are shown in Fig. 90 [216, 217, 222–224] together with the TENDL calculations. All datasets were used for the statistical fitting procedure. The data and their experimental

uncertainties are shown in Fig. 91 together with the Padé fit ($L=10, N=70, \chi^2=2.43$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale). An additional dataset published after the evaluation cut-off date was also included in the fit (Breunig et al. [224]) and is shown in Fig. 90.

Fig. 90 Five experimental datasets for the $^{75}\text{As}(\alpha,3n)^{76}\text{Br}$ reaction available in the literature [216, 217, 222–224], and TENDL calculations

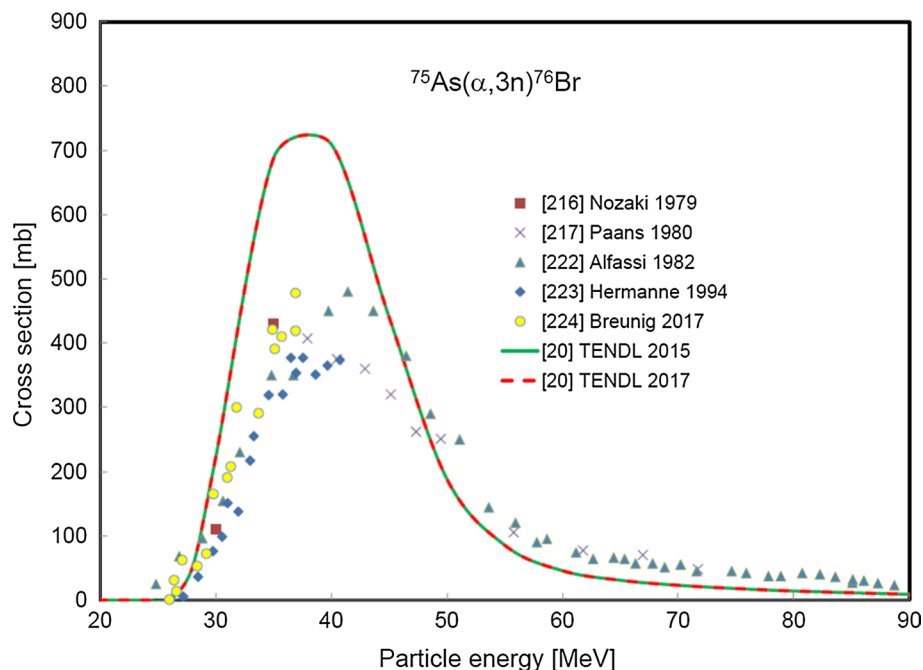
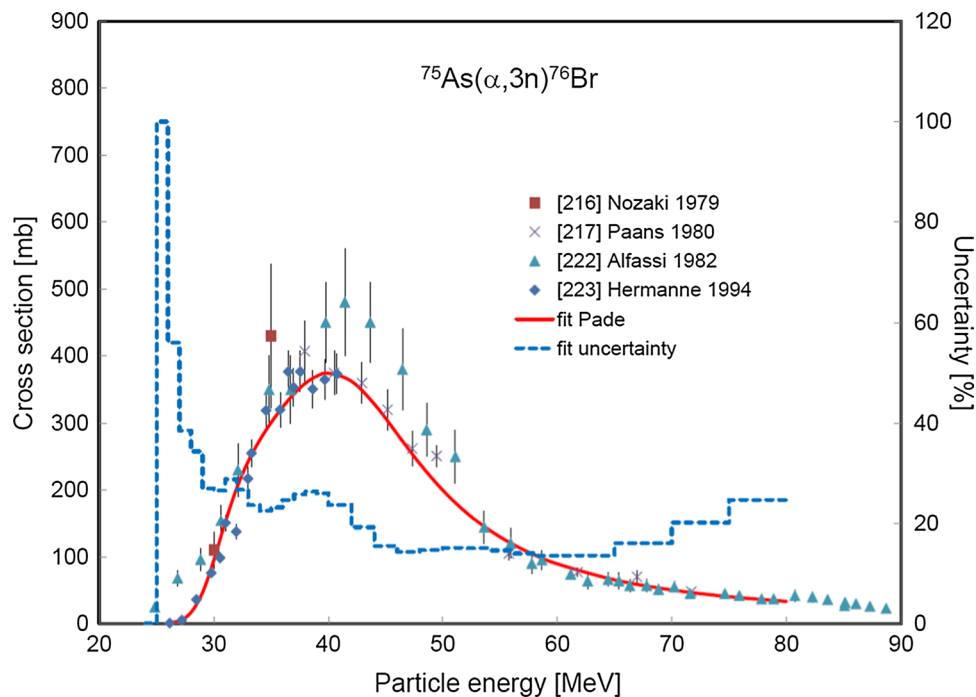


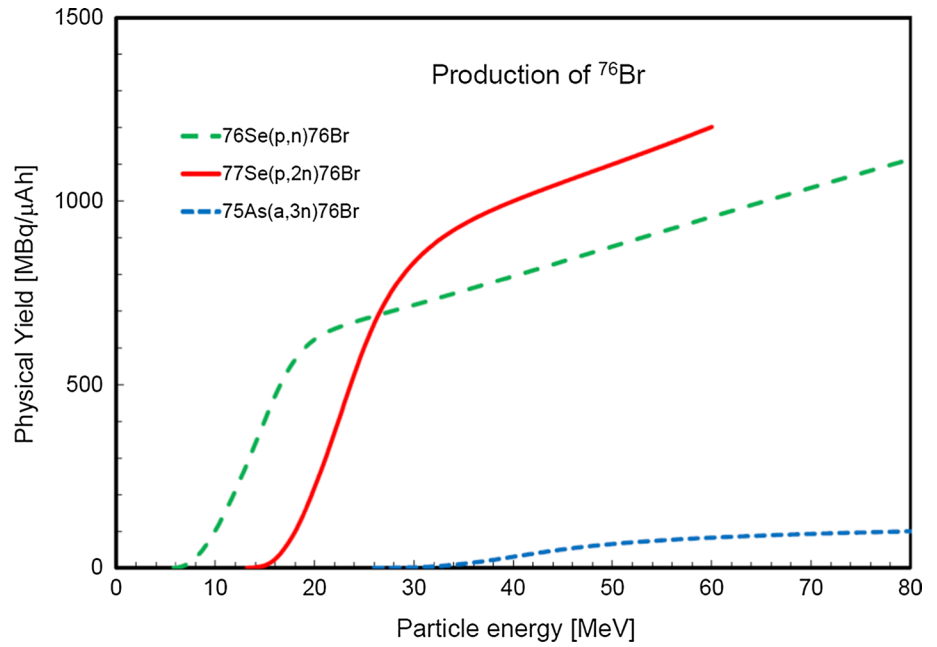
Fig. 91 Five experimental datasets for the $^{75}\text{As}(\alpha,3n)^{76}\text{Br}$ reaction [216, 217, 222–224] with the Padé fit ($L=10, N=70, \chi^2=2.43$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for ^{76}Br

See Fig. 92.

Fig. 92 Thick target yields calculated from the recommended cross sections for the $^{76}\text{Se}(p,n)^{76}\text{Br}$, $^{77}\text{Se}(p,2n)^{76}\text{Br}$ and $^{75}\text{As}(\alpha,3n)^{76}\text{Br}$ reactions



Production of ^{82}Sr parent ($T_{1/2} = 25.35$ d) of short-lived ^{82}Rb ($T_{1/2} = 1.2575$ min)

Applications: Generator-produced ^{82}Rb is widely used in myocardial perfusion imaging, particularly in the USA. This isotope undergoes rapid uptake by myocardiocytes, and therefore is a valuable tool for identifying myocardial ischemia by means of PET. Such a short half-life allows one to perform both stress and rest perfusion studies within 30 min.

^{82}Rb (1.2575 min): β^+ (95.43%), and E_γ (keV) ($P_\gamma(\%)$): 776.52 (15.08).

^{82}Sr (25.35 d): detected by means of radiation emitted by daughter ^{82}Rb .

Evaluations have been undertaken of the $^{\text{nat}}\text{Rb}(p,xn)^{82}\text{Sr}$ and $^{85}\text{Rb}(p,4n)^{82}\text{Sr}$ parent production routes.

$^{\text{nat}}\text{Rb}(p,xn)^{82}\text{Sr}$

The seven experimental datasets available in the literature are shown in Fig. 93 [138, 225–230] together with the TENDL calculations. Two datasets were rejected (Horiguchi et al. [225] (values too high), and Deptula et al. [226] (values too high)), and the remaining five sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 94 together with the Padé fit ($L = 13$, $N = 49$, $\chi^2 = 1.15$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 93 Seven experimental datasets for the $^{\text{nat}}\text{Rb}(p,xn)^{82}\text{Sr}$ reaction available in the literature [138, 225–230], and TENDL calculations

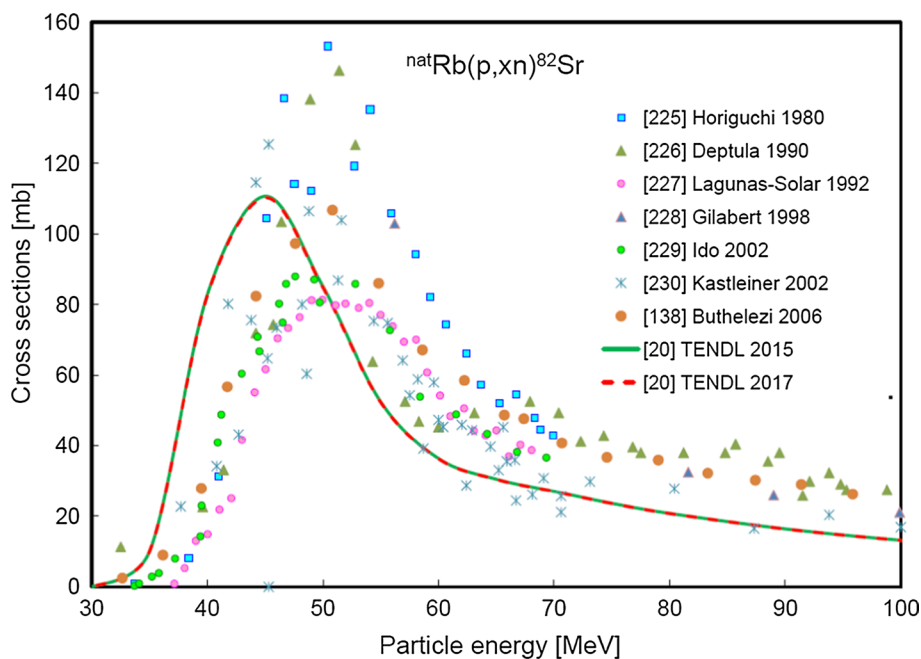
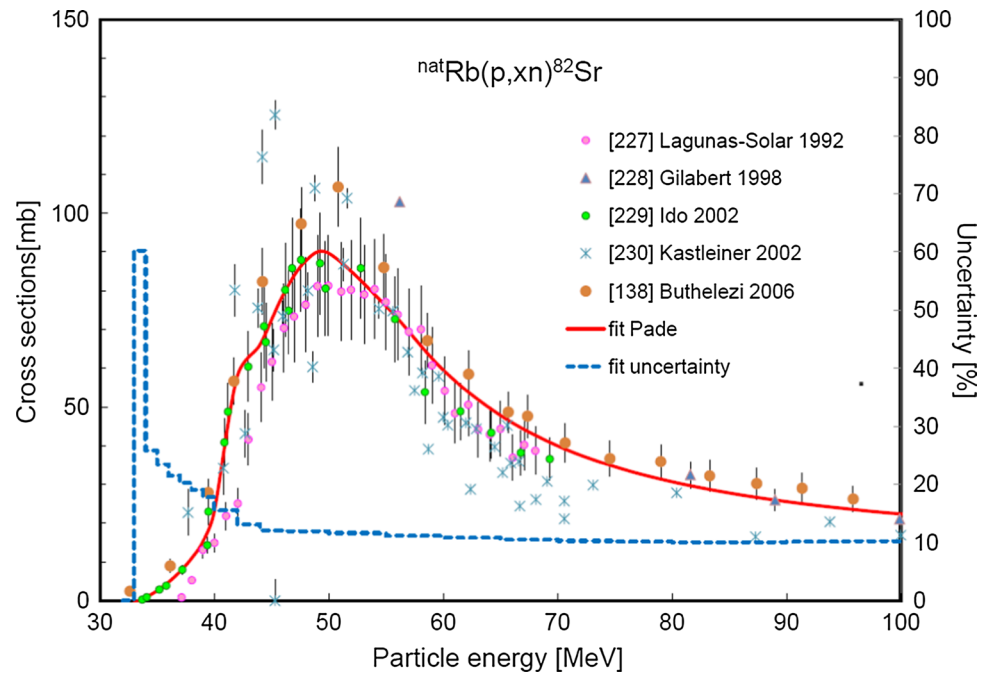


Fig. 94 Five selected experimental datasets for the ${}^{\text{nat}}\text{Rb}(p,xn){}^{82}\text{Sr}$ reaction [138, 227–230] with the Padé fit ($L=13$, $N=49$, $\chi^2=1.15$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{85}\text{Rb}(p,4n)^{82}\text{Sr}$

The five experimental datasets available in the literature are shown in Fig. 95 [138, 225, 227, 229, 230] together with the TENDL calculations. All datasets were used in the statistical fitting procedure. The data and their experimental

uncertainties are shown in Fig. 96 together with the Padé fit ($L=9$, $N=49$, $\chi^2=1.60$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 95 Five experimental datasets for the $^{85}\text{Rb}(p,4n)^{82}\text{Sr}$ reaction available in the literature [138, 225, 227, 229, 230], and TENDL calculations

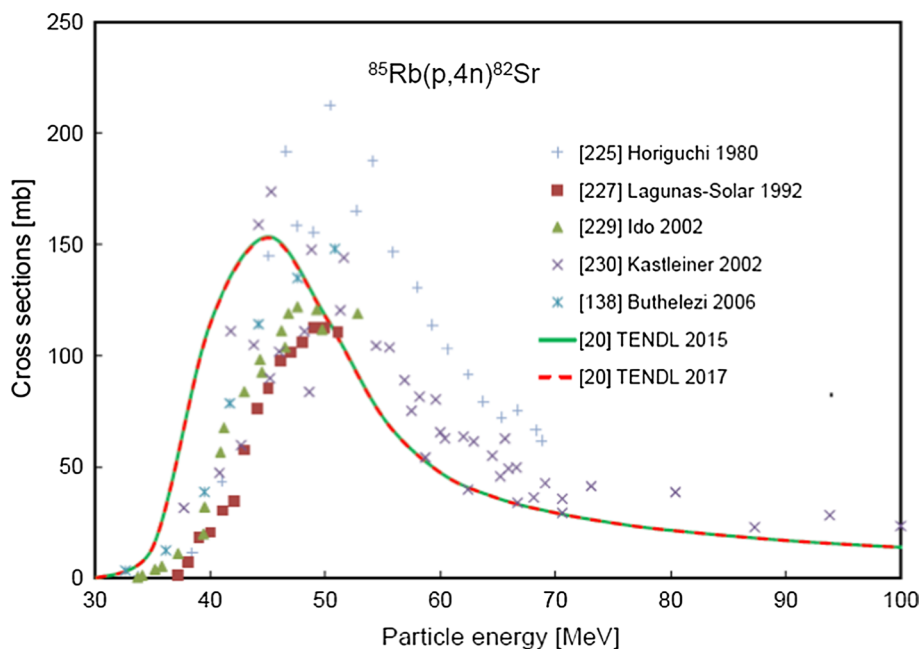
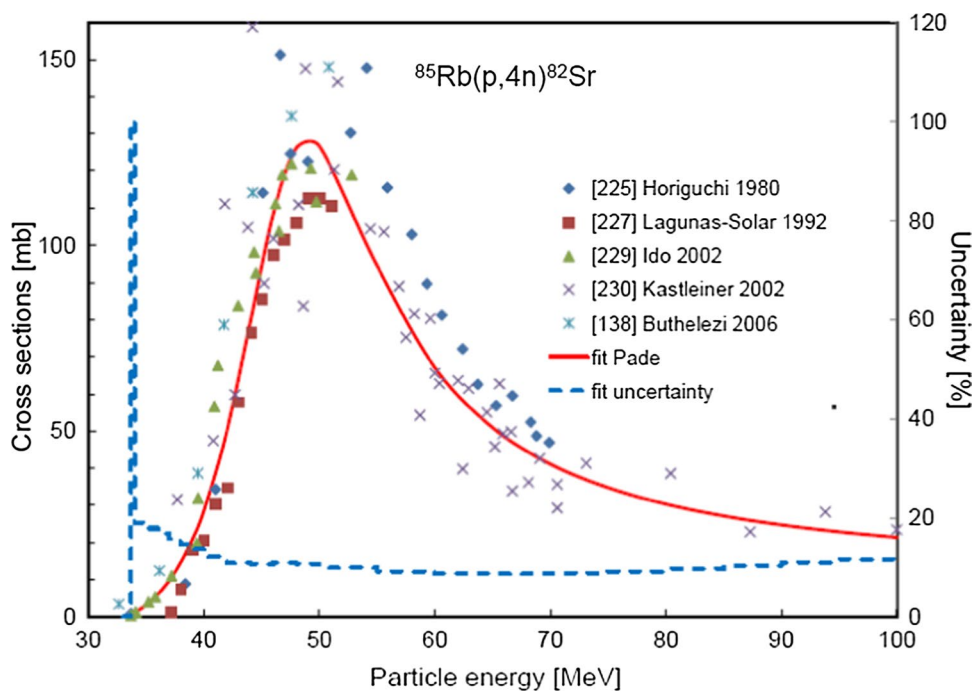


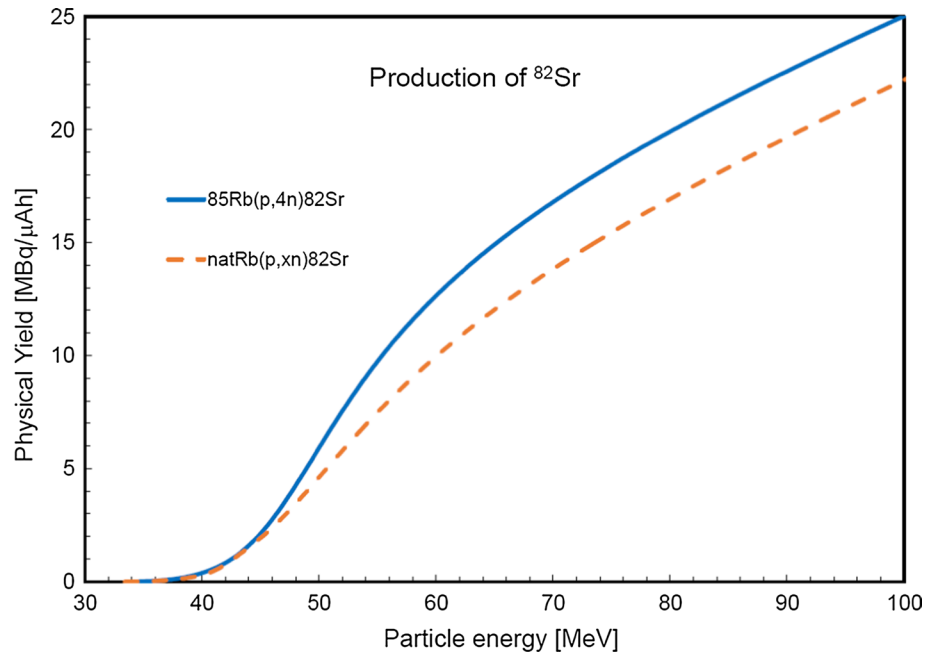
Fig. 96 Five experimental datasets for the $^{85}\text{Rb}(p,4n)^{82}\text{Sr}$ reaction [138, 225, 227, 229, 230] with the Padé fit ($L=9$, $N=49$, $\chi^2=1.60$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for ^{82}Sr parent of short-lived ^{82}Rb

See Fig. 97.

Fig. 97 Thick target yields calculated from the recommended cross sections for the $^{nat}\text{Rb}(p,xn)^{82}\text{Sr}$ and $^{85}\text{Rb}(p,4n)^{82}\text{Sr}$ reactions to produce long-lived parent for short-lived ^{82}Rb



Production of ^{82m}Rb ($T_{1/2} = 6.472\text{ h}$)

Applications: Longer-lived ^{82m}Rb isomeric state could possibly act as a substitute for generator-produced ^{82}Rb in PET cardiology centres that operate a cyclotron. However, this isomer suffers from a relatively high radiation burden that arises from the longer half-life and gamma-ray emissions.

^{82m}Rb (6.472 h): β^+ (21.2%), and E_γ (keV) ($P_\gamma(\%)$): 554.35 (62.4), 619.11 (37.98), 698.37 (26.3), 776.52 (84.39), 827.83 (21.0), 1044.08 (32.07), 1317.43 (23.7), 1474.88 (15.5).

Evaluations have been undertaken of the $^{82}\text{Kr}(p,n)^{82m}\text{Rb}$ and $^{82}\text{Kr}(d,2n)^{82m}\text{Rb}$ reactions.

$^{82}\text{Kr}(p,n)^{82m}\text{Rb}$

The four experimental datasets available in the literature are shown in Fig. 98 [231, 232] (each reference contains two datasets labelled (a) and (b)), together with the TENDL calculations. All datasets were used in the statistical fitting procedure. The data and their experimental uncertainties are shown in Fig. 99 together with the Padé fit ($L = 9$, $N = 33$, $\chi^2 = 1.13$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 98 Four experimental datasets for the $^{82}\text{Kr}(p,n)^{82m}\text{Rb}$ reaction available in the literature [231, 232] (each reference contains two datasets labelled (a) and (b)), and TENDL calculations

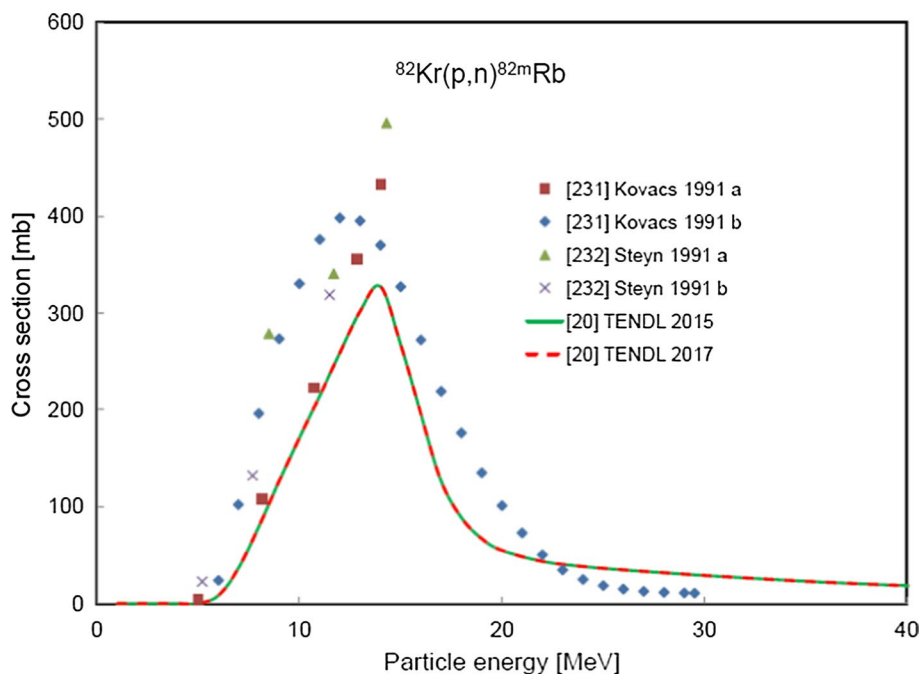
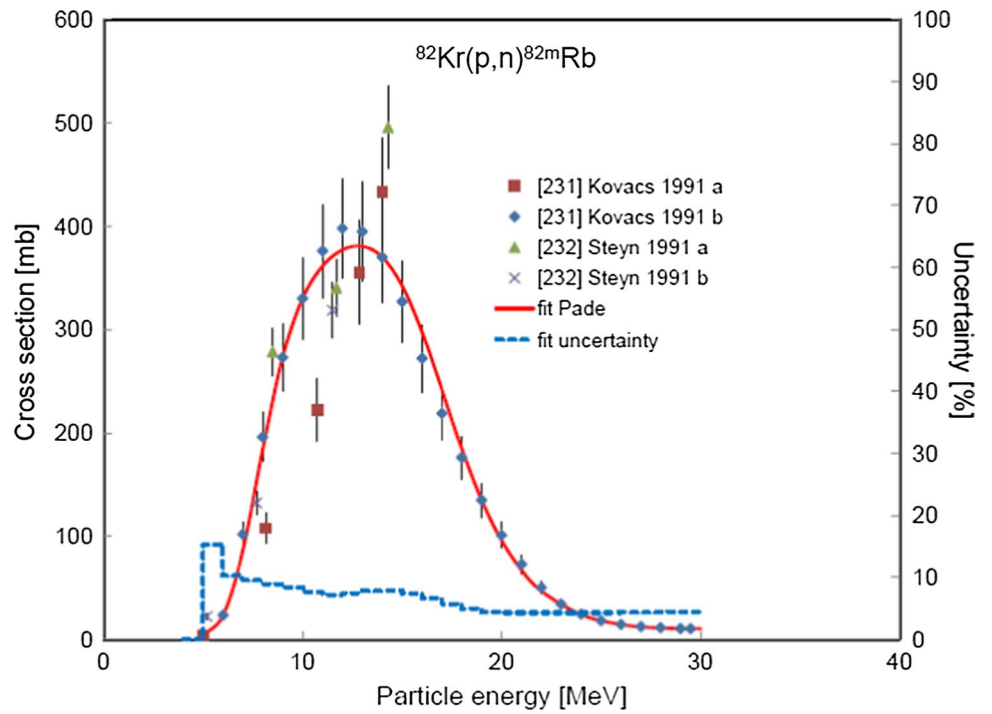


Fig. 99 Four experimental data-sets for the $^{82}\text{Kr}(p,n)^{82\text{m}}\text{Rb}$ reaction [231, 232] with the Padé fit ($L=9$, $N=33$, $\chi^2=1.13$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{82}\text{Kr}(d,2n)^{82\text{m}}\text{Rb}$

A single experimental dataset available in the literature is shown in Fig. 100 [233] together with the TENDL calculations. This one dataset was used in the statistical fitting

procedure. The data and their experimental uncertainties are shown in Fig. 101 together with the Padé fit ($L=5$, $N=14$, $\chi^2=2.27$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 100 One experimental dataset for the $^{82}\text{Kr}(d,2n)^{82\text{m}}\text{Rb}$ reaction available in the literature [233], and TENDL calculations

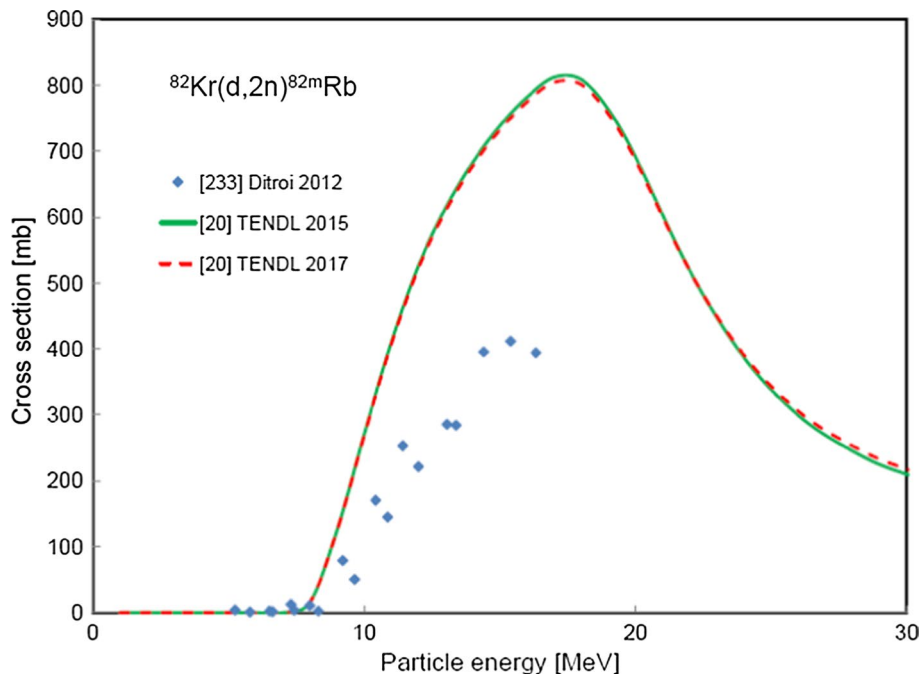
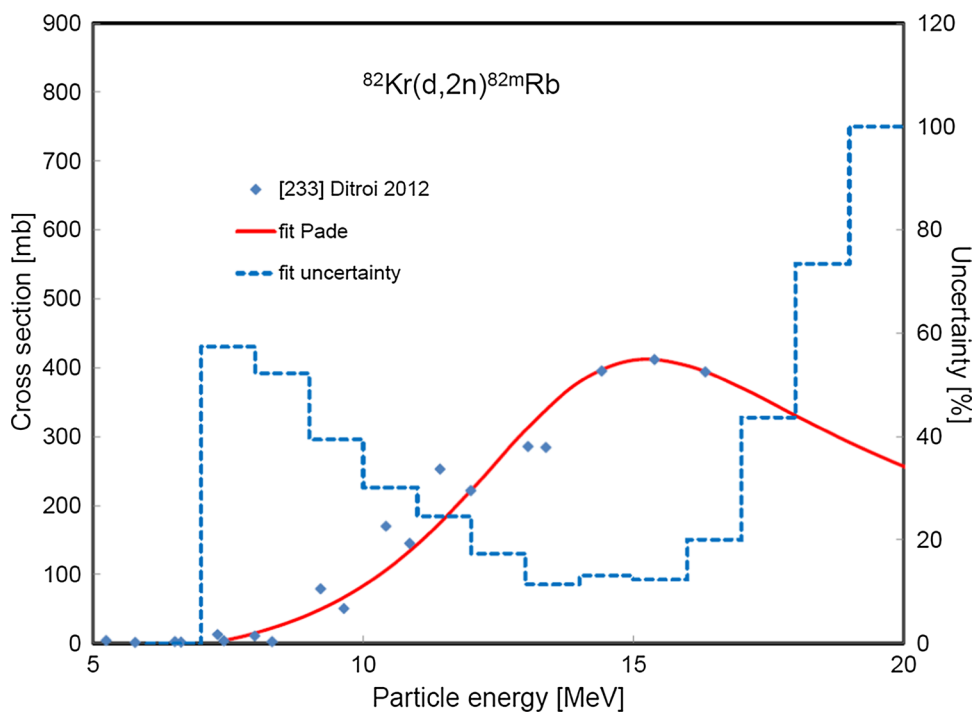


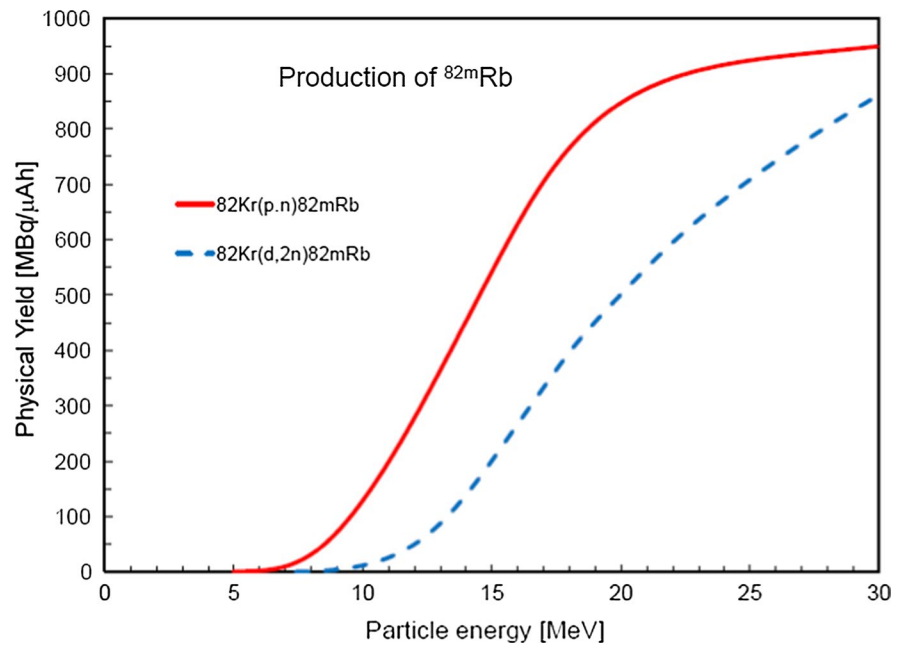
Fig. 101 One experimental dataset for the $^{82}\text{Kr}(d,2n)^{82\text{m}}\text{Rb}$ reaction [233] with the Padé fit ($L=5$, $N=14$, $\chi^2=2.27$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{82m}Rb

See Fig. 102.

Fig. 102 Thick target yields calculated from the recommended cross sections for the $^{82}\text{Kr}(p,n)^{82m}\text{Rb}$ and $^{82}\text{Kr}(d,2n)^{82m}\text{Rb}$ reactions



Production of ^{86}Y ($T_{1/2} = 14.74\text{ h}$)

Applications: Extensive studies of ^{86}Y have been performed as a positron emitter (31.9%) with 14.74 h half-life that can be adopted as a theranostic pair with clinically-established therapeutic beta-emitting ^{90}Y . The role of ^{86}Y is to monitor the localised therapeutic dose distribution in the body for dosimetry calculations. It has also been studied for prostate cancer imaging, and used to label monoclonal antibodies in EGFR targeting. However, interest in this radionuclide has declined because of the high radiation burden and resultant poor imaging properties.

^{86}Y (14.74 h): β^+ (31.9%), and E_γ (keV) ($P_\gamma(\%)$): 627.72 (32.6), 1076.63 (82.5), 1153.05 (30.5).

Evaluations have been made of the $^{86}\text{Sr}(p,n)^{86}\text{Y}$, $^{88}\text{Sr}(p,3n)^{86}\text{Y}$ and $^{85}\text{Rb}(\alpha,3n)^{86}\text{Y}$ production routes.

$^{86}\text{Sr}(p,n)^{86}\text{Y}$

The four experimental datasets available in the literature are shown in Fig. 103 [36, 82, 234, 235] together with the TENDL calculations. One dataset was rejected (Rösch et al. [235] (scattered data, and values too high near maximum)), while the three remaining sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 104 together with the Padé fit ($L=9$, $N=28$, $\chi^2=0.615$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 103 Four experimental datasets for the $^{86}\text{Sr}(p,n)^{86}\text{Y}$ reaction available in the literature [36, 82, 234, 235], and TENDL calculations

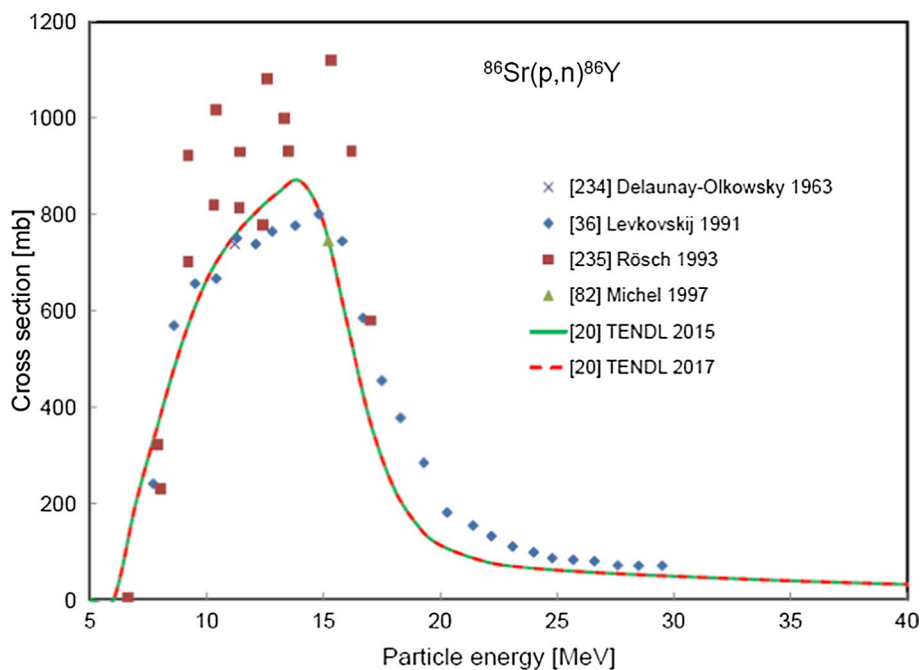
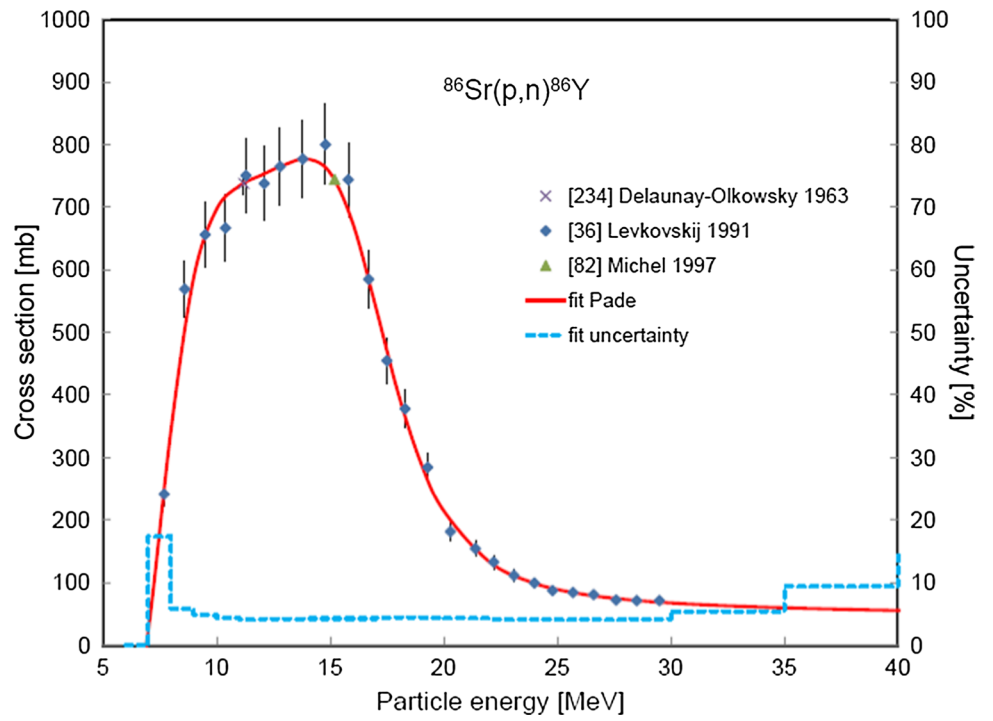


Fig. 104 Three selected experimental datasets for the $^{86}\text{Sr}(p,n)^{86}\text{Y}$ reaction [36, 82, 234] with the Padé fit ($L=9$, $N=28$, $\chi^2=0.615$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{88}\text{Sr}(p,3n)^{86}\text{Y}$

The two experimental datasets available in the literature are shown in Fig. 105 [36, 236] together with the TENDL calculations. Both datasets were used in the statistical fitting

procedure. These data and their experimental uncertainties are shown in Fig. 106 together with the Padé fit ($L=8$, $N=15$, $\chi^2=1.27$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 105 Two experimental datasets for the $^{88}\text{Sr}(p,3n)^{86}\text{Y}$ reaction available in the literature [36, 236], and TENDL calculations

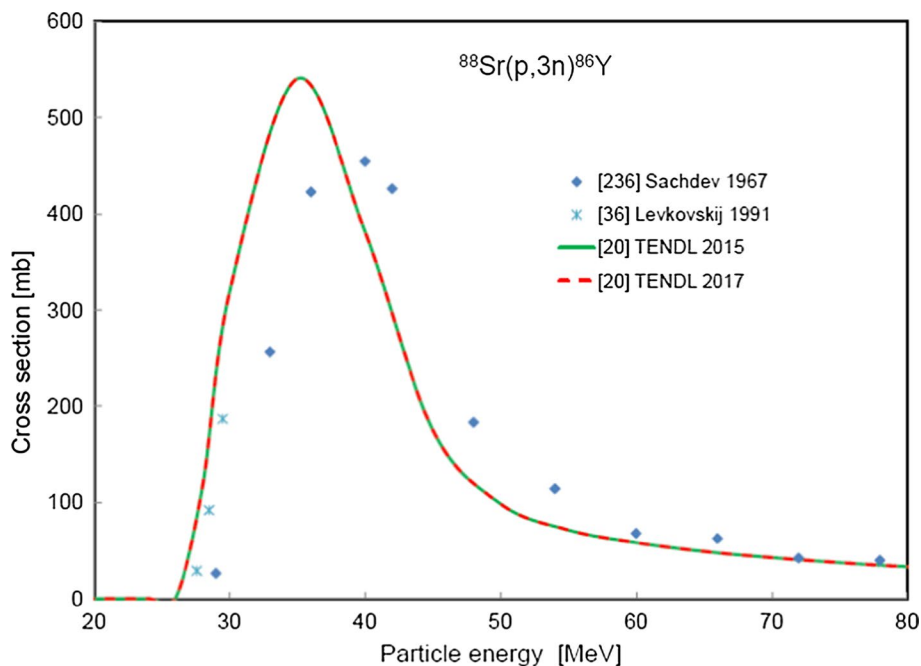
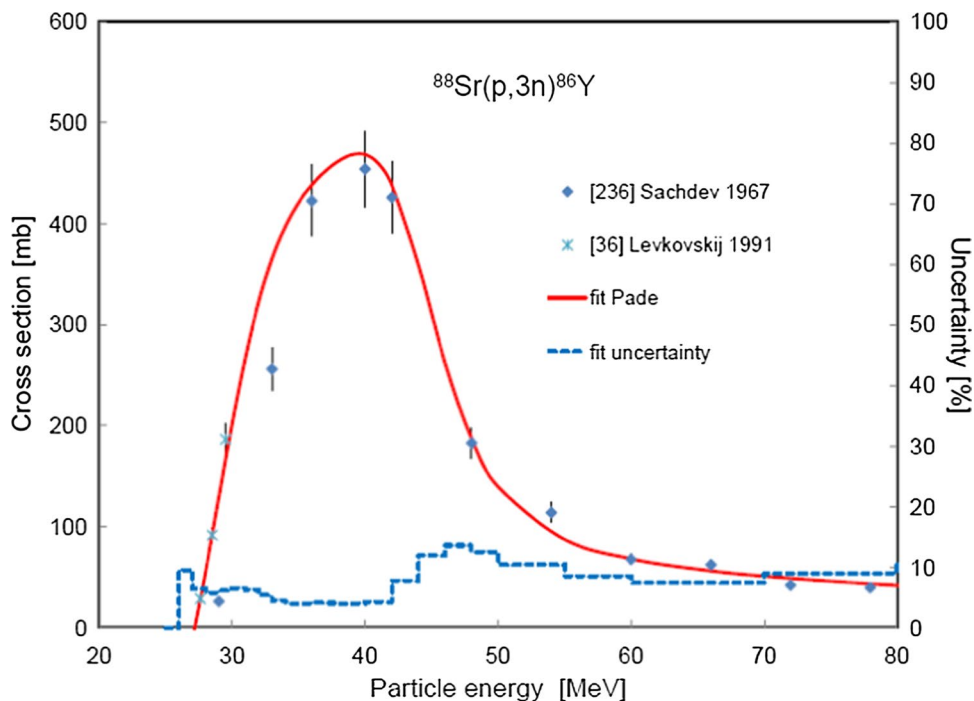


Fig. 106 Two experimental datasets for the $^{88}\text{Sr}(p,3n)^{86}\text{Y}$ reaction [36, 236] with the Padé fit ($L=8$, $N=15$, $\chi^2=1.27$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{85}\text{Rb}(\alpha,3n)^{86}\text{Y}$

Five experimental datasets available in the literature are shown in Fig. 107 [36, 237–240] together with the TENDL calculations. Three datasets were rejected (Guin et al. [239], Iwata [237], and Agarwal et al. [240] (values refer to direct ground state production only, and are not cumulative). The data points of Demeyer et al. [238] below 45 MeV are

discrepant, and were also deleted. Thus, the remaining data points for only two datasets were used in the statistical fitting procedure [36, 238]. These selected data and their experimental uncertainties are shown in Fig. 108 together with the Padé fit ($L=8$, $N=32$, $\chi^2=0.91$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 107 Five experimental datasets for the $^{85}\text{Rb}(\alpha,3n)^{86}\text{Y}$ reaction available in the literature [36, 237–240], and TENDL calculations

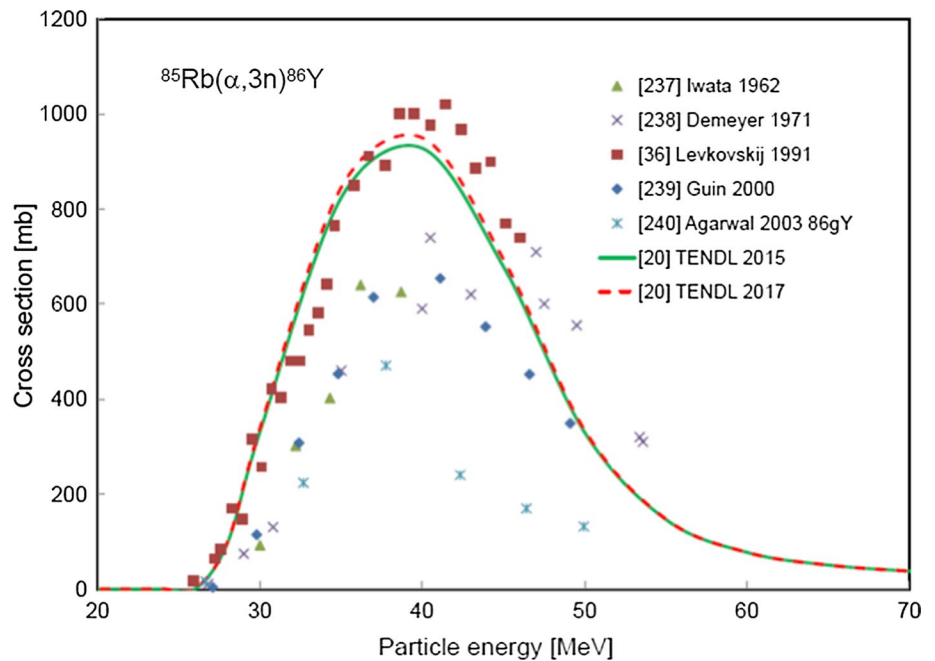
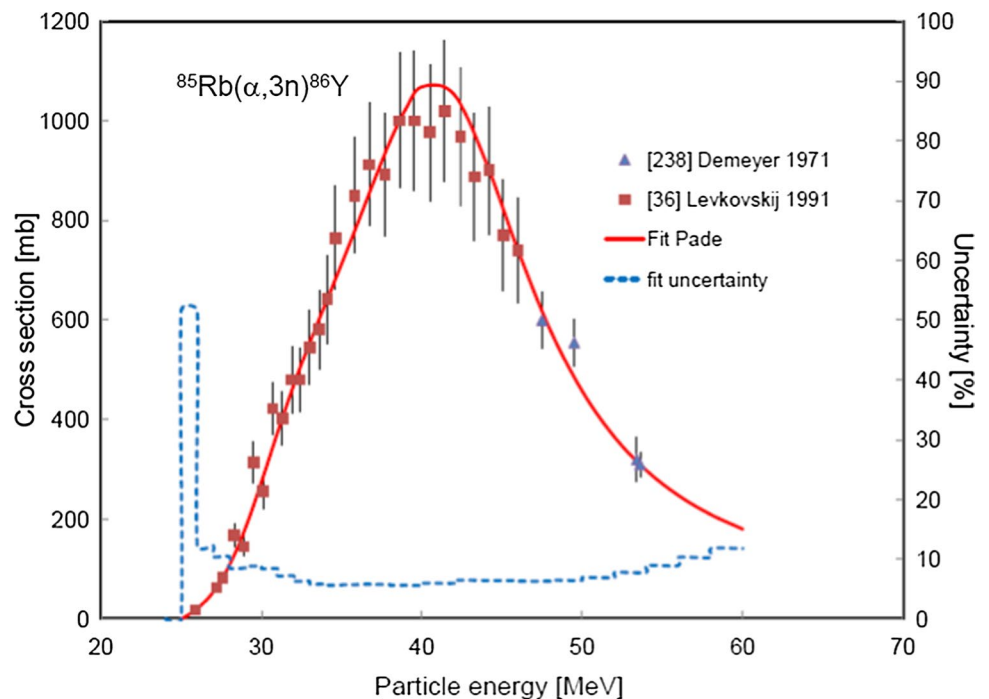


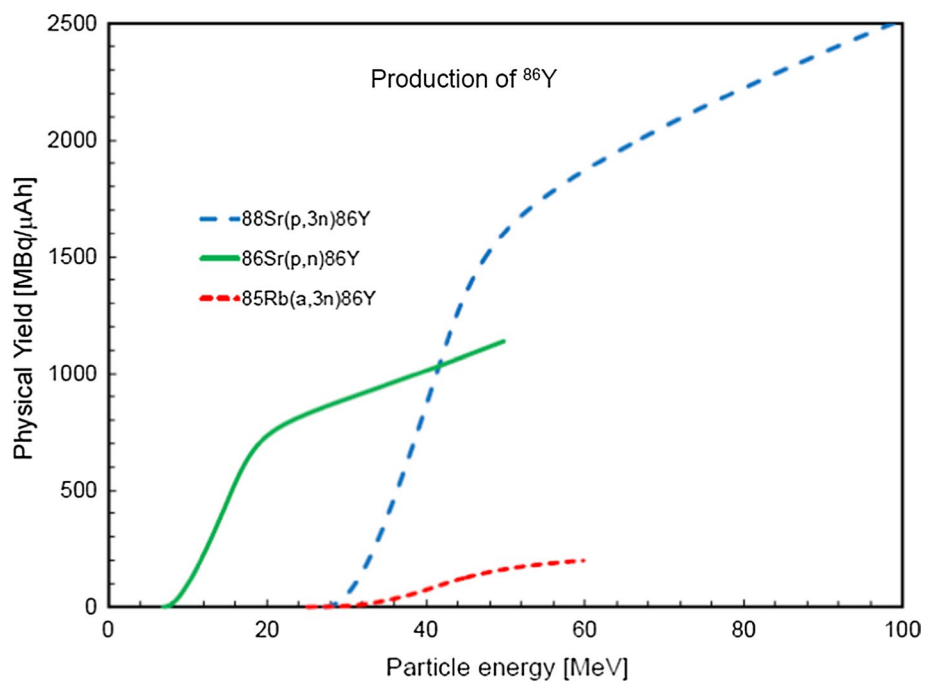
Fig. 108 Two selected experimental datasets for the $^{85}\text{Rb}(\alpha,3n)^{86}\text{Y}$ reaction [36, 238] with the Padé fit ($L=8$, $N=32$, $\chi^2=0.91$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{86}Y

See Fig. 109.

Fig. 109 Thick target yields calculated from the recommended cross sections for the $^{86}\text{Sr}(p,n)^{86}\text{Y}$, $^{88}\text{Sr}(p,3n)^{86}\text{Y}$ and $^{85}\text{Rb}(\alpha,3n)^{86}\text{Y}$ reactions



Production of ^{89}Zr ($T_{1/2} = 78.41$ h)

Applications: Long-lived positron-emitting ^{89}Zr has been extensively studied with respect to following the in vivo behaviour of therapeutic monoclonal antibodies (mAbs) and other biomolecules with slow biokinetics. One significant disadvantage is the limited number of suitable ^{89}Zr chelating agents and difficulties related to their development.

^{89}Zr (78.41 h): β^+ (22.74%), and E_γ (keV) ($P_\gamma(\%)$): 909.15 (99.04).

Evaluations have been made of the $^{89}\text{Y}(p,n)^{89}\text{Zr}$ and $^{89}\text{Y}(d,2n)^{89}\text{Zr}$ production routes.

$^{89}\text{Y}(p,n)^{89}\text{Zr}$

The sixteen experimental datasets available in the literature are shown in Fig. 110 [36, 56, 82, 110, 234, 241–251] together with the TENDL calculations. Five datasets were rejected (Birattari et al. [244] (energy shift), Blosser and Handley [56] (value too high), Satheesh et al. [250] (energy shift), Delaunay-Olkowsky et al. [234] (value too low), and Saha et al. [242] (values too high)), and the remaining eleven datasets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 111 together with the Padé fit ($L=11$, $N=316$, $\chi^2=3.74$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 110 Sixteen experimental datasets for the $^{89}\text{Y}(p,n)^{89}\text{Zr}$ reaction available in the literature [36, 56, 82, 110, 234, 241–251], and TENDL calculations

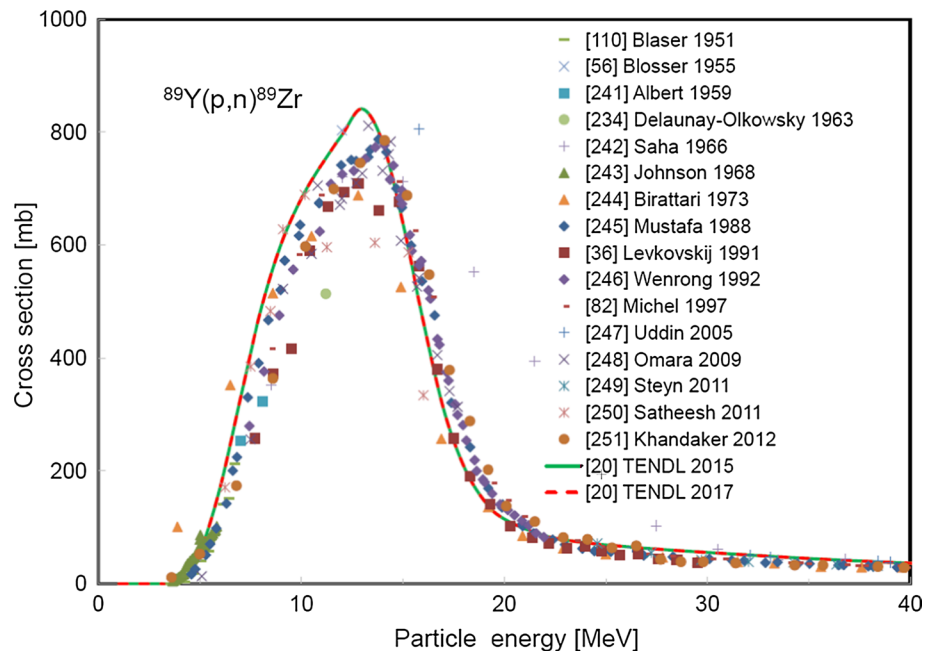
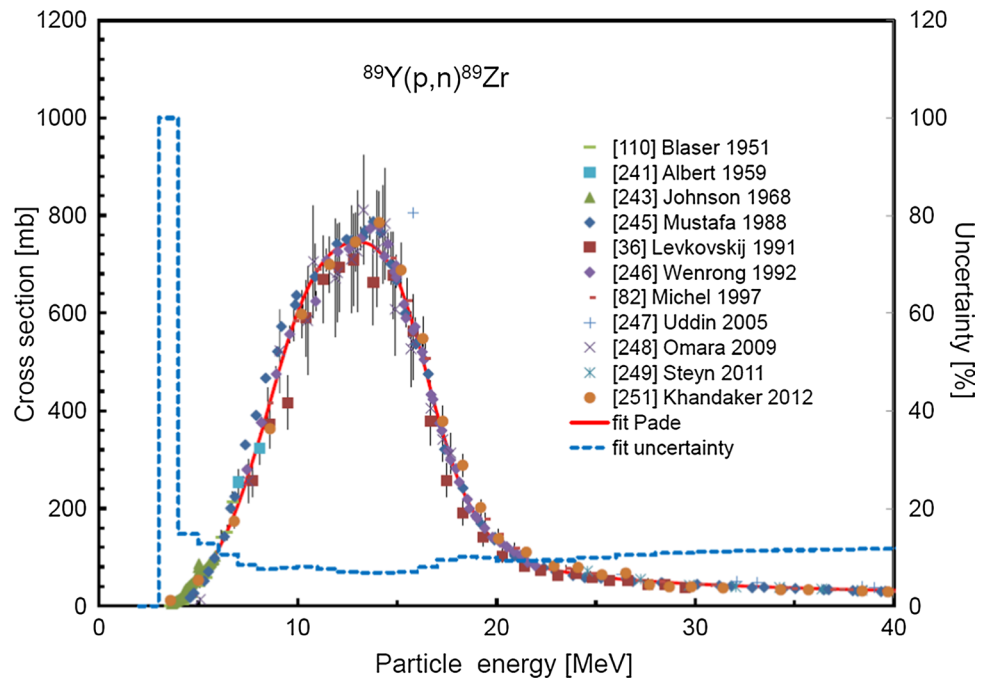


Fig. 111 Eleven selected experimental datasets for the $^{89}\text{Y}(p,n)^{89}\text{Zr}$ reaction [36, 82, 110, 241, 243, 245–249, 251] with the Padé fit ($L=11$, $N=316$, $\chi^2=3.74$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{89}\text{Y}(\text{d},2\text{n})^{89}\text{Zr}$

The seven experimental datasets available in the literature are shown in Fig. 112 [252–258] together with the TENDL calculations. Two datasets were rejected (La Gamma and Nassiff [253] (values too low), and Degering et al. [255] (energy shift)), and the remaining five sets were used in

the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 113 together with the Padé fit ($L=9$, $N=64$, $\chi^2=2.95$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 112 Seven experimental datasets for the $^{89}\text{Y}(\text{d},2\text{n})^{89}\text{Zr}$ reaction available in the literature [252–258], and TENDL calculations

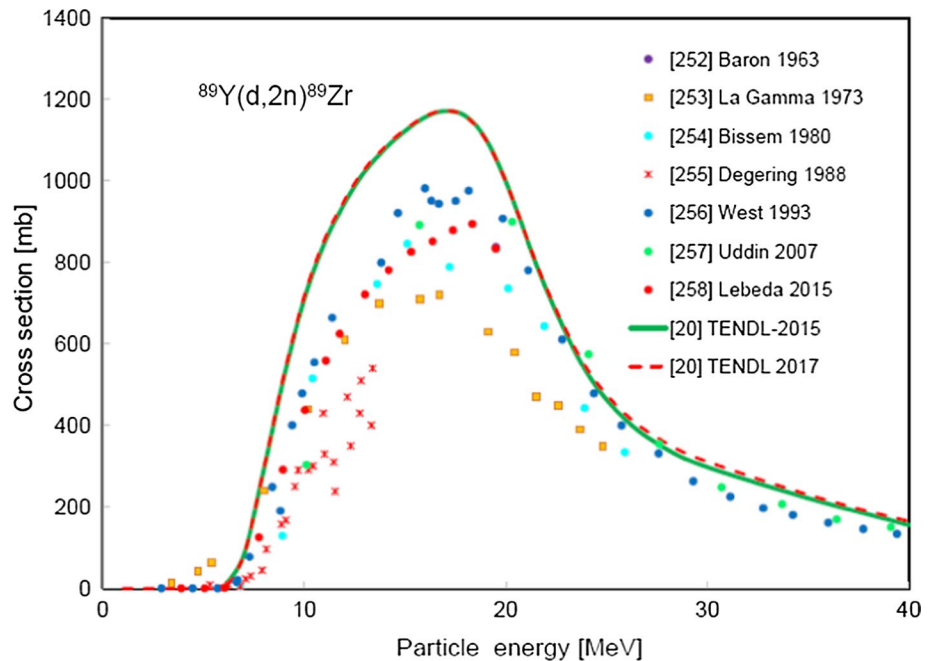
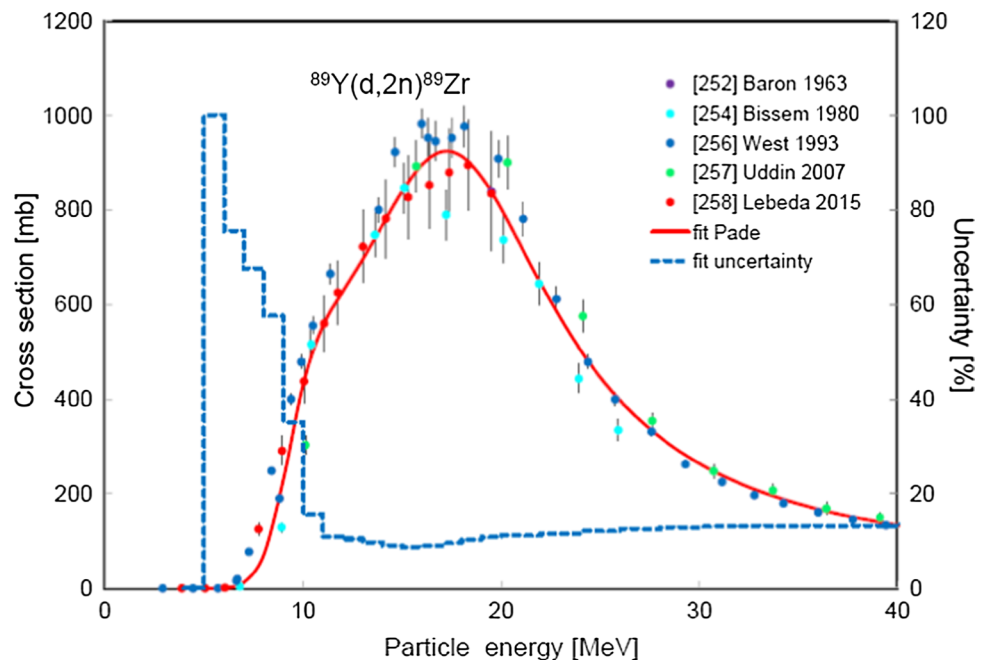


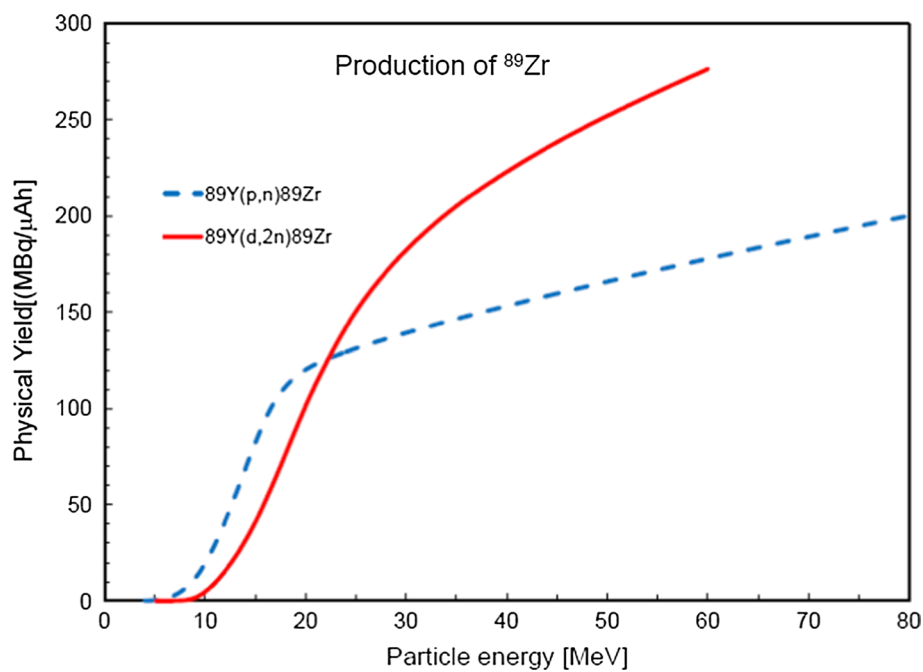
Fig. 113 Five selected experimental datasets for the $^{89}\text{Y}(\text{d},2\text{n})^{89}\text{Zr}$ reaction [252, 254, 256–258] with the Padé fit ($L=9$, $N=64$, $\chi^2=2.95$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{89}Zr

See Fig. 114.

Fig. 114 Thick target yields calculated from the recommended cross sections for the $^{89}\text{Y}(p,n)^{89}\text{Zr}$ and $^{89}\text{Y}(d,2n)^{89}\text{Zr}$ reactions



Production of ^{90}Nb ($T_{1/2} = 14.60$ h)

Applications: As a non-conventional positron emitter, ^{90}Nb with a half-life of 14.60 h can be used to visualise and quantify processes with medium and slow kinetics, such as tumour accumulation of antibodies and antibody fragments, or polymers and other nanoparticles. Exhibits promise in immuno-PET, although a search for appropriate chelators is desirable. Also emits several high-energy gamma rays that increase the radiation burden.

^{90}Nb (14.60 h): β^+ (51.2%), and E_γ (keV) ($P_\gamma(\%)$): 132.716 (4.13), 141.178 (66.8), 1129.224 (92.7).

Evaluations have been undertaken of the $^{93}\text{Nb}(p,x)^{90}\text{Nb}$ and $^{89}\text{Y}(\alpha,3n)^{90}\text{Nb}$ production.

$^{93}\text{Nb}(p,x)^{90}\text{Nb}$

The six experimental datasets available in the literature are shown in Fig. 115 [82, 249, 259–262] together with the TENDL calculations. All datasets were used in the statistical fitting procedure. The data and their experimental uncertainties are shown in Fig. 116 together with the Padé fit ($L=9$, $N=94$, $\chi^2=3.18$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 115 Six experimental datasets for the $^{93}\text{Nb}(p,x)^{90}\text{Nb}$ reaction available in the literature [82, 249, 259–262], and TENDL calculations

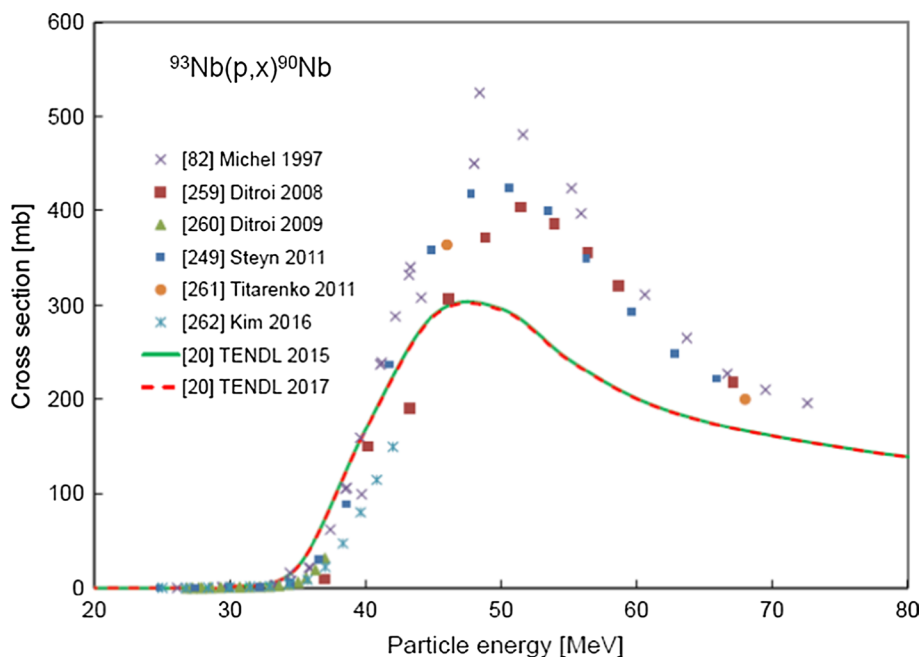
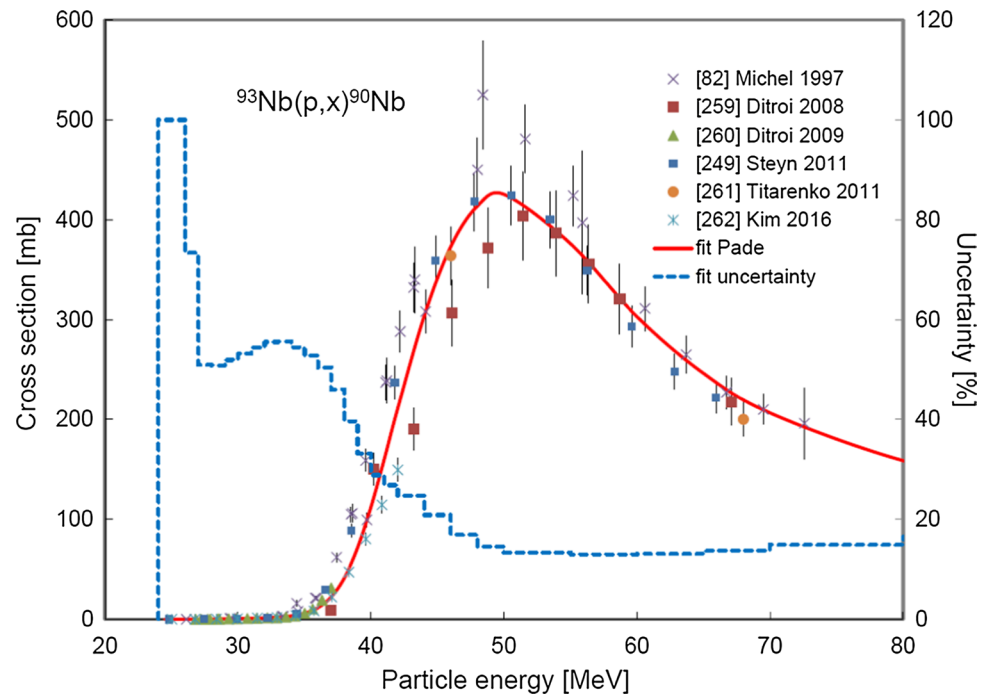


Fig. 116 Six experimental datasets for the $^{93}\text{Nb}(p,x)^{90}\text{Nb}$ reaction [82, 249, 259–262] with the Padé fit ($L=9$, $N=94$, $\chi^2=3.18$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{89}\text{Y}(\alpha,3n)^{90}\text{Nb}$

The six experimental datasets available in the literature are shown in Fig. 117 [36, 263–267] together with the TENDL calculations. Four datasets were rejected (Singh et al. [266], Chaubey and Rizvi [265], Mukherjee et al. [264], and

Smend et al. [263], all systematically lower values), while the remaining two sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 118 together with the Padé fit ($L = 16$, $N = 33$, $\chi^2 = 1.29$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 117 Six experimental datasets for the $^{89}\text{Y}(\alpha,3n)^{90}\text{Nb}$ reaction available in the literature [36, 263–267], and TENDL calculations

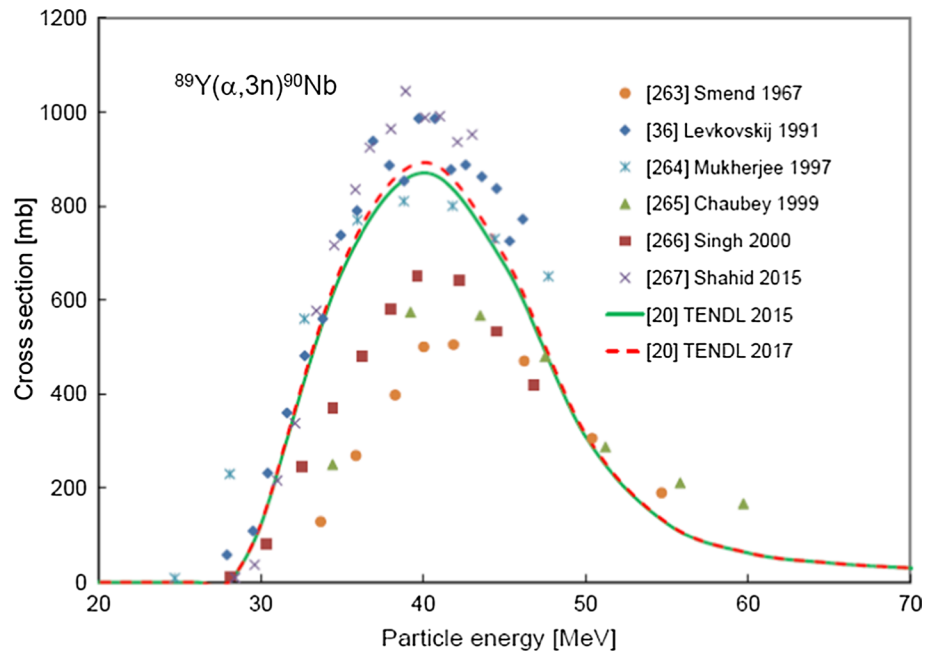
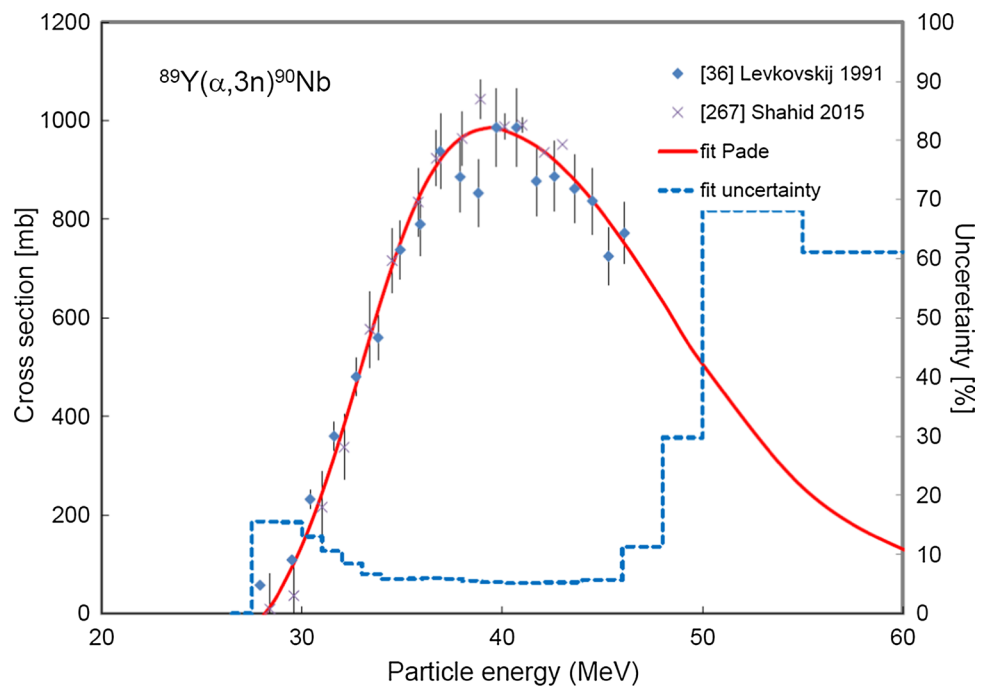


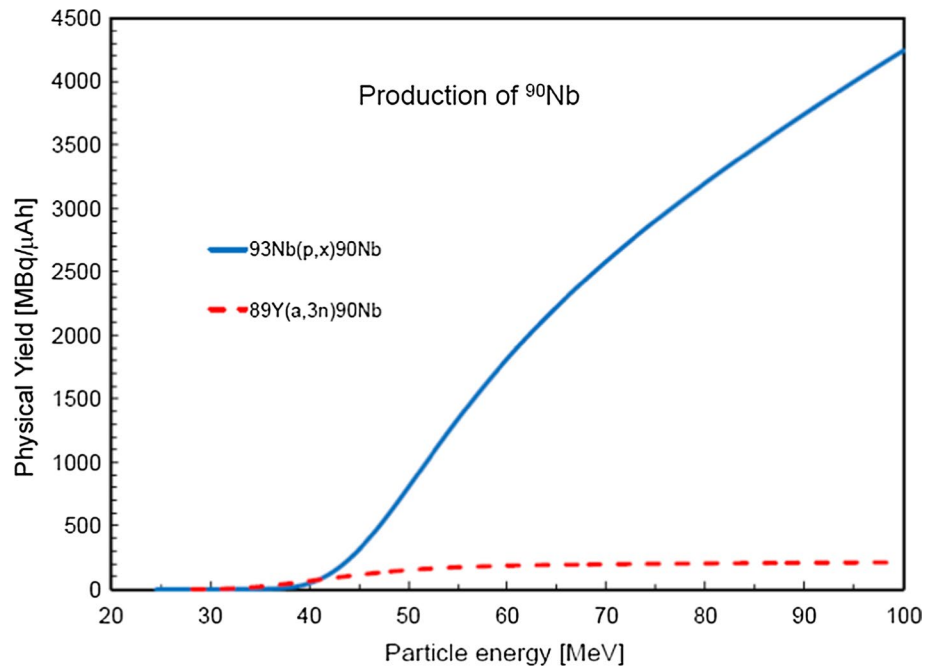
Fig. 118 Two selected experimental datasets for the $^{89}\text{Y}(\alpha,3n)^{90}\text{Nb}$ reaction [36, 267] with the Padé fit ($L = 16$, $N = 33$, $\chi^2 = 1.29$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{90}Nb

See Fig. 119.

Fig. 119 Thick target yields calculated from the recommended cross sections for the $^{93}\text{Nb}(p,x)^{90}\text{Nb}$ and $^{89}\text{Y}(\alpha,3n)^{90}\text{Nb}$ reactions



Production of ^{94m}Tc ($T_{1/2} = 52.0$ min)

Applications: Gamma-ray emitting ^{99m}Tc is the most widespread medical radionuclide for diagnosis, whereas ^{94m}Tc with a half-life of 52.0 min. is a positron emitter with a positron branch of 70.2% and $E_{\beta^+}(\text{max})$ of 2.44 MeV. Therefore, there has been interest in ^{94m}Tc as a PET analogue to ^{99m}Tc since they both undergo the same chemistry. Obvious disadvantages of ^{94m}Tc are the rather short half-life of 52.0 min., with many accompanying gamma rays and the inability to prepare the pure isomer without also generating significant amounts of ground state ^{94g}Tc .

^{94m}Tc (52.0 min): β^+ (70.2%), and E_γ (keV) (P_γ (%)): 871.05 (94.2), 1522.1 (4.5), 1868.68 (5.7).

Evaluations have been made of the $^{92}\text{Mo}(\alpha, x)^{94m}\text{Tc}$ and $^{94}\text{Mo}(p, n)^{94m}\text{Tc}$ production routes.

$^{92}\text{Mo}(\alpha, x)^{94m}\text{Tc}$

The four experimental datasets available in the literature are shown in Fig. 120 [36, 268–270] together with the TENDL calculations. Three datasets were rejected (Graf and Münzel [268], Denzler et al. [269], and Ditrói et al. [270], all contradictory sets of data), while the remaining single set of Levkovskij [36] was used in the statistical fitting procedure (and also accepted as a standard for the monitoring of α beams). The selected data and their experimental uncertainties are shown in Fig. 121 together with the Padé fit ($L = 12$, $N = 28$, $\chi^2 = 1.33$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 120 Four experimental datasets for the $^{92}\text{Mo}(\alpha, x)^{94m}\text{Tc}$ reaction available in the literature [36, 268–270], and TENDL calculations

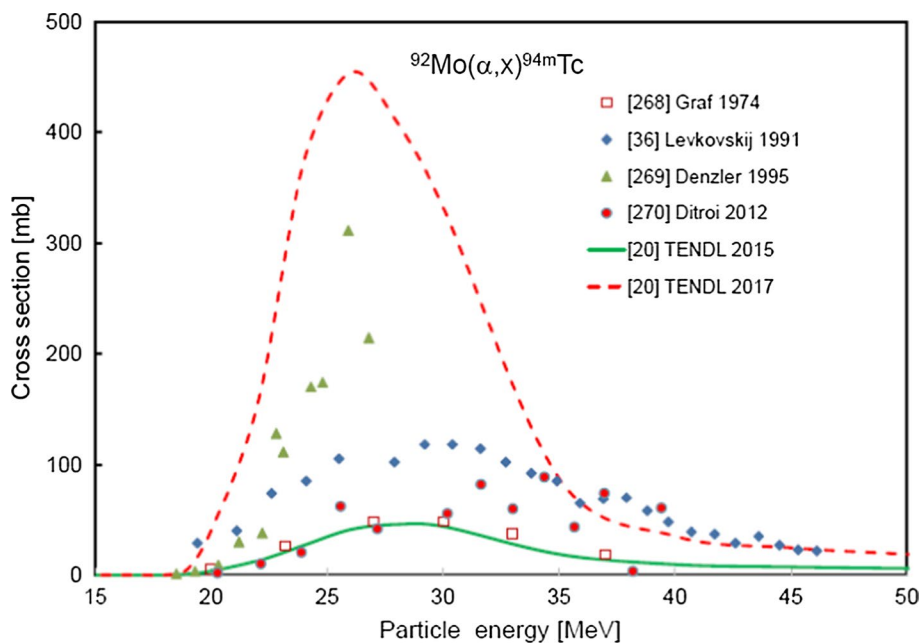
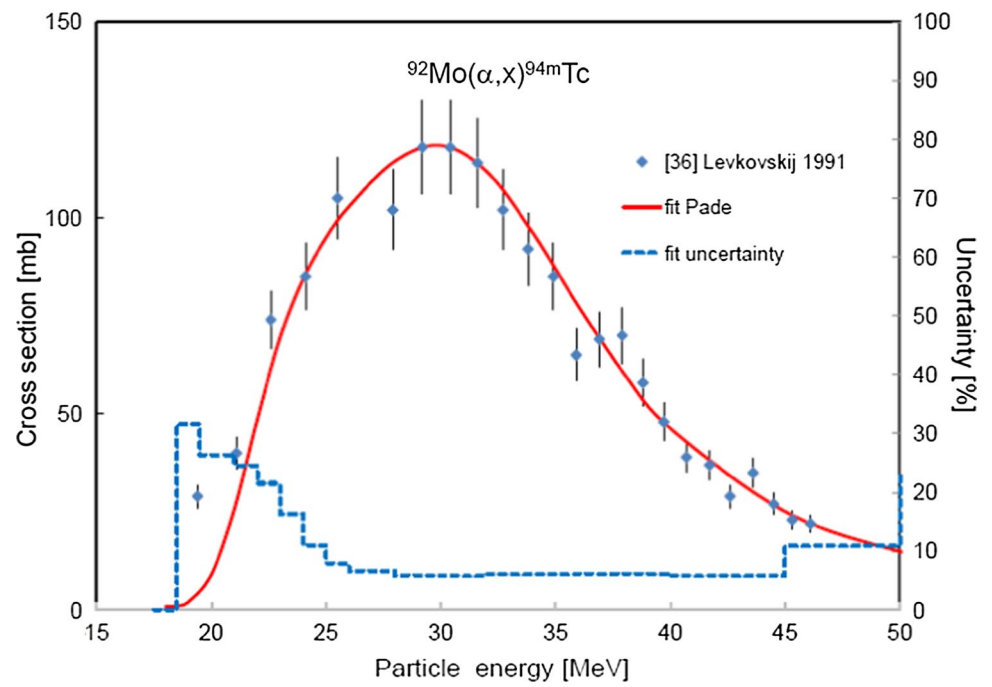


Fig. 121 One selected experimental dataset for the $^{92}\text{Mo}(\alpha, x)^{94\text{m}}\text{Tc}$ reaction [36] with the Padé fit ($L=12$, $N=28$, $\chi^2=1.33$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{94}\text{Mo}(p,n)^{94m}\text{Tc}$

The seven experimental datasets available in the literature are shown in Fig. 122 [36, 142, 271–275] together with the TENDL calculations. All datasets were used in the statistical fitting procedure. These data and their experimental

uncertainties are shown in Fig. 123 together with the Padé fit ($L=9$, $N=57$, $\chi^2=1.21$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 122 Seven experimental datasets for the $^{94}\text{Mo}(p,n)^{94m}\text{Tc}$ reaction available in the literature [36, 142, 271–275], and TENDL calculations

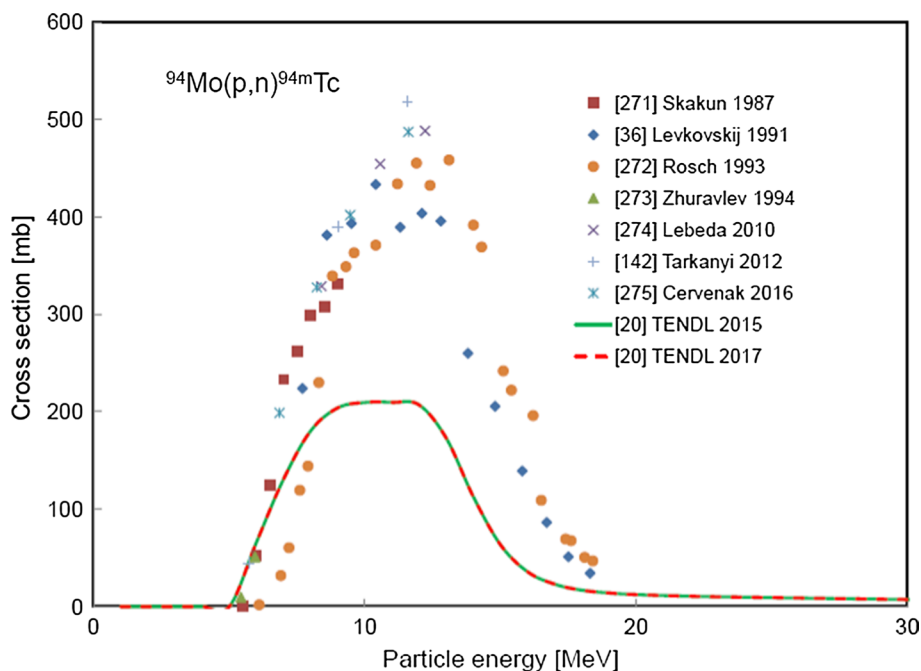
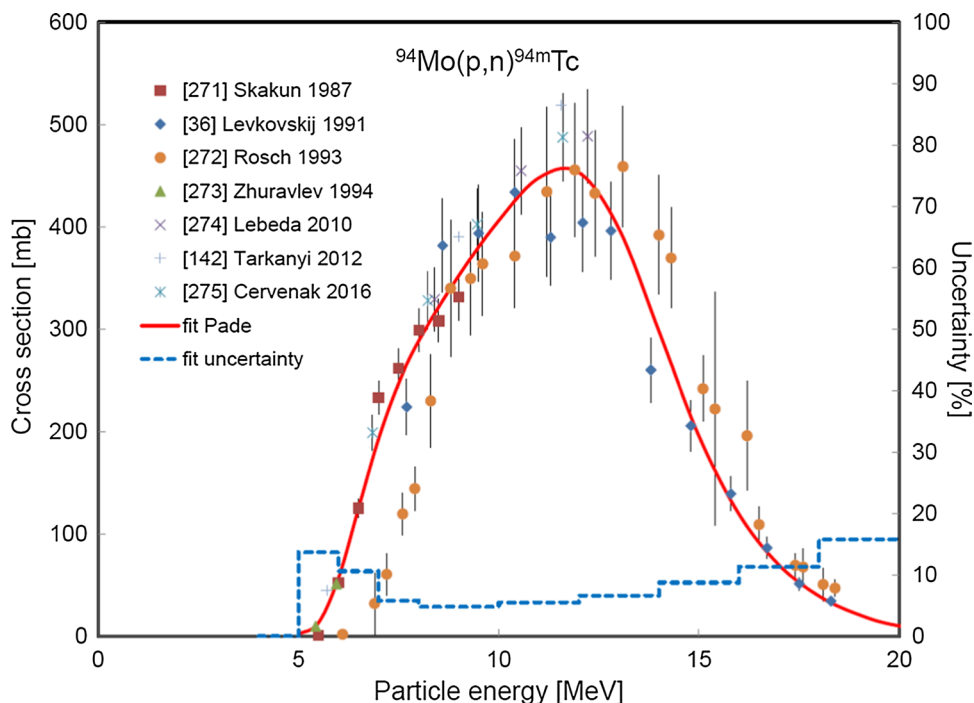


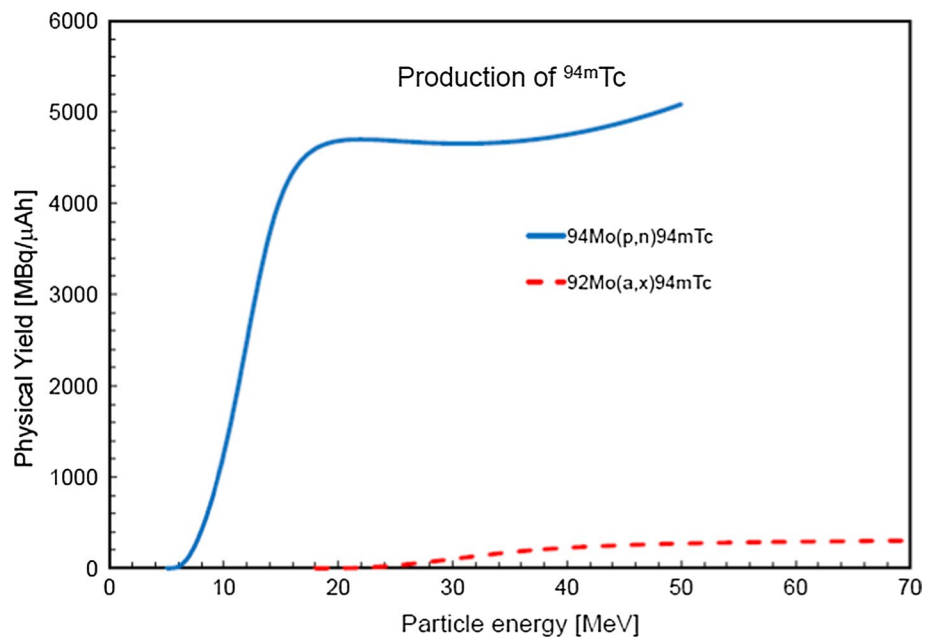
Fig. 123 Seven experimental datasets for the $^{94}\text{Mo}(p,n)^{94m}\text{Tc}$ reaction [36, 142, 271–275] with the Padé fit ($L=9$, $N=57$, $\chi^2=1.21$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{94m}Tc

See Fig. 124.

Fig. 124 Thick target yields calculated from the recommended cross sections for the $^{92}\text{Mo}(\alpha,x)^{94m}\text{Tc}$ and $^{94}\text{Mo}(\text{p},\text{n})^{94m}\text{Tc}$ reactions



Production of ^{110m}In ($T_{1/2} = 69.1$ min) and longer-lived ^{110}Sn parent ($T_{1/2} = 4.154$ h)

Applications: ^{110m}In is a positron-emitting analogue for established SPECT ^{111}In . Potential to provide more quantitative diagnostic information as well as in vivo quantification of the uptake kinetics of radiopharmaceuticals (e.g., applied along with ^{111}In -labelled DTPA-D-Phe1-octeotide for neuroendocrine tumours).

^{110m}In can be produced directly and via parent ^{110}Sn .

^{110m}In (69.1 min): β^+ (61.3%), and E_γ (keV) (P_γ (%)): 2129.40 (2.15), 2211.33 (1.74), 2317.41 (1.285).

^{110}Sn (4.154 h): E_γ (keV) (P_γ (%)): 280.459 (97.06).

Evaluations have been made of the $^{\text{nat}}\text{In}(p,xn)^{110}\text{Sn}$, $^{108}\text{Cd}(\alpha,2n)^{110}\text{Sn}$, $^{110}\text{Cd}(p,n)^{110m}\text{In}$, $^{110}\text{Cd}(d,2n)^{110m}\text{In}$ and $^{107}\text{Ag}(\alpha,n)^{110m}\text{In}$ production routes.

$^{\text{nat}}\text{In}(p,xn)^{110}\text{Sn}$

The four experimental datasets available in the literature are shown in Fig. 125 [276–279] together with the TENDL calculations. All datasets were used in the statistical fitting procedure. The data and their experimental uncertainties are shown in Fig. 126 together with the Padé fit ($L = 17$, $N = 112$, $\chi^2 = 1.50$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 125 Four experimental datasets for the $^{\text{nat}}\text{In}(p,xn)^{110}\text{Sn}$ reaction available in the literature [276–279], and TENDL calculations

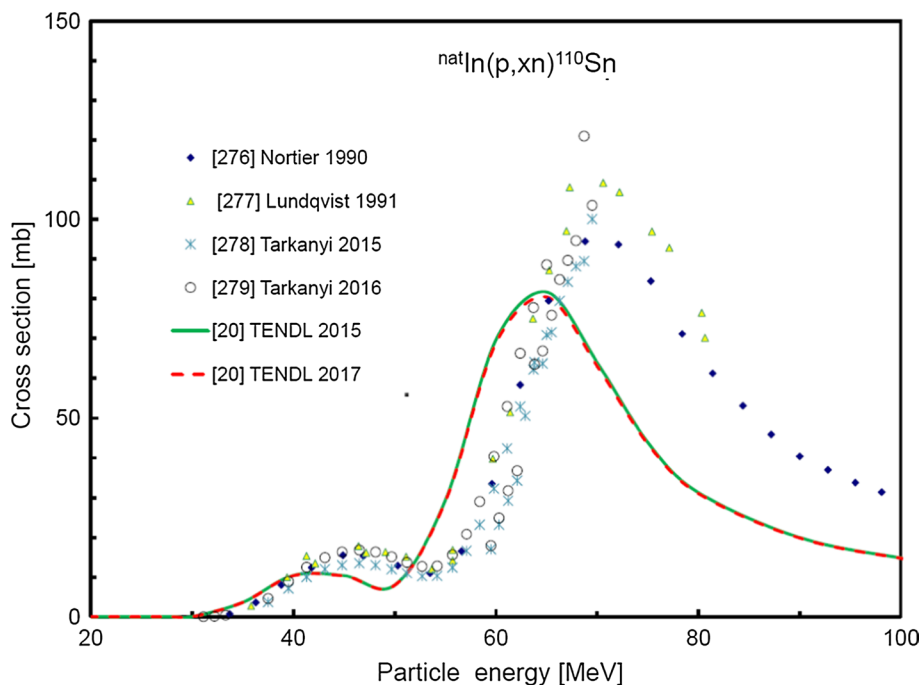
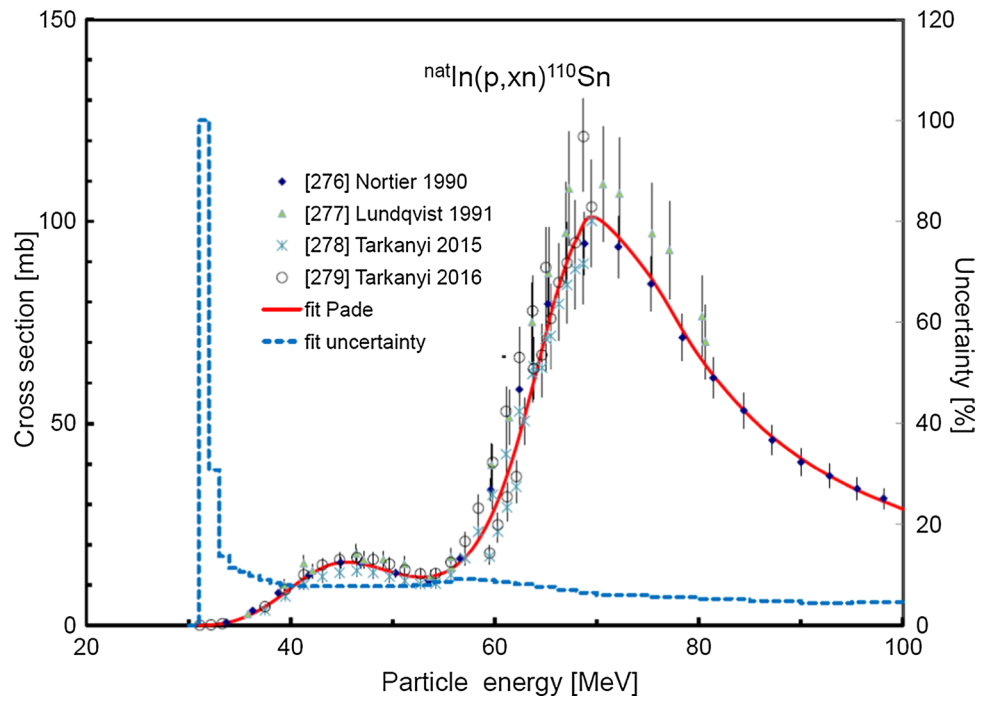


Fig. 126 Four experimental datasets for the $^{nat}\text{In}(p,xn)^{110}\text{Sn}$ reaction [276–279] with the Padé fit ($L=17$, $N=112$, $\chi^2=1.50$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{108}\text{Cd}(\alpha,2n)^{110}\text{Sn}$

The four experimental datasets available in the literature are shown in Fig. 127 [280–283] together with the TENDL calculations. One dataset was rejected (Duchemin et al. [282], values too low), while another became available after the evaluation cut-off date and therefore was not included (Ditrói

et al. [283]). The two remaining sets were used in the statistical fitting procedure, and these selected data and their experimental uncertainties are shown in Fig. 128 together with the Padé fit ($L = 10$, $N = 24$, $\chi^2 = 1.99$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 127 Four experimental datasets for the $^{108}\text{Cd}(\alpha,2n)^{110}\text{Sn}$ reaction available in the literature [280–283], and TENDL calculations

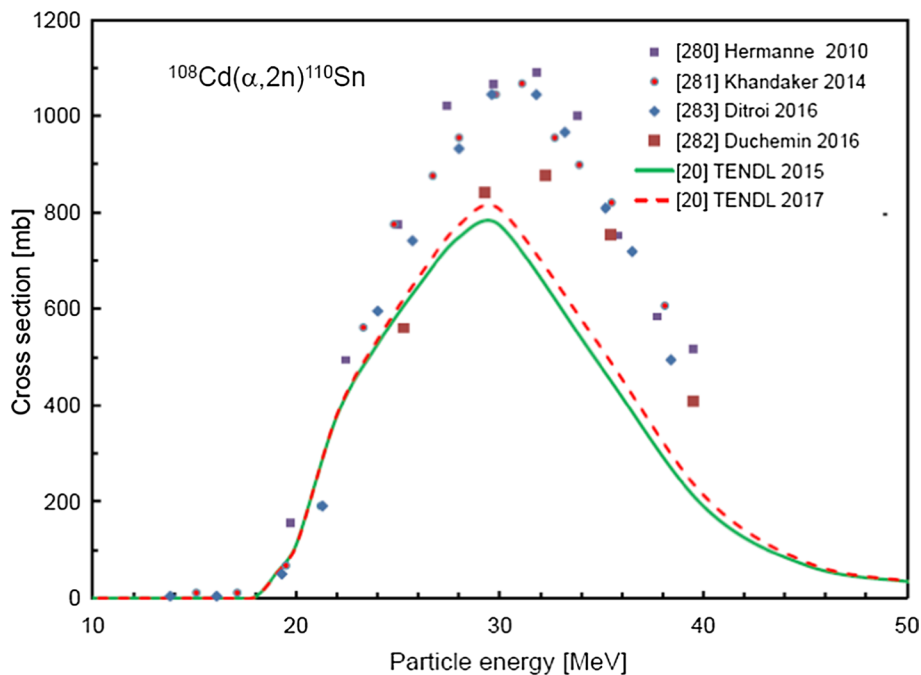
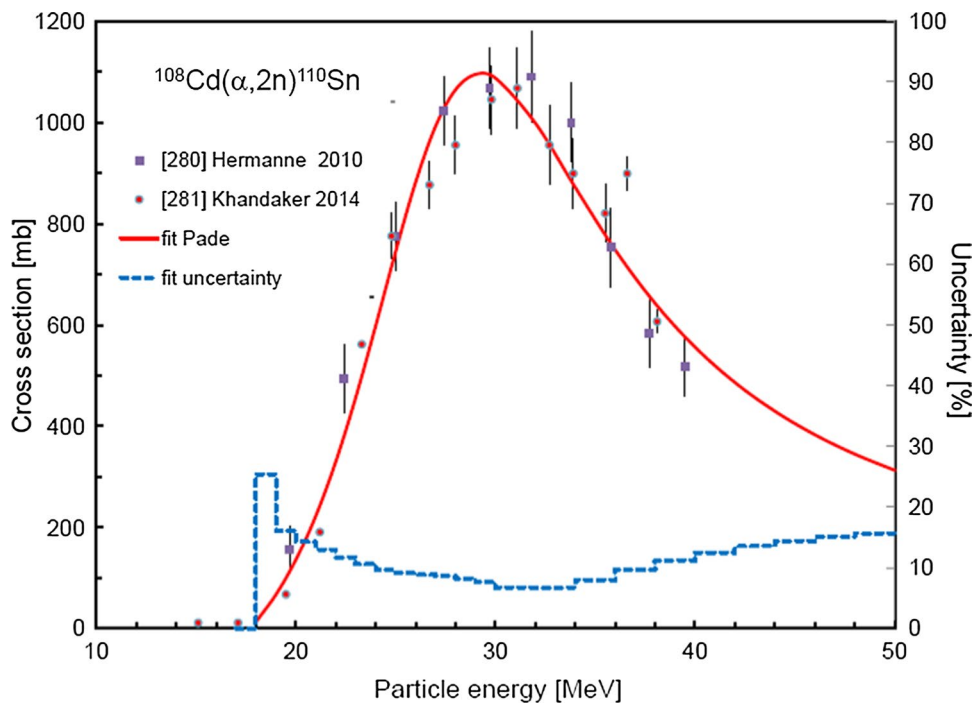


Fig. 128 Two selected experimental datasets for the $^{108}\text{Cd}(\alpha,2n)^{110}\text{Sn}$ reaction [280, 281] with the Padé fit ($L = 10$, $N = 24$, $\chi^2 = 1.99$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{110}\text{Cd}(p,n)^{110m}\text{In}$

The three experimental datasets available in the literature for production of the metastable state [164, 284, 285] and the six datasets for simultaneously produced impurity ground state [276, 285–289] are shown in Fig. 129 together with the TENDL calculations for the separate metastable and ground

states. After full assessment, the three datasets were used in the statistical fitting procedure for the metastable state [164, 284, 285]. These data and their experimental uncertainties are shown in Fig. 130 together with the Padé fit ($L=11$, $N=29$, $\chi^2=0.57$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 129 Three experimental datasets for the $^{110}\text{Cd}(p,n)^{110m}\text{In}$ reaction available in the literature [164, 284, 285], along with six experimental datasets for the $^{110}\text{Cd}(p,n)^{110g}\text{In}$ reaction [276, 285–289], and TENDL calculations

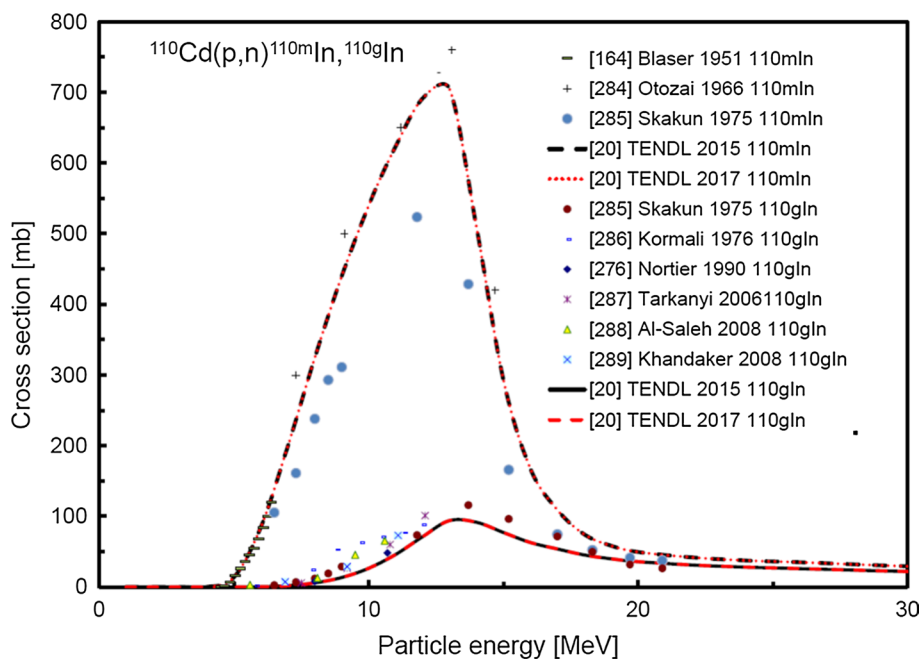
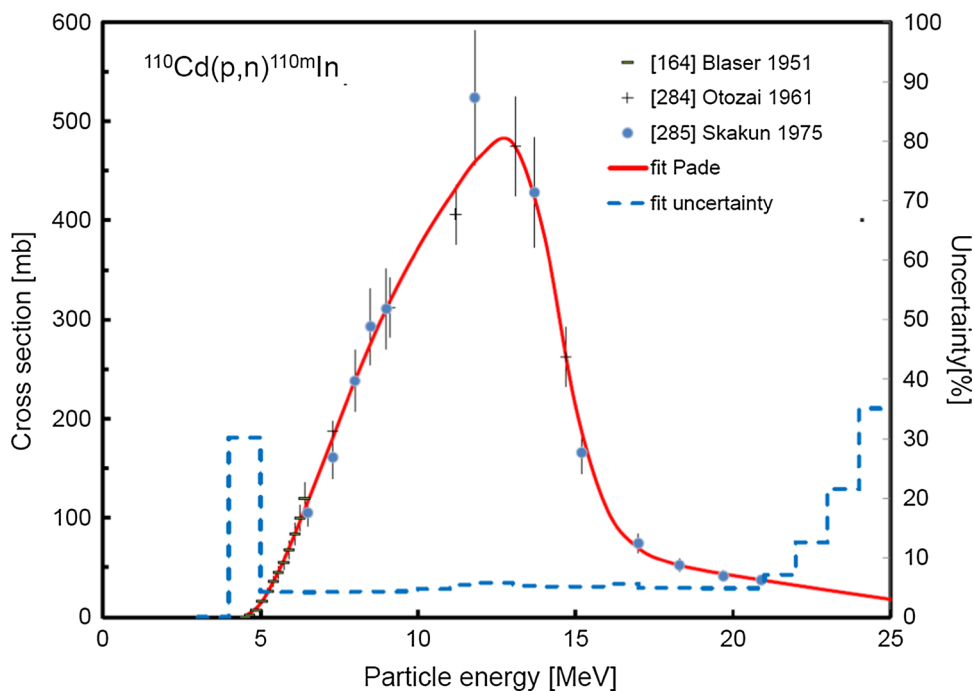


Fig. 130 Three experimental datasets for the $^{110}\text{Cd}(p,n)^{110m}\text{In}$ reaction [164, 284, 285] with the Padé fit ($L=11$, $N=29$, $\chi^2=0.57$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{110}\text{Cd}(d,2n)^{110\text{m}}\text{In}$

The two experimental datasets available in the literature for production of the metastable state are shown in Fig. 131 [290, 291] together with two datasets for simultaneous production of the contaminating ground state [291, 292] and the TENDL calculations. Cross sections determined by Usher

et al. [290] were normalised to the data of Tárkányi et al. [291], and both datasets were used in the statistical fitting procedure for $^{110\text{m}}\text{In}$ production. These data and their experimental uncertainties are shown in Fig. 132 together with the Padé fit ($L=5$, $N=18$, $\chi^2=0.74$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 131 Two experimental datasets for the $^{110}\text{Cd}(d,2n)^{110\text{m}}\text{In}$ reaction available in the literature [290, 291] and two experimental datasets for the contaminating $^{110}\text{Cd}(d,2n)^{110\text{g}}\text{In}$ reaction [291, 292], and their TENDL calculations. All data from Ref. [290] have been normalised with respect to the data of Ref. [291]

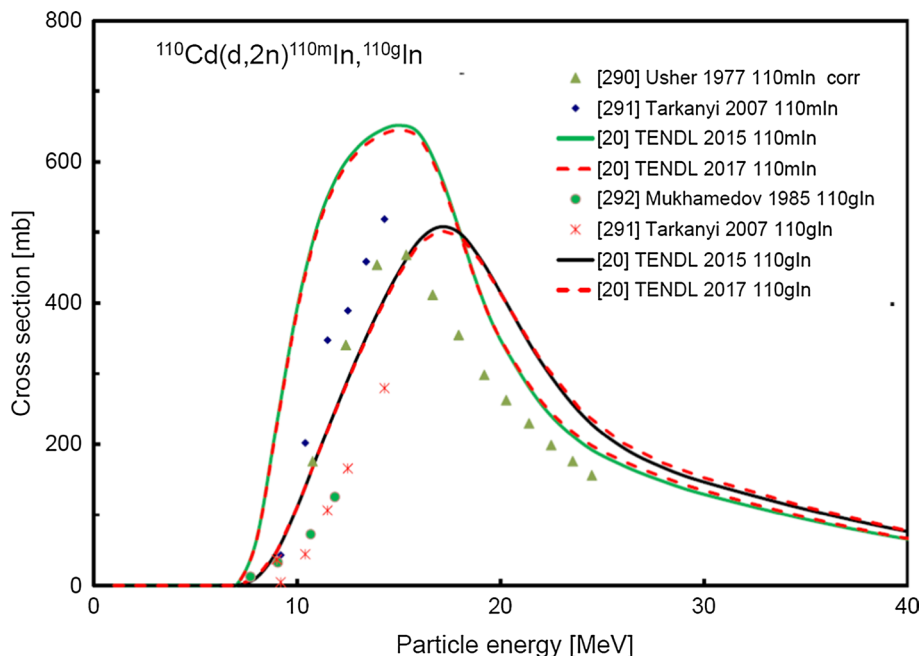
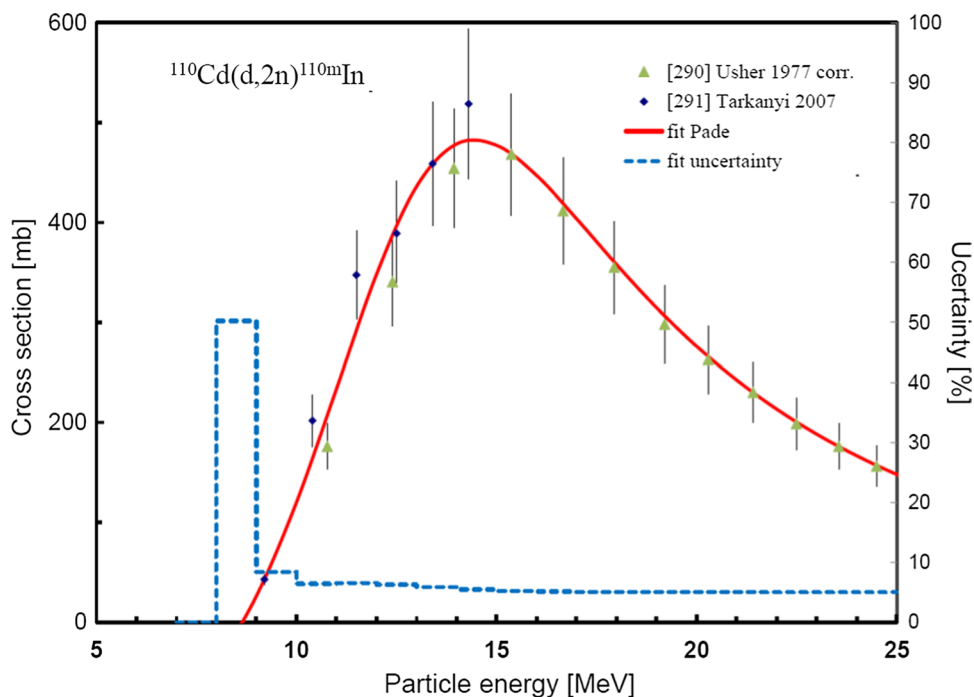


Fig. 132 Two experimental datasets for the $^{110}\text{Cd}(d,2n)^{110\text{m}}\text{In}$ reaction [290, 291] with the Padé fit ($L=5$, $N=18$, $\chi^2=0.74$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{107}\text{Ag}(\alpha, n)^{110\text{m}}\text{In}$

The nine experimental datasets available in the literature are shown in Fig. 133 [178, 278, 293–299] together with the TENDL calculations. Six datasets were rejected (Wasilevsky et al. [295] (discrepant values), Misaelides and Münzel [294] (energy steps too large, can not be controlled), Chaubey et al. [296] (values too high), Fukushima et al. [293] (values

too low at higher energy), Patel et al. [297] (values too low), Takács et al. [298] (values too low)), and the remaining three sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 134 together with the Padé fit $L=9, N=32$, $\chi^2=1.94$ and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 133 Nine experimental datasets for the $^{107}\text{Ag}(\alpha, n)^{110\text{m}}\text{In}$ reaction available in the literature [178, 278, 293–299], and TENDL calculations

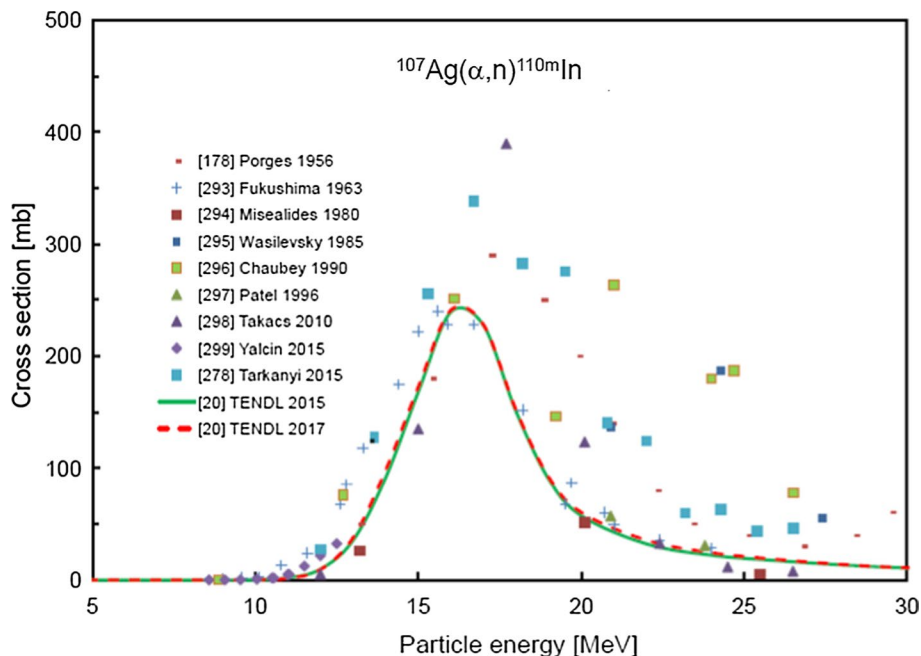
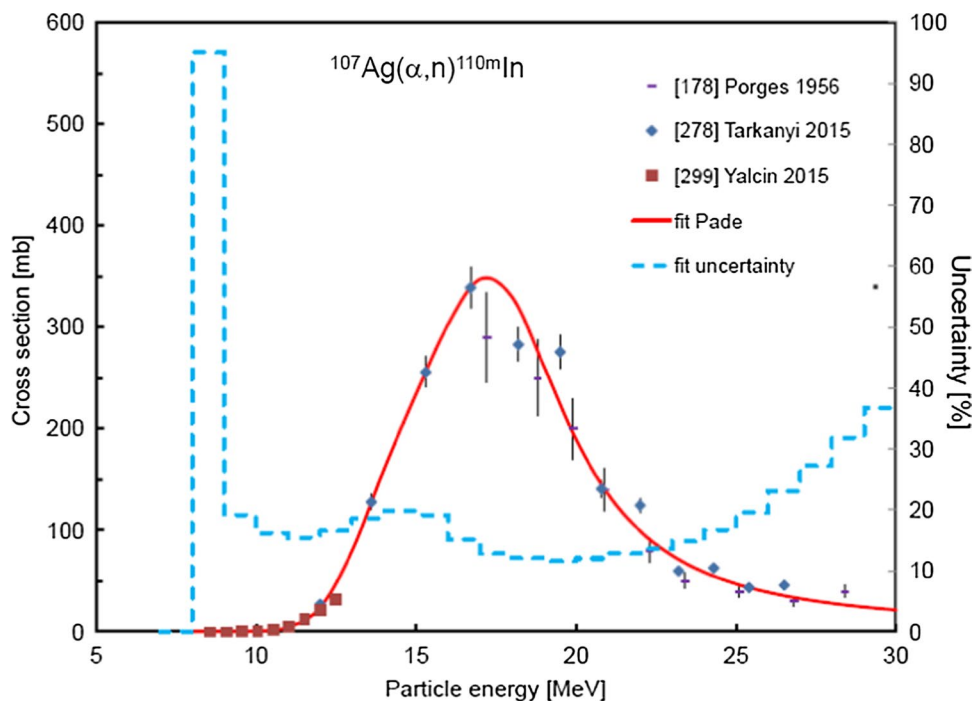


Fig. 134 Three selected experimental datasets for the $^{107}\text{Ag}(\alpha, n)^{110\text{m}}\text{In}$ reaction [178, 278, 299] with the Padé fit ($L=9, N=32, \chi^2=1.94$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for ^{110m}In , and ^{110}Sn parent

See Figs. 135 and 136.

Fig. 135 Thick target yields calculated from the recommended cross sections for $^{110}\text{Cd}(p,n)^{110m}\text{In}$, $^{110}\text{Cd}(d,2n)^{110m}\text{In}$ and $^{107}\text{Ag}(\alpha,n)^{110m}\text{In}$ reactions

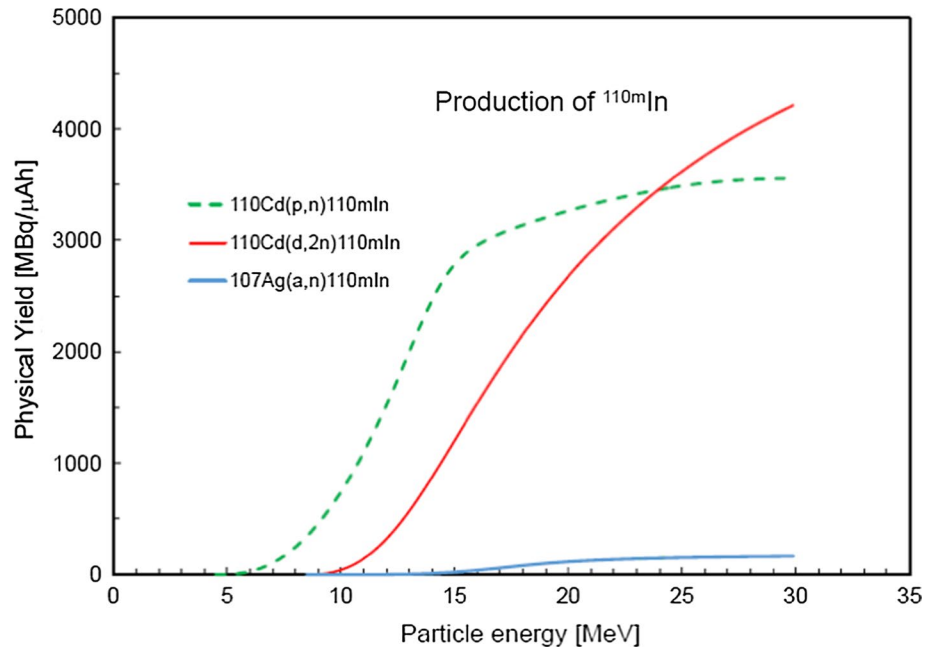
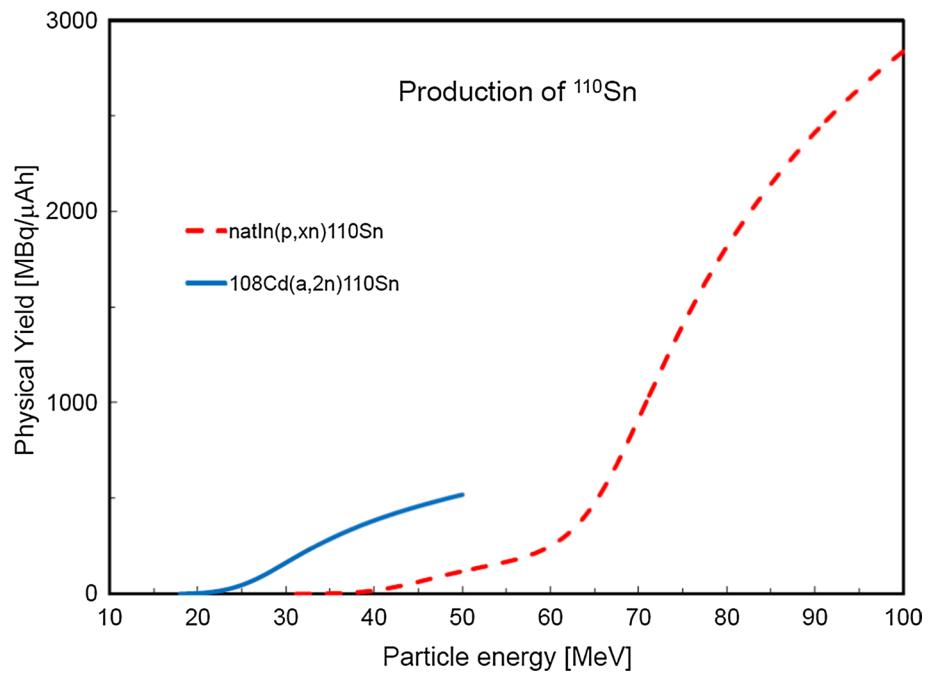


Fig. 136 Thick target yields calculated from the recommended cross sections for the $^{nat}\text{In}(p,xn)^{110}\text{Sn}$ and $^{108}\text{Cd}(\alpha,2n)^{110}\text{Sn}$ reactions



Production of ^{118}Te parent ($T_{1/2} = 6.00\text{ d}$) of short-lived ^{118}Sb ($T_{1/2} = 3.6\text{ min}$)

Applications: EC decay of ^{118}Te produces 3.6 min half-life ^{118}Sb daughter, which decays primarily by positron emission and can be used as a flow tracer.

^{118}Sb (3.6 min): β^+ (73.5%), and E_γ (keV) ($P_\gamma(\%)$): 1229.33 (2.5).

^{118}Te (6.00 d): detected by means of radiation emitted by daughter ^{118}Sb .

Evaluations have been undertaken for the $^{115}\text{Sn}(\alpha, n)^{118}\text{Te}$, $^{116}\text{Sn}(\alpha, 2n)^{118}\text{Te}$, $^{\text{nat}}\text{Sb}(p, xn)^{118}\text{Te}$ and $^{\text{nat}}\text{Sb}(d, xn)^{118}\text{Te}$ production routes.

$^{115}\text{Sn}(\alpha, n)^{118}\text{Te}$

The two experimental datasets available in the literature are shown in Fig. 137 [300, 301] together with the TENDL calculations. These two datasets were used as the basis of the fitting procedure. However, to obtain reasonable cross-section behaviour above $\sim 18\text{ MeV}$, three artificial points were added in accord with the TENDL-2017 calculations for beam energies of 20, 25 and 30 MeV given assigned uncertainties of 25%. The data and their experimental uncertainties are shown in Fig. 138 together with the Padé fit ($L=7$, $N=8$, $\chi^2=1.07$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 137 Two experimental datasets for the $^{115}\text{Sn}(\alpha, n)^{118}\text{Te}$ reaction available in the literature [300, 301], and TENDL calculations

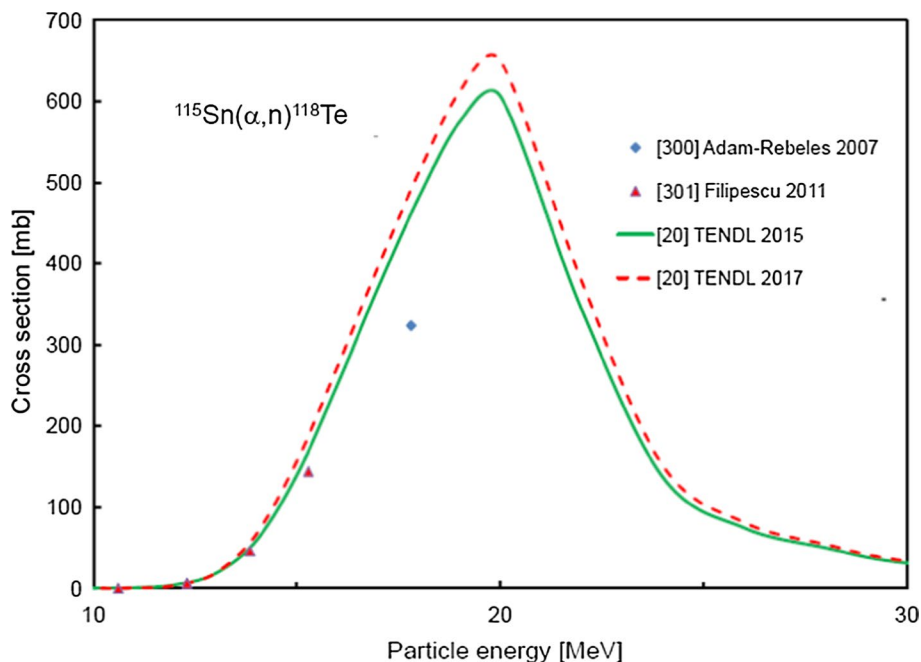
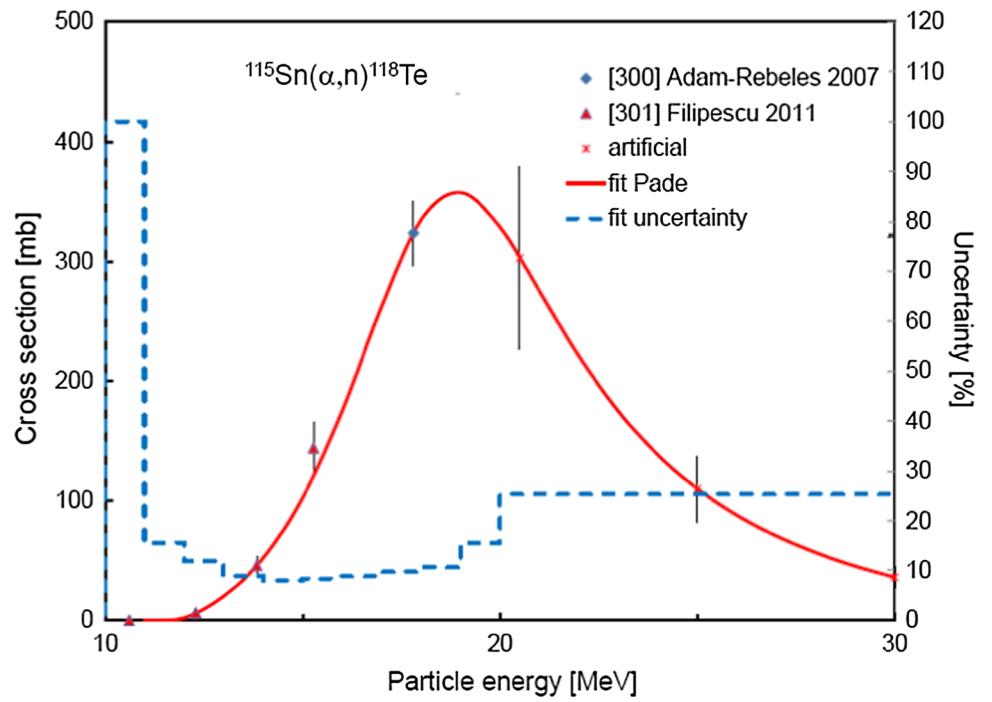


Fig. 138 Two experimental datasets for the $^{115}\text{Sn}(\alpha,n)^{118}\text{Te}$ reaction [300, 301] with the Padé fit ($L=7, N=8, \chi^2=1.07$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{116}\text{Sn}(\alpha,2n)^{118}\text{Te}$

The two experimental datasets available in the literature are shown in Fig. 139 [300, 302] together with the TENDL calculations. Both datasets were used in the statistical fitting

procedure. The data and their experimental uncertainties are shown in Fig. 140 together with the Padé fit ($L=6, N=13, \chi^2=1.34$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 139 Two experimental datasets for the $^{116}\text{Sn}(\alpha,2n)^{118}\text{Te}$ reaction available in the literature [300, 302], and TENDL calculations

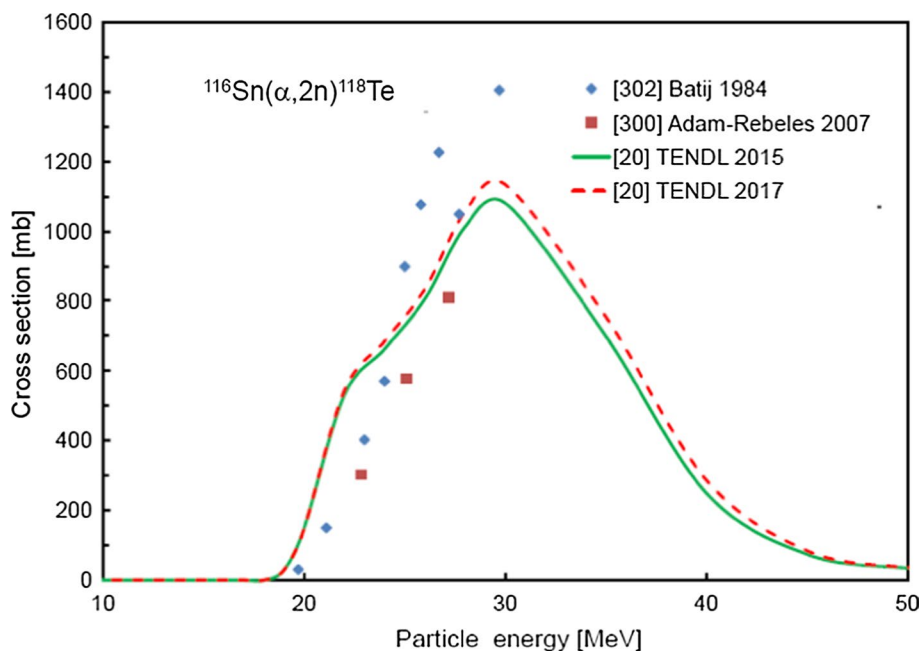
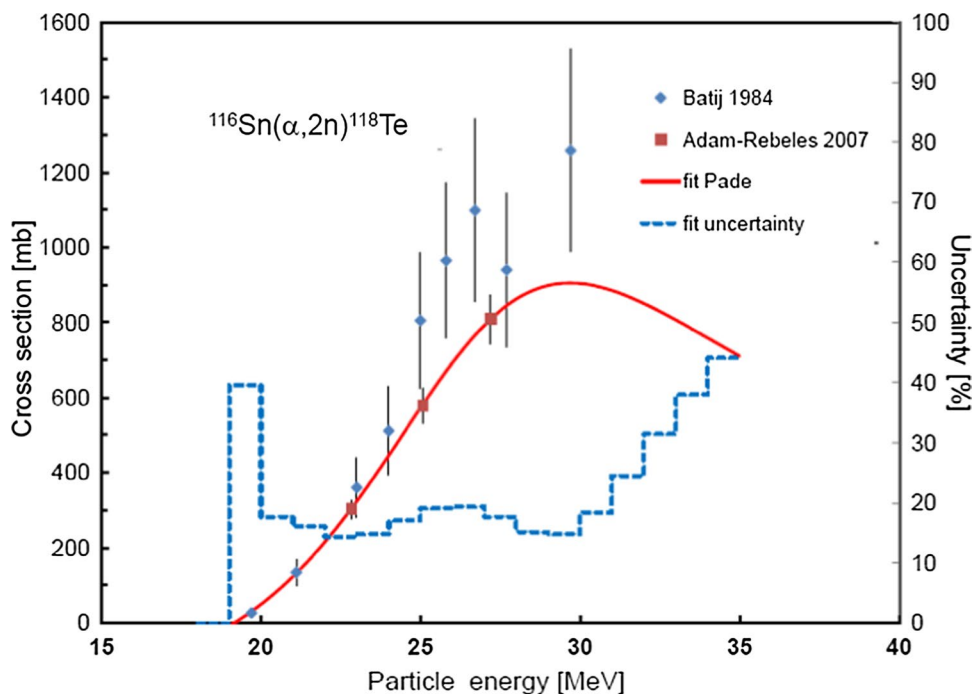


Fig. 140 Two experimental datasets for the $^{116}\text{Sn}(\alpha,2n)^{118}\text{Te}$ reaction [300, 302] with the Padé fit ($L=6, N=13, \chi^2=1.34$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{nat}\text{Sb}(p,xn)^{118}\text{Te}$

The three experimental datasets available in the literature are shown in Fig. 141 [303–305] together with the TENDL calculations. One dataset was normalised and energy-shifted (Lagunas-Solar et al. [304]), and all three sets were used in

the statistical fitting procedure. These data and their experimental uncertainties are shown in Fig. 142 together with the Padé fit ($L=12, N=43, \chi^2=0.53$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale). Contributions of the $^{121}\text{Sb}(p,4n)$ and $^{123}\text{Sb}(p,6n)$ reactions can clearly be distinguished.

Fig. 141 Three experimental datasets for the $^{nat}\text{Sb}(p,xn)^{118}\text{Te}$ reaction available in the literature [303–305], and TENDL calculations

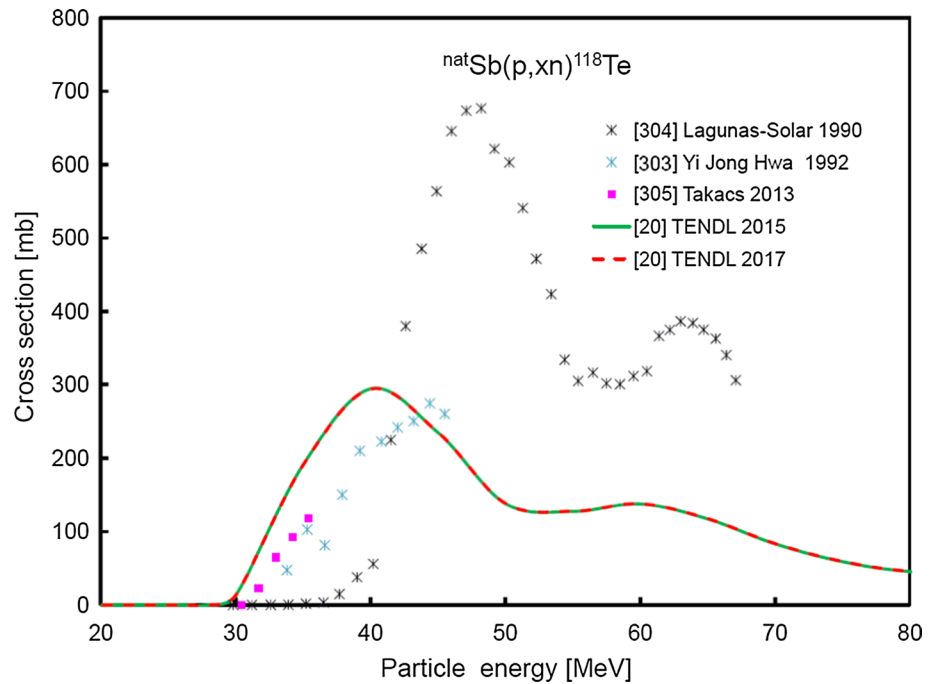
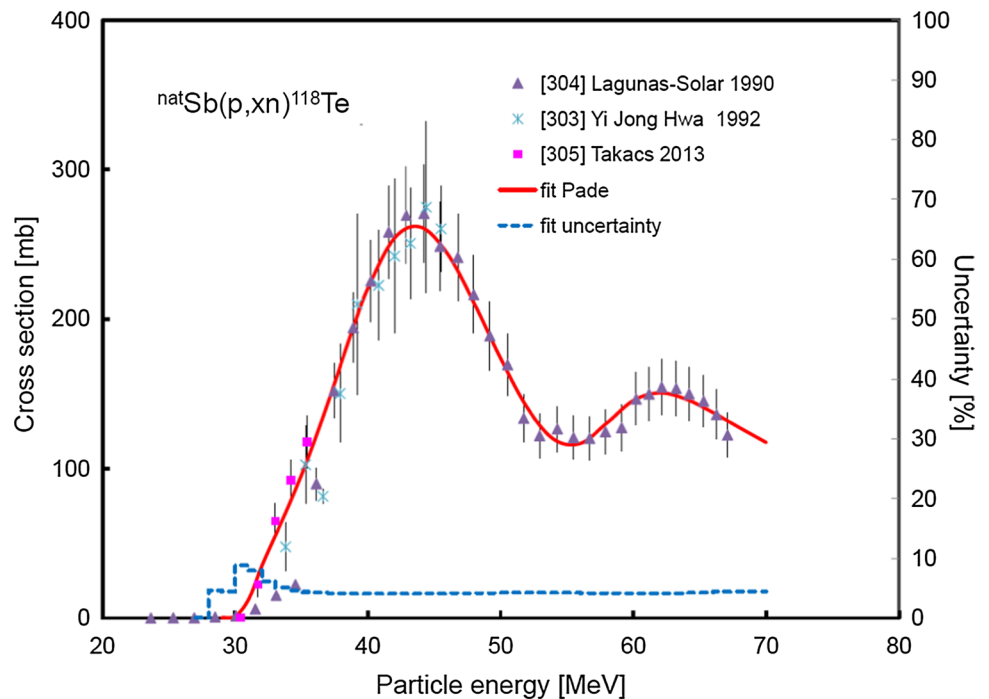


Fig. 142 Three experimental datasets for the $^{nat}\text{Sb}(p,xn)^{118}\text{Te}$ reaction [303–305] with the Padé fit ($L=12, N=43, \chi^2=0.53$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale) – dataset from Ref. [304] has been normalised and energy-shifted



$^{nat}\text{Sb}(d,xn)^{118}\text{Te}$

The single experimental dataset available in the literature is shown in Fig. 143 [306] together with the TENDL calculations. This one dataset was used in the statistical fitting

procedure. The data and their experimental uncertainties are shown in Fig. 144 together with the Padé fit ($L=4, N=7, \chi^2=0.52$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 143 One experimental dataset for the $^{nat}\text{Sb}(d,xn)^{118}\text{Te}$ reaction available in the literature [306], and TENDL calculations

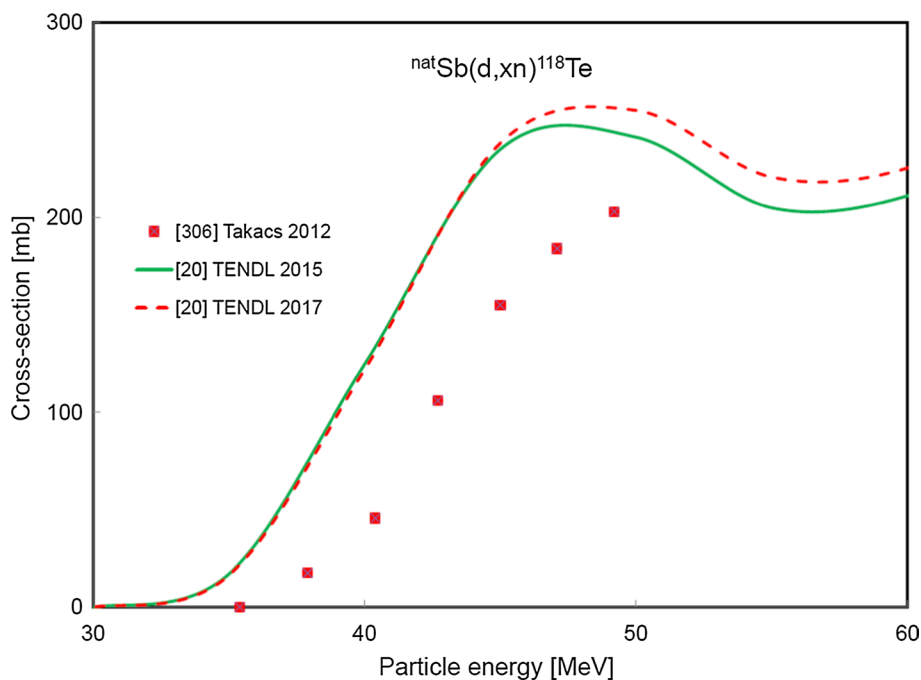
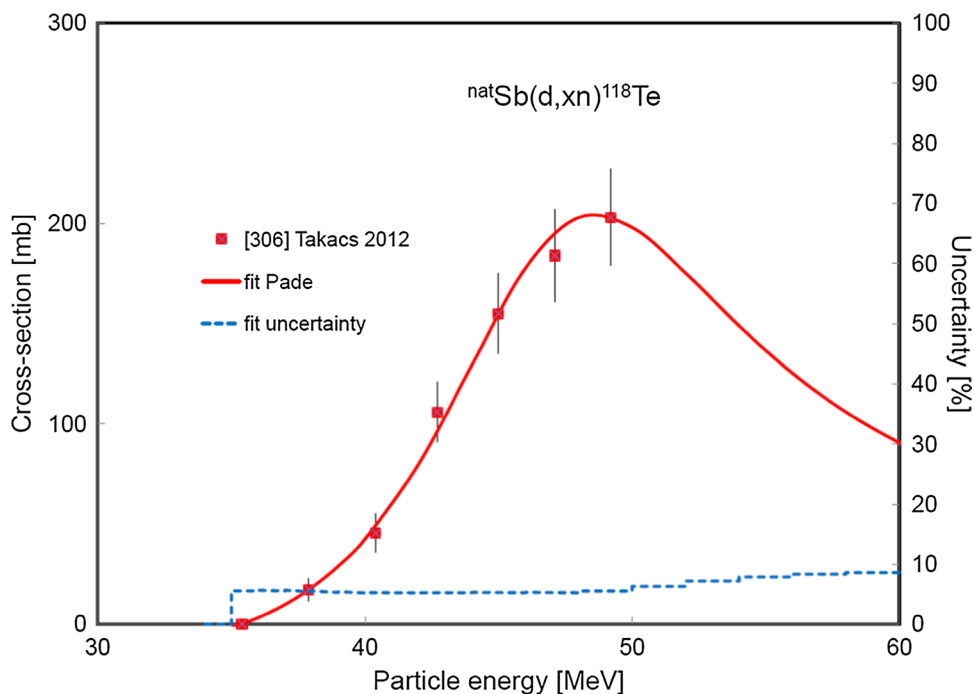


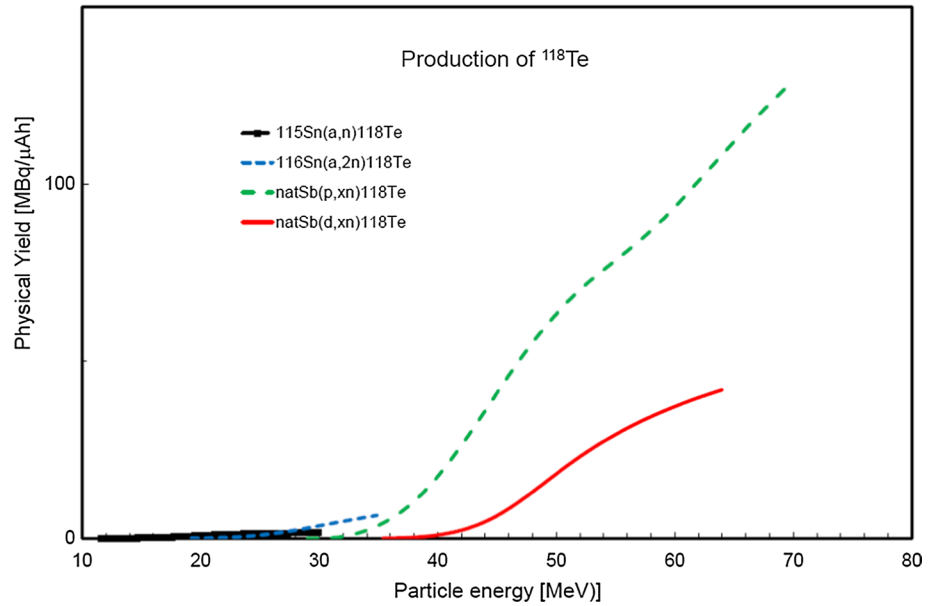
Fig. 144 One experimental dataset for the $^{nat}\text{Sb}(d,xn)^{118}\text{Te}$ reaction [306] with the Padé fit ($L=4, N=7, \chi^2=0.52$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{118}Te parent of short-lived ^{118}Sb

See Fig. 145.

Fig. 145 Thick target yields calculated from the recommended cross sections for the $^{115}\text{Sn}(\alpha, n)^{118}\text{Te}$, $^{116}\text{Sn}(\alpha, 2n)^{118}\text{Te}$, $^{\text{nat}}\text{Sb}(p, xn)^{118}\text{Te}$ and $^{\text{nat}}\text{Sb}(d, xn)^{118}\text{Te}$ reactions



Production of ^{120}I ($T_{1/2} = 81.6$ min)

Applications: Positron-emitting ^{120}I ($T_{1/2} = 81.6$ min) is a short-lived alternative to ^{124}I and ^{123}I . This iodine radionuclide has a positron abundance more than twice that of ^{124}I and a maximum positron energy of 4.593 MeV. Can be used for radiohalogenation of molecules with rapid kinetics.

^{120}I (81.6 min): β^+ (68.2%), and E_γ (keV) ($P_\gamma(\%)$): 601.1 (5.51). 1523.0 (10.9).

Evaluations have been made of the $^{120}\text{Te}(p,n)^{120}\text{I}$ and $^{122}\text{Te}(p,3n)^{120}\text{I}$ reactions.

 $^{120}\text{Te}(p,n)^{120}\text{I}$

The four experimental datasets available in the literature are shown in Fig. 146 [307–310] together with the TENDL calculations. Two datasets were rejected (El-Azony et al. [308] and Ahmed et al. [310], both exhibit energy shift around 10 MeV), and the remaining two datasets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 147 together with the Padé fit ($L = 18$, $N = 38$, $\chi^2 = 0.806$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 146 Four experimental datasets for the $^{120}\text{Te}(p,n)^{120}\text{I}$ reaction available in the literature [307–310], and TENDL calculations

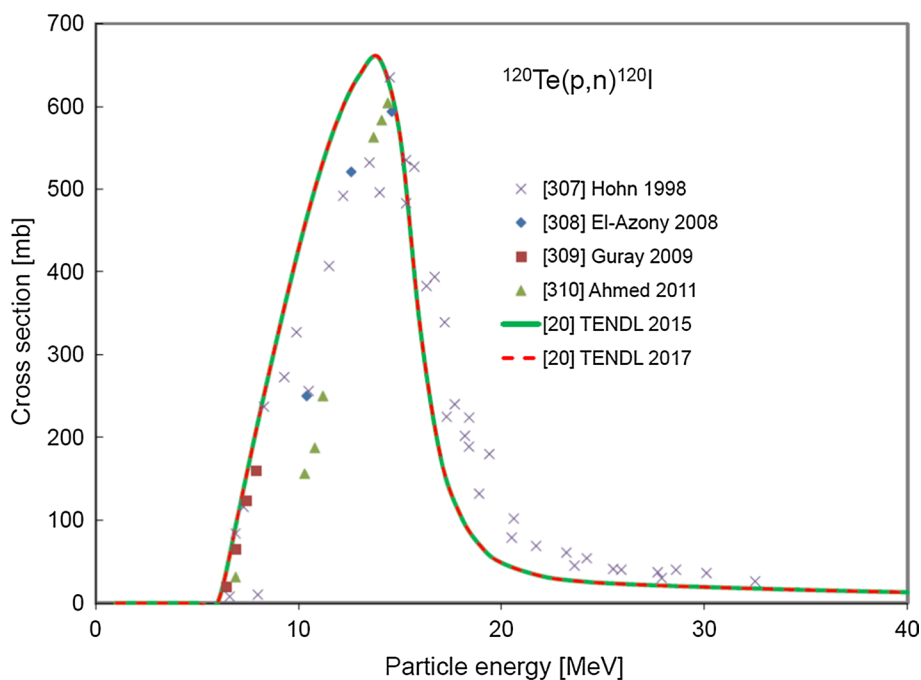
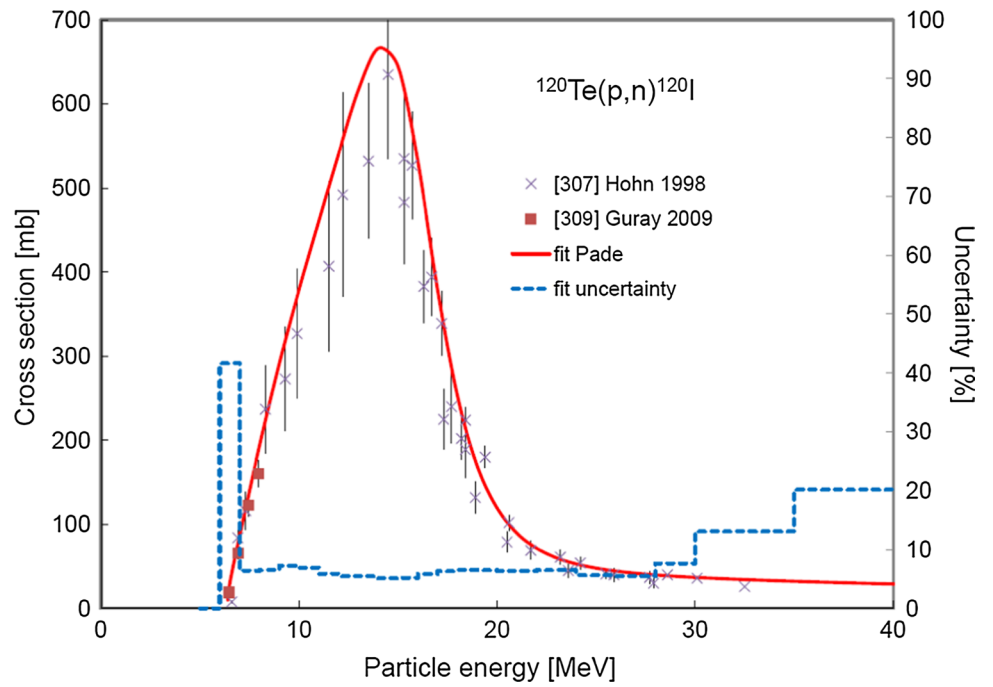


Fig. 147 Two selected experimental datasets for the $^{120}\text{Te}(p,n)^{120}\text{I}$ reaction [307, 309] with the Padé fit ($L=18$, $N=38$, $\chi^2=0.806$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{122}\text{Te}(p,3n)^{120}\text{I}$

The two experimental datasets available in the literature are shown in Fig. 148 [307, 308] together with the TENDL calculations. These two datasets were used in the statistical

fitting procedure. The data and their experimental uncertainties are shown in Fig. 149 together with the Padé fit ($L=7$, $N=18$, $\chi^2=0.463$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 148 Two experimental datasets for the $^{122}\text{Te}(p,3n)^{120}\text{I}$ reaction available in the literature [307, 308], and TENDL calculations

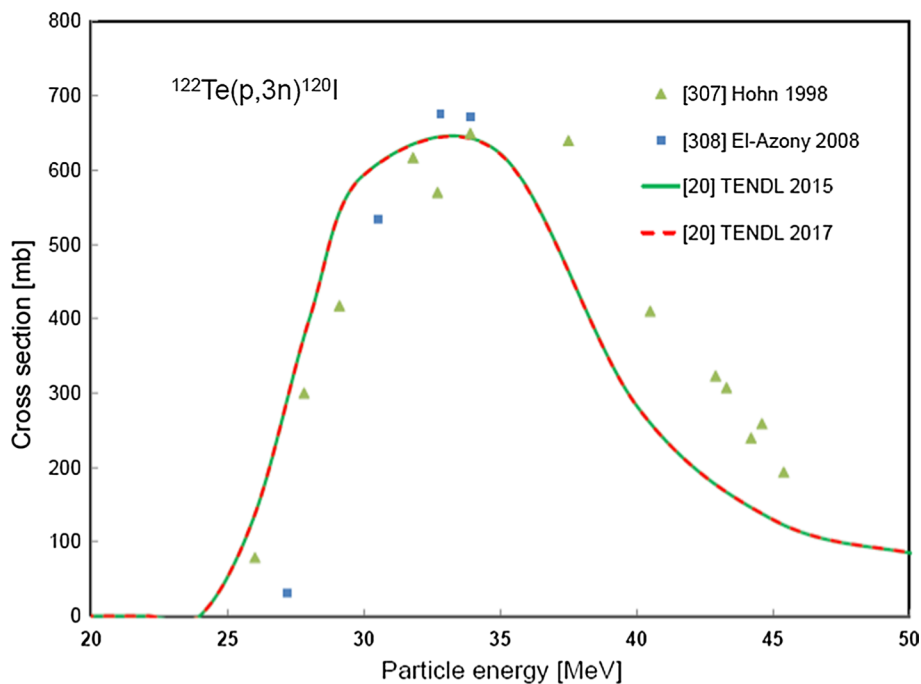
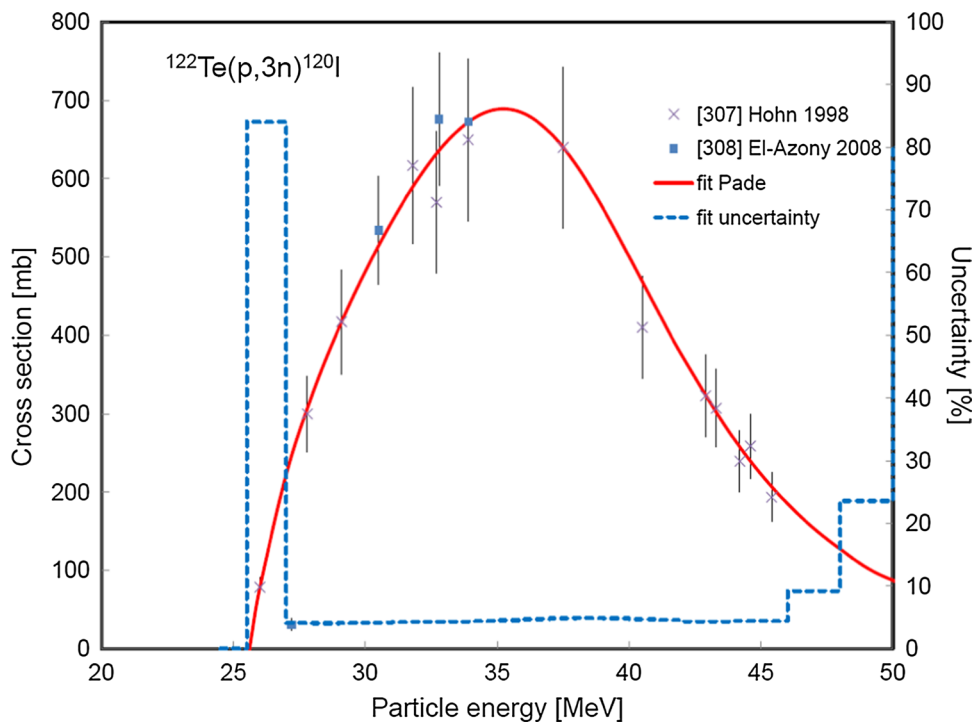


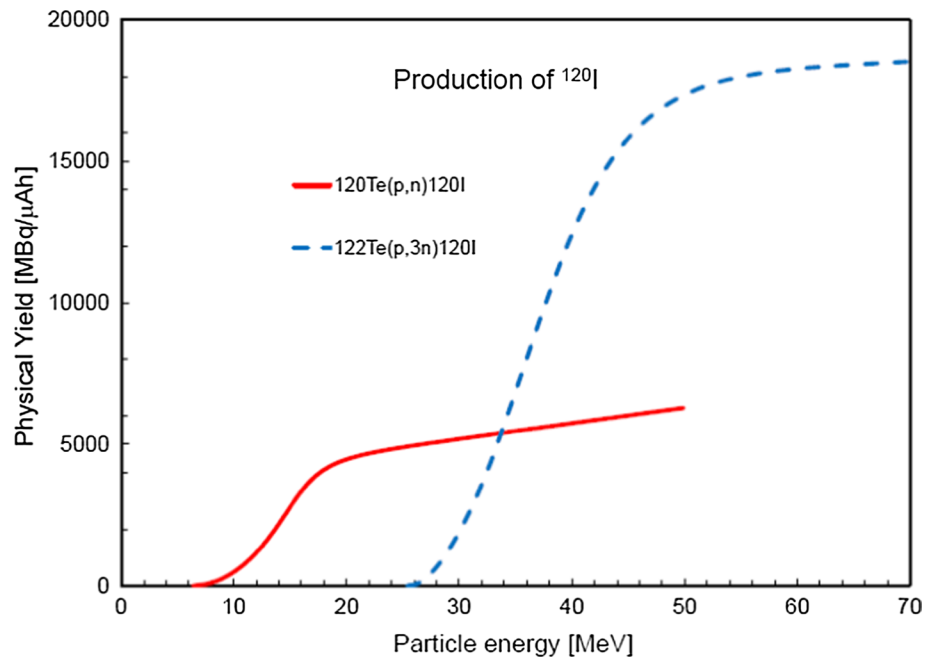
Fig. 149 Two experimental datasets for the $^{122}\text{Te}(p,3n)^{120}\text{I}$ reaction [307, 308] with the Padé fit ($L=7$, $N=18$, $\chi^2=0.463$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{120}I

See Fig. 150.

Fig. 150 Thick target yields calculated from the recommended cross sections for the $^{120}\text{Te}(p,n)^{120}\text{I}$ and $^{122}\text{Te}(p,3n)^{120}\text{I}$ reactions



Production of ^{122}Xe parent ($T_{1/2} = 20.1 \text{ h}$) of short-lived ^{122}I ($T_{1/2} = 3.63 \text{ min}$)

Applications: ^{122}I with a half-life of 3.63 min. has potential as a generator-produced positron emitter for various PET studies such as brain and heart perfusion.

^{122}I (3.63 min): detected through β^+ (78%), and E_γ (keV) (P_γ (%)): 564.119 (18).

^{122}Xe (20.1 h): E_γ (keV) (P_γ (%)): 350.065 (7.80), and radiation emitted by daughter ^{122}I .

Evaluations have been undertaken of the $^{124}\text{Xe}(p,x)^{122}\text{Xe}$, $^{127}\text{I}(p,6n)^{122}\text{Xe}$ and $^{127}\text{I}(d,7n)^{122}\text{Xe}$ production routes.

$^{124}\text{Xe}(p,x)^{122}\text{Xe}$

The two experimental datasets available in the literature are shown in Fig. 151 [311, 312] together with the TENDL calculations. These two datasets were used in the statistical fitting procedure. The data and their experimental uncertainties are shown in Fig. 152 together with the Padé fit ($L = 5$, $N = 15$, $\chi^2 = 1.01$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 151 Two experimental datasets for the $^{124}\text{Xe}(p,x)^{122}\text{Xe}$ reaction available in the literature [311, 312], and TENDL calculations

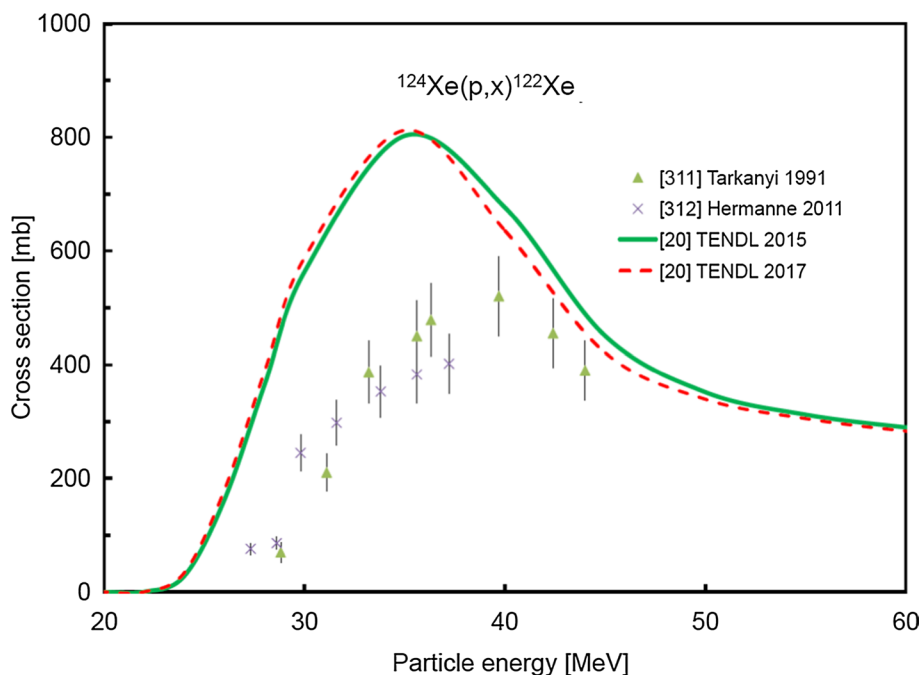
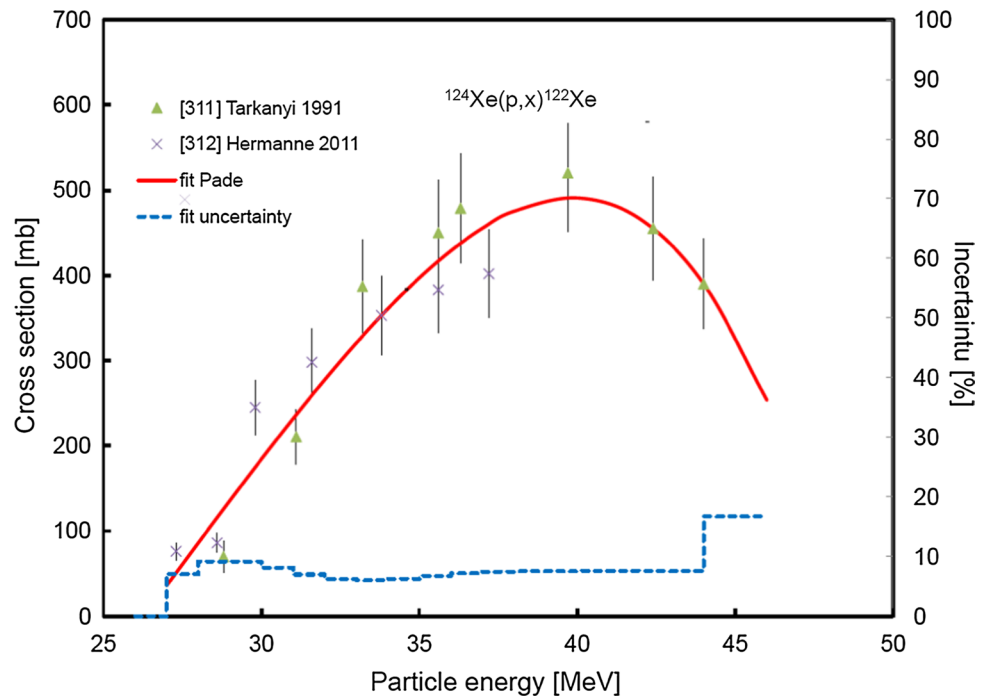


Fig. 152 Two experimental datasets for the $^{124}\text{Xe}(p,x)^{122}\text{Xe}$ reaction [311, 312] with the Padé fit ($L=5, N=15$, $\chi^2=1.01$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{127}\text{I}(p,6n)^{122}\text{Xe}$

The three experimental datasets available in the literature are shown in Fig. 153 [313–315] together with the TENDL calculations. All three datasets were used in the statistical

fitting procedure. These data and their experimental uncertainties are shown in Fig. 154 together with the Padé fit ($L=9, N=21, \chi^2=0.99$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 153 Three experimental datasets for the $^{127}\text{I}(p,6n)^{122}\text{Xe}$ reaction available in the literature [313–315], and TENDL calculations

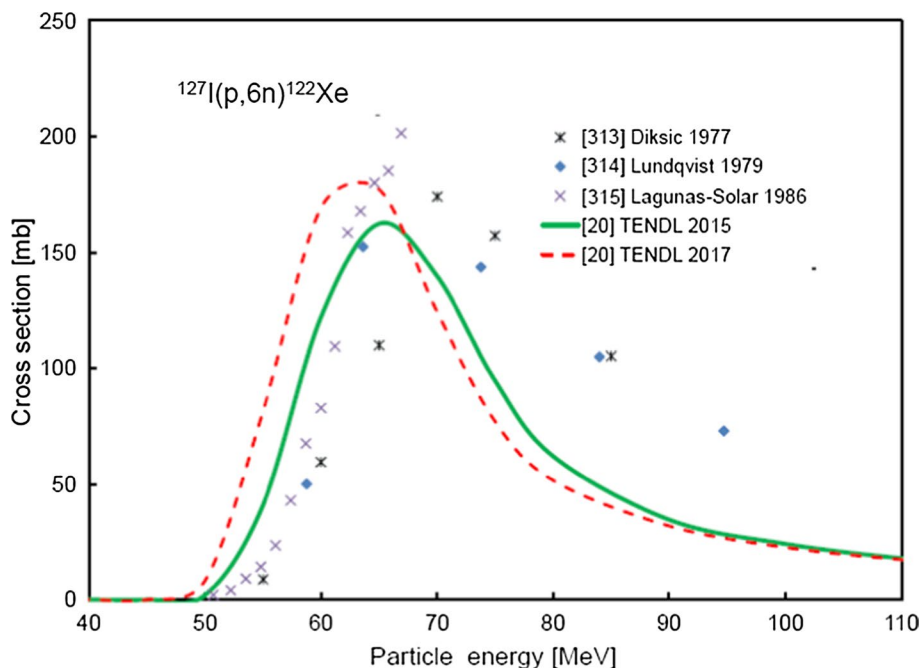
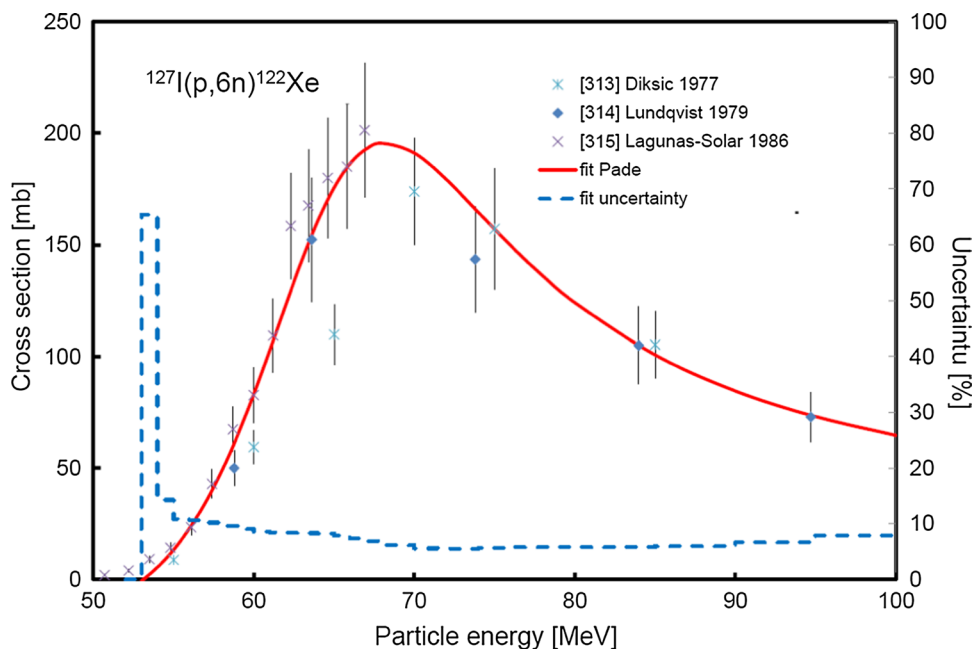


Fig. 154 Three experimental datasets for the $^{127}\text{I}(p,6n)^{122}\text{Xe}$ reaction [313–315] with the Padé fit ($L=7, N=21, \chi^2=1.03$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{127}\text{I}(\text{d},7\text{n})^{122}\text{Xe}$

The two experimental datasets available in the literature are shown in Fig. 155 [316, 317] together with the TENDL calculations – with corrected energy scale for Ref. [316],

the two datasets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 156 together with the Padé fit ($L=12$, $N=21$, $\chi^2=1.31$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 155 Two experimental datasets for the $^{127}\text{I}(\text{d},7\text{n})^{122}\text{Xe}$ reaction available in the literature [316, 317], and TENDL calculations – with corrected energy scale for Ref. [316] data

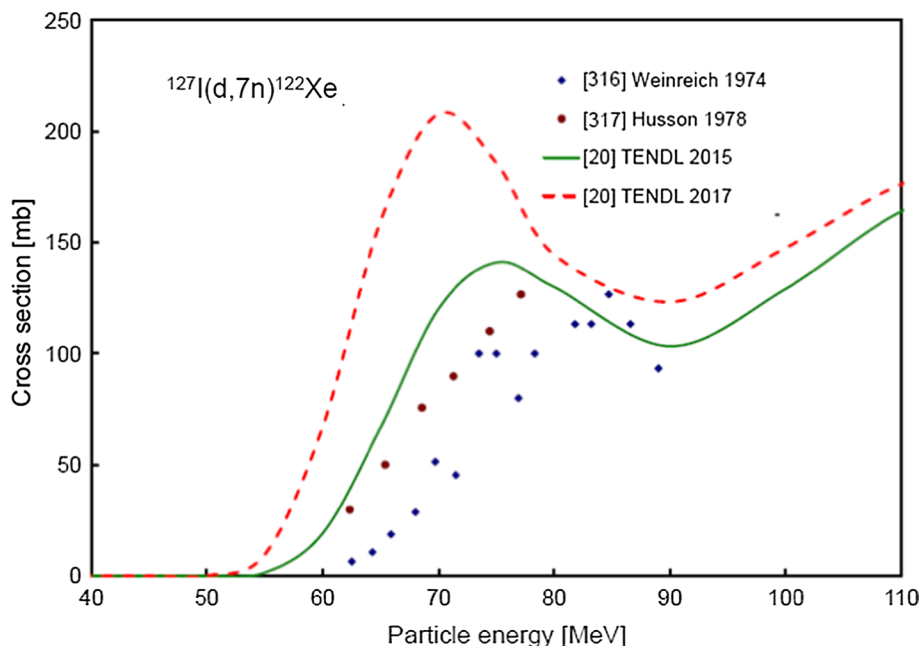
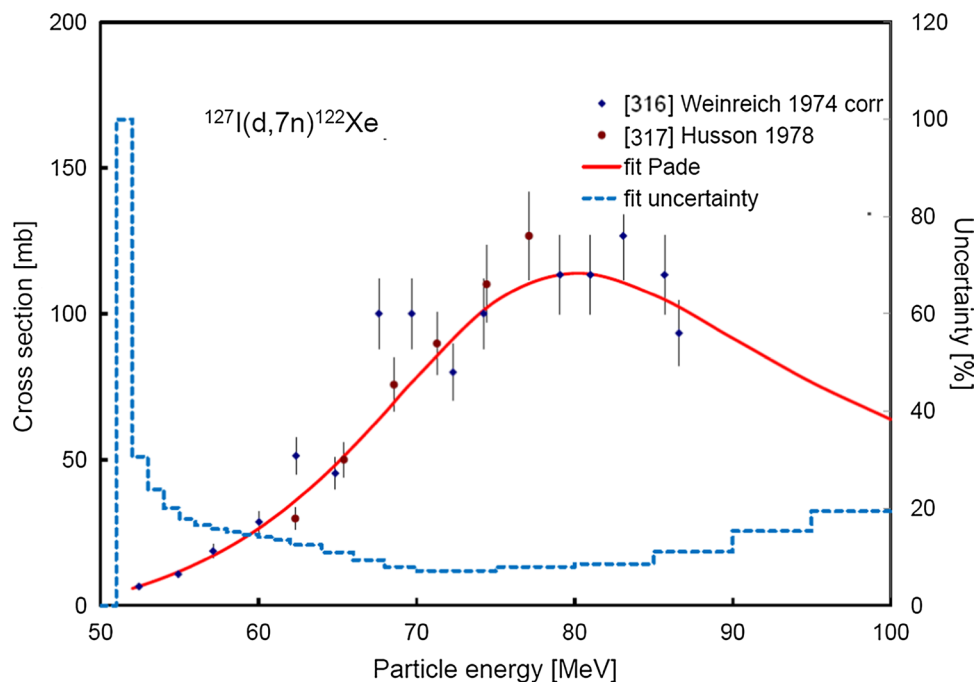


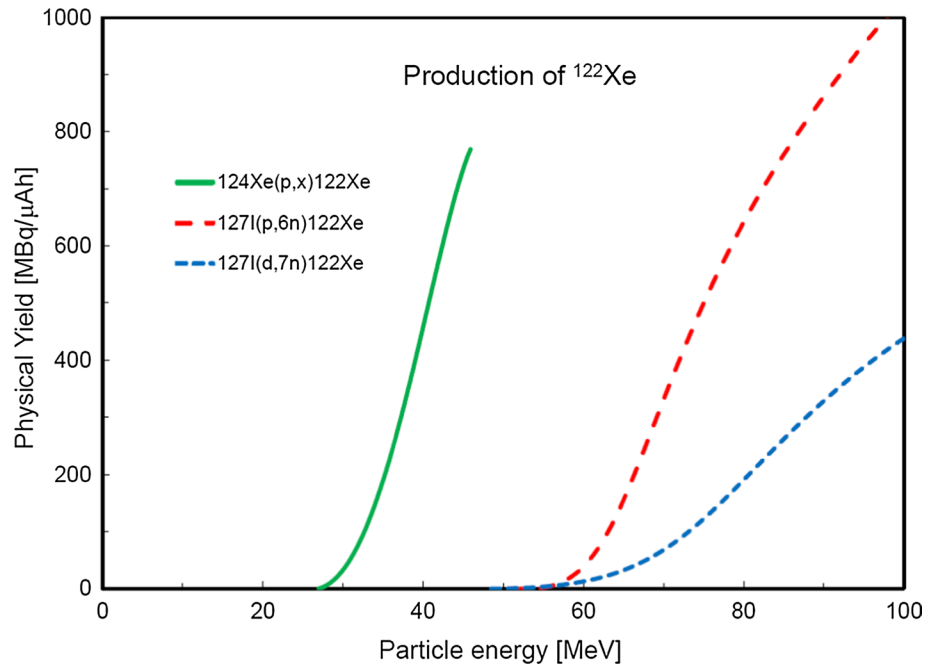
Fig. 156 Two experimental datasets for the $^{127}\text{I}(\text{d},7\text{n})^{122}\text{Xe}$ reaction [316, 317] with the Padé fit ($L=12$, $N=21$, $\chi^2=1.31$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{122}Xe parent of short-lived ^{122}I

See Fig. 157.

Fig. 157 Thick target yields calculated from the recommended cross sections for the $^{124}\text{Xe}(p,x)^{122}\text{Xe}$, $^{127}\text{I}(p,6n)^{122}\text{Xe}$ and $^{127}\text{I}(d,7n)^{122}\text{Xe}$ reactions



Production of ^{128}Ba parent ($T_{1/2} = 2.43\text{ d}$) of short-lived ^{128}Cs ($T_{1/2} = 3.66\text{ min}$)

Applications: Short-lived generator-produced ^{128}Cs can be used in a similar manner to ^{82}Rb for myocardial perfusion examinations.

^{128}Cs (3.66 min): β^+ (68.8%), and E_γ (keV) ($P_\gamma(\%)$): 442.901 (26.8).

^{128}Ba (2.43 d): E_γ (keV) ($P_\gamma(\%)$): 273.44 (14.5), and by means of radiation from daughter ^{128}Cs .

Fig. 158 Four experimental datasets for the $^{133}\text{Cs}(p,6n)^{128}\text{Ba}$ reaction available in the literature [318–321], and TENDL calculations

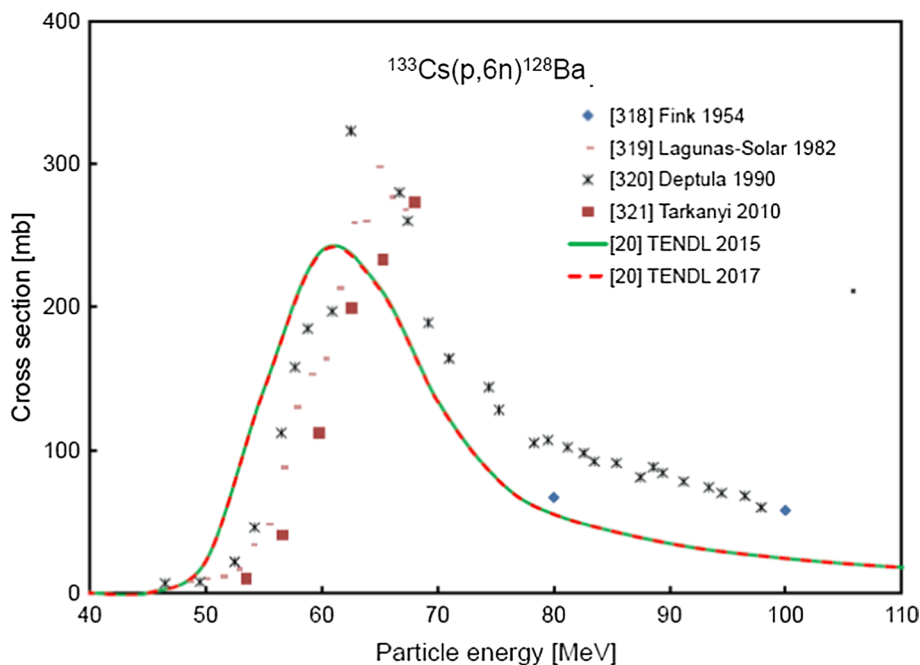
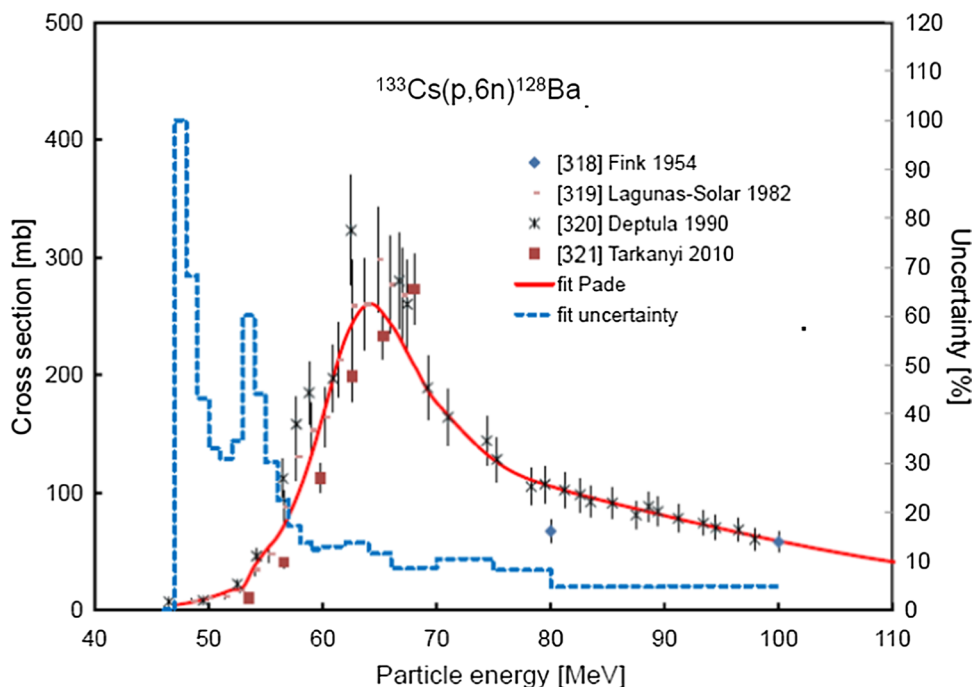


Fig. 159 Four experimental datasets for the $^{133}\text{Cs}(p,6n)^{128}\text{Ba}$ reaction [318–321] with the Padé fit ($L = 18$, $N = 51$, $\chi^2 = 1.79$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Only the $^{133}\text{Cs}(p,6n)^{128}\text{Ba}$ reaction has been evaluated.

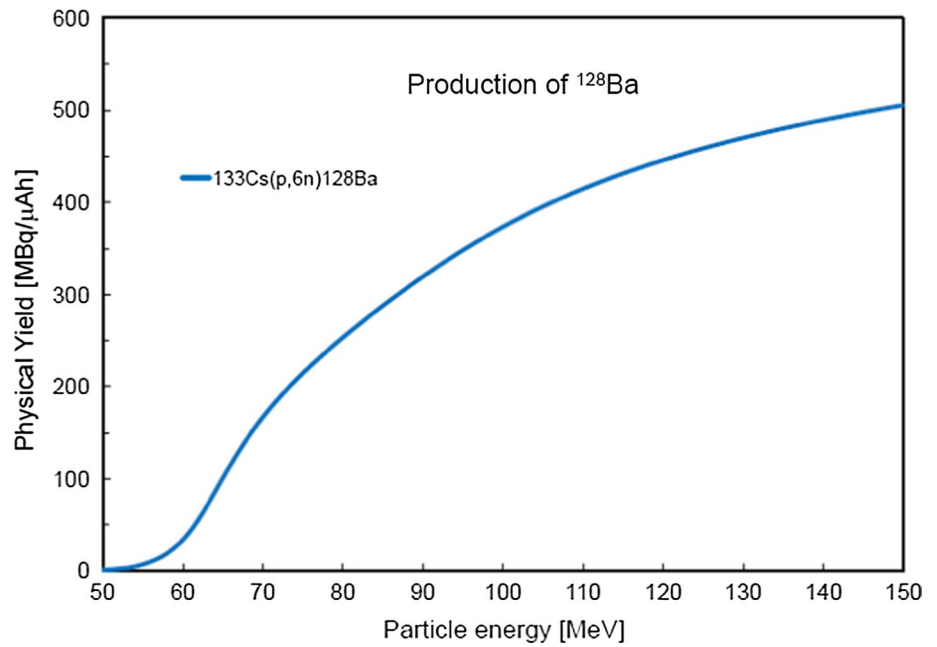
$^{133}\text{Cs}(p,6n)^{128}\text{Ba}$

The four experimental datasets available in the literature are shown in Fig. 158 [318–321] together with the TENDL calculations. All four datasets were used in the statistical fitting procedure. These data and their experimental uncertainties are shown in Fig. 159 together with the Padé fit ($L = 18$, $N = 51$, $\chi^2 = 1.79$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Thick target yields for ^{128}Ba parent of short-lived ^{128}Cs

See Fig. 160.

Fig. 160 Thick target yields calculated from the recommended cross sections for the $^{133}\text{Cs}(p,6n)^{128}\text{Ba}$ reaction



Production of ^{140}Nd parent ($T_{1/2} = 3.37$ d) of short-lived ^{140}Pr ($T_{1/2} = 3.39$ min)

Applications: EC decay of ^{140}Nd (EC = 100%, $T_{1/2} = 3.37$ d) produces short-lived ^{140}Pr ($T_{1/2} = 3.39$ min, $\beta^+ = 51.0\%$, $E_{\beta^+}(\text{max}) = 2.366$ MeV), which undergoes EC/ β^+ decay to stable ^{140}Ce . Parent-daughter $^{140}\text{Nd}/^{140}\text{Pr}$ has been proposed as a radionuclide generator, or as an in vivo generator system for PET studies.

^{140}Pr (3.39 min): β^+ (51.0%), and E_γ (keV) ($P_\gamma(\%)$): 306.9 (0.147), 1596.1 (0.49).

^{140}Nd (3.37 d): detected by means of radiation emitted by daughter ^{140}Pr .

Evaluations have been undertaken of the $^{141}\text{Pr}(p,2n)^{140}\text{Nd}$, $^{141}\text{Pr}(d,3n)^{140}\text{Nd}$ and $^{\text{nat}}\text{Ce}(^3\text{He},xn)^{140}\text{Nd}$ production routes.

$^{141}\text{Pr}(p,2n)^{140}\text{Nd}$

The three experimental datasets available in the literature are shown in Fig. 161 [322–324] together with the TENDL calculations. One dataset was rejected (Hogan [322], values too high), and the remaining two sets were used in the statistical fitting procedure. The selected data and their experimental uncertainties are shown in Fig. 162 together with the Padé fit ($L = 10$, $N = 121$, $\chi^2 = 0.78$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 161 Three experimental datasets for the $^{141}\text{Pr}(p,2n)^{140}\text{Nd}$ reaction available in the literature [322–324], and TENDL calculations

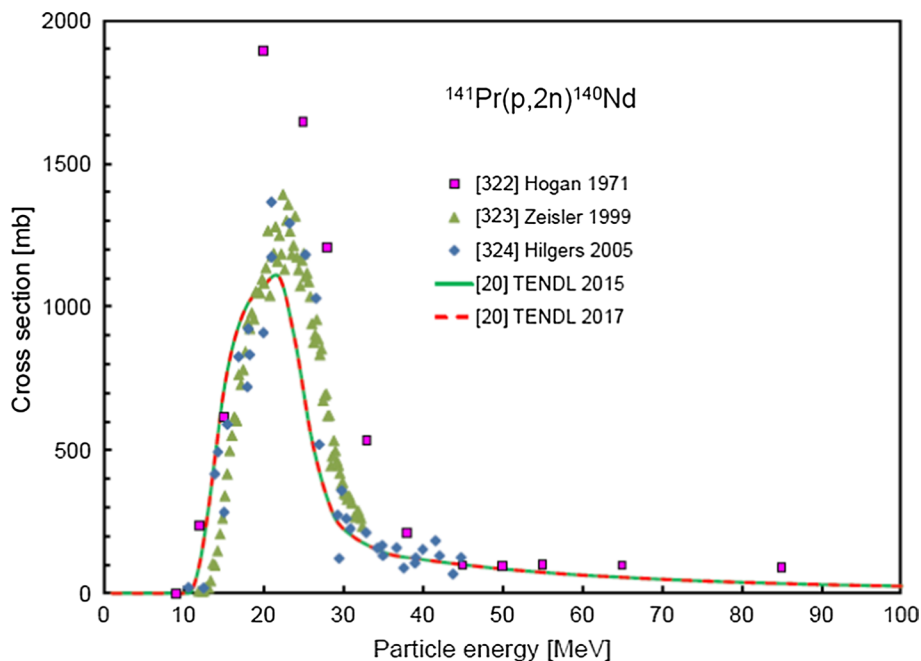
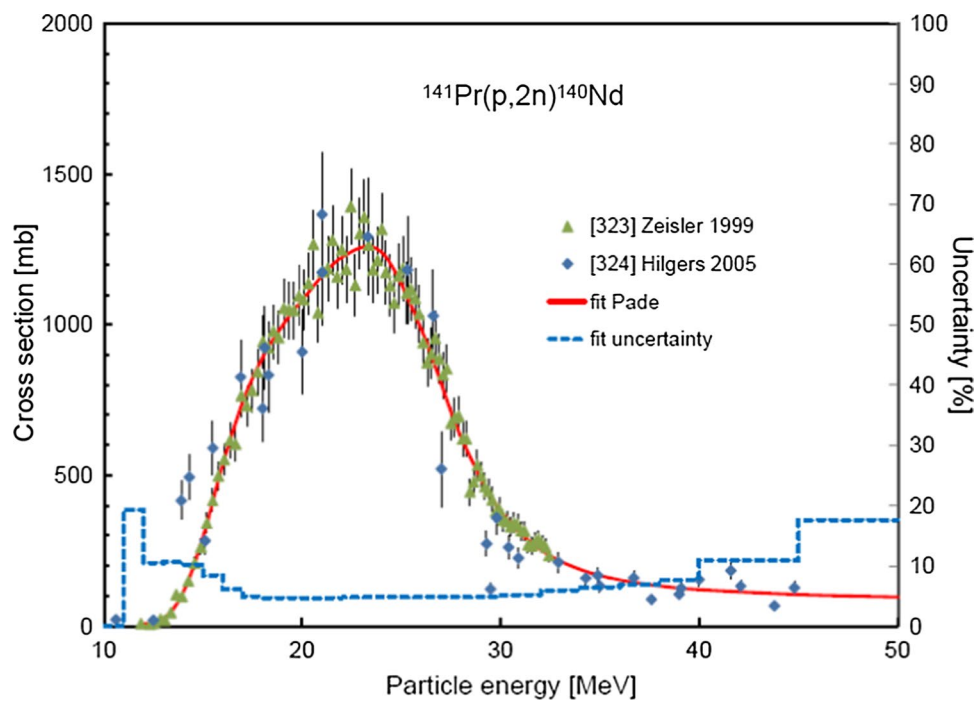


Fig. 162 Two selected experimental datasets for the $^{141}\text{Pr}(p,2n)^{140}\text{Nd}$ reaction [323, 324] with the Padé fit ($L=10$, $N=121$, $\chi^2=0.78$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



$^{141}\text{Pr}(d,3n)^{140}\text{Nd}$

The two experimental datasets available in the literature are shown in Fig. 163 [325, 326] together with the TENDL calculations. Both datasets were used in the statistical fitting

procedure, as shown in Fig. 164 together with the Padé fit ($L=9, N=17, \chi^2=0.466$) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 163 Two experimental datasets for the $^{141}\text{Pr}(d,3n)^{140}\text{Nd}$ reaction available in the literature [325, 326], and TENDL calculations

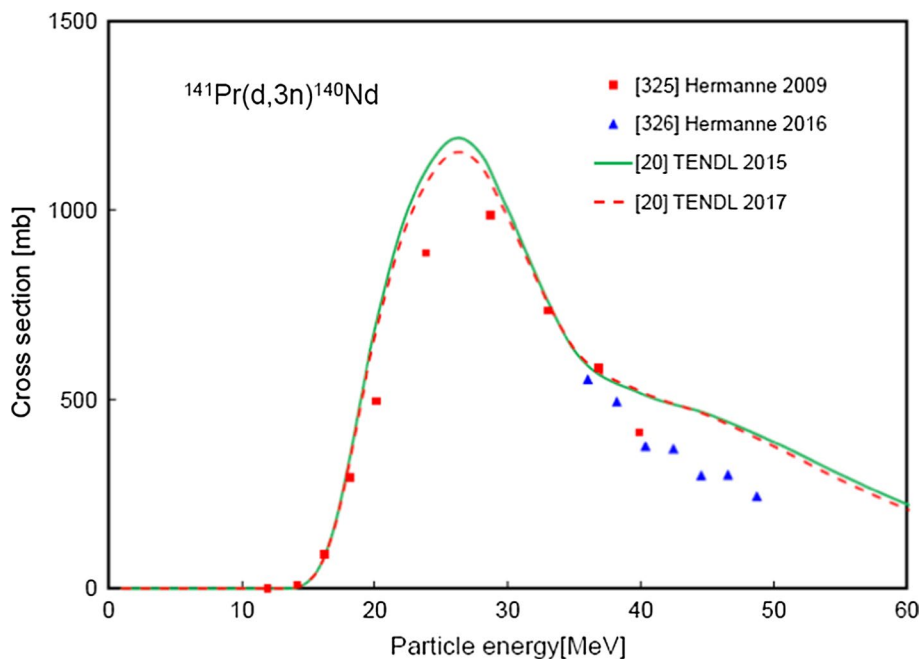
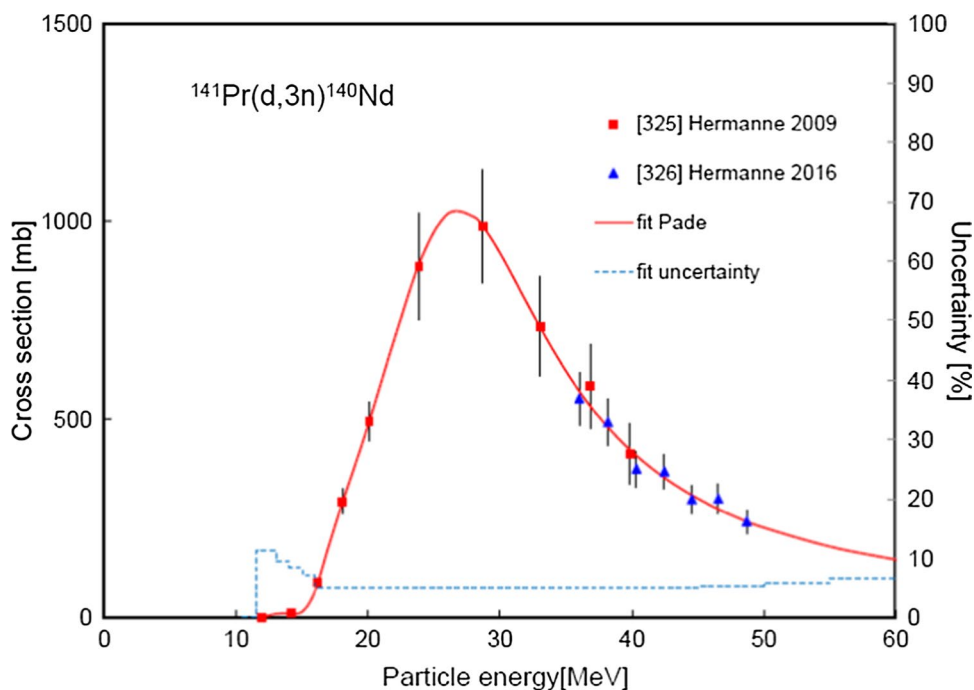


Fig. 164 Two experimental datasets for the $^{141}\text{Pr}(d,3n)^{140}\text{Nd}$ reaction [325, 326] with the Padé fit ($L=9, N=17, \chi^2=0.466$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



${}^{\text{nat}}\text{Ce}({}^3\text{He},\text{xn}){}^{140}\text{Nd}$

Only a single experimental dataset has been found in the literature [324], as illustrated in Fig. 165 together with the TENDL calculations. ${}^3\text{He}$ beams are rarely available for use, and therefore TENDL evaluators have not attempted to improve the description of this complicated channel, in

which break-up and transfer effects may dramatically change the shape and magnitude of the calculated cross sections. This dataset and associated experimental uncertainties were adopted in the statistical fitting procedure. The results are shown in Fig. 166 together with the Padé fit ($L=9$, $N=18$, $\chi^2=1.59$, solid line) and estimated uncertainty in percentages, including 4% systematic uncertainty (right-hand scale).

Fig. 165 One experimental dataset for the ${}^{\text{nat}}\text{Ce}({}^3\text{He},\text{xn}){}^{140}\text{Nd}$ reaction available in the literature [324], and TENDL calculations

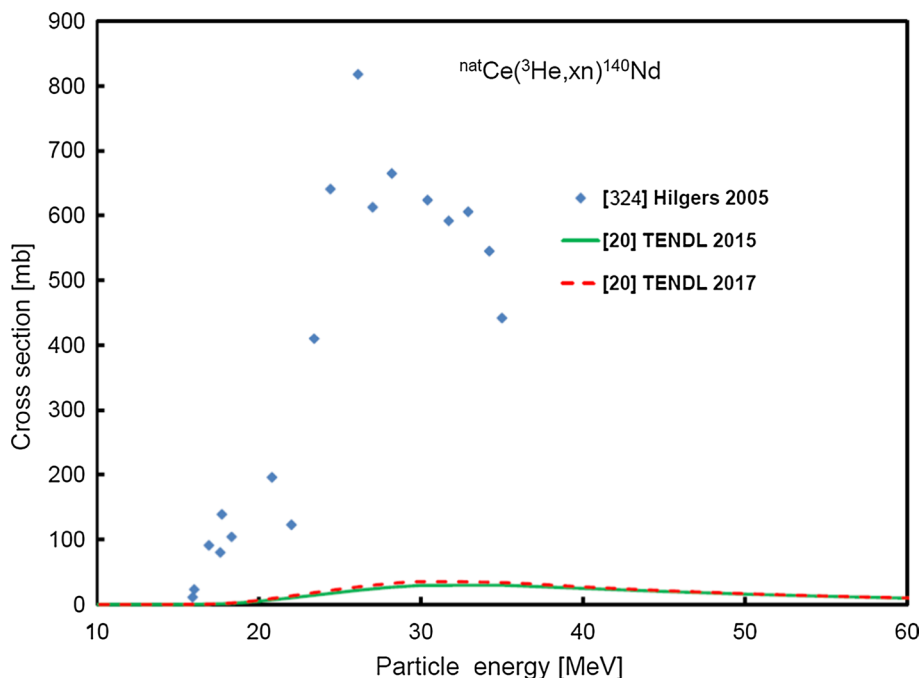
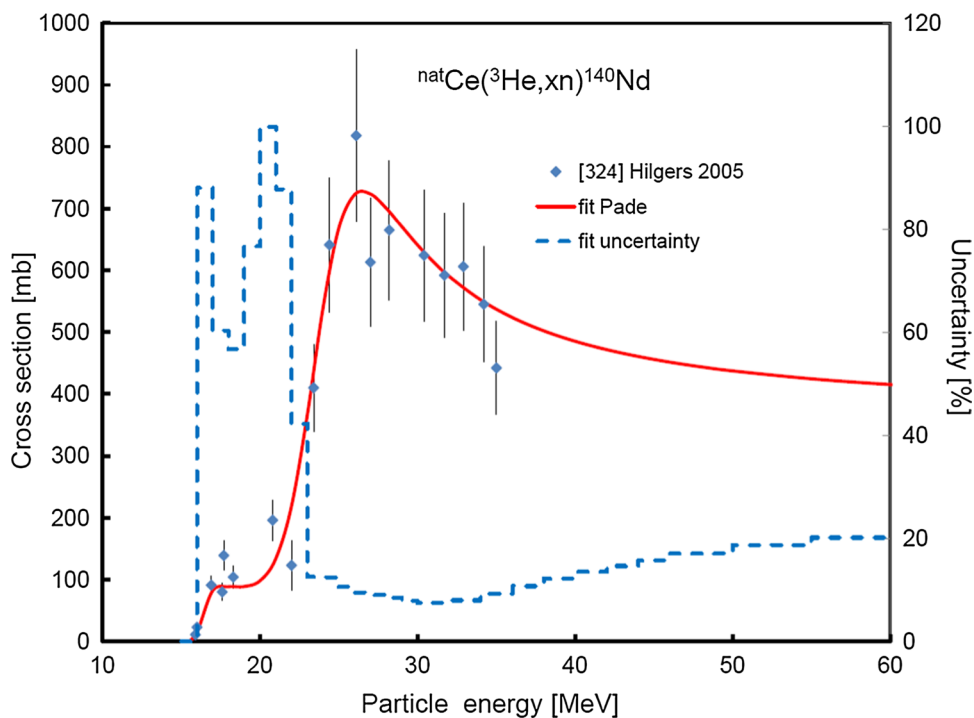


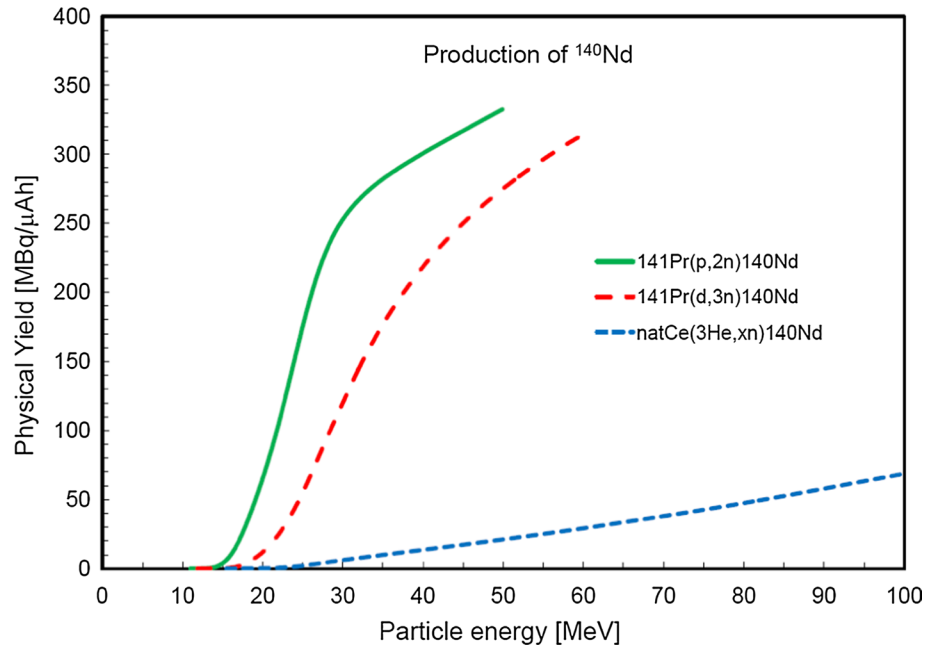
Fig. 166 One experimental dataset for the ${}^{\text{nat}}\text{Ce}({}^3\text{He},\text{xn}){}^{140}\text{Nd}$ reaction [324] with the Padé fit ($L=9$, $N=18$, $\chi^2=1.59$, solid line) and estimated total uncertainties in percentages, including 4% systematic uncertainty (dashed line, right-hand scale)



Thick target yields for production of ^{140}Nd parent of short-lived ^{140}Pr

See Fig. 167.

Fig. 167 Thick target yields calculated from the recommended cross sections for the $^{141}\text{Pr}(p,2n)^{140}\text{Nd}$, $^{141}\text{Pr}(d,3n)^{140}\text{Nd}$ and $^{\text{nat}}\text{Ce}(^3\text{He},xn)^{140}\text{Nd}$ reactions



Evaluated excitation functions: an overall assessment

A significant amount of effort has been expended to assemble, evaluate, analyse and recommend suitable cross-section datasets to ensure that a series of radionuclides may be generated with acceptable purity in an optimum manner for PET imaging. Obviously, confidence in such recommended data is highly dependent on their quality and validity as addressed and improved by in-depth evaluations. As derived, these data can also be assessed to identify those cross sections and their resulting excitation functions that can be improved further by means of additional measurements. Additionally, integral measurements (production thick target yields) are very important and need to be performed in order to assist in the benchmarking and validation of the recommended data.

Improved radionuclidic purity may be an issue that emerges from research-based applications in nuclear medicine. Under such circumstances, excitation functions for these radionuclidic impurities are also required to aid in the optimisation of target composition and energy range of the beam within the target in order to avoid or at least minimise their production. These data requirements have not been addressed in the current studies, but remain an important part of what would normally constitute an evolutionary programme of work that may hopefully lead up to regular medical application.

Some critical comments can be justifiably applied as to the quality of any evaluated cross-section data, particularly when the quoted uncertainties of such recommended excitation functions do not reflect the complexity of various underlying and often ill-defined factors. For example, difficulties arise when attempting to judge the quality of experimental data on the basis of only the original publication(s), as significant details on the measurement and associated data evaluations are required for such an exercise but are often omitted from journal papers. Reported uncertainties do not exceed seven or eight percent in many cases for very different types of reaction and measurement methodology that makes such modest percentages effectively unrealistic. Some laboratories are known to possess greater expertise than others, and/or have a better technical background in cross-section studies. Such personnel and facilities most frequently generate more reliable experimental data that implies greater weight should be applied to their datasets in the evaluation process. However, under such circumstances, less reliable data and their questionable uncertainties are considered in many evaluations with the same weighting, and so distort the final recommended values. The thoroughness of compilation, systematic application of all known corrections, and strictness in data selection also depend strongly

on the subjective knowledge and analytical behaviour of individual evaluators. This results in a quality difference between the recommendations of evaluators that is not reflected in the uncertainties of their final sets of recommended nuclear data.

Comprehensive comparisons have been made of the measured cross-section results of the 69 reactions studied in this work with the equivalent evolving predictions of the two TENDL libraries based on theoretical cross-section calculations of the TALYS code system. No important changes would appear to have been introduced into the code between 2015 and 2017 that affect these particular reactions because, in the majority of cases, the results for TENDL-2017 are identical to or only marginally differ from the contents of the TENDL-2015 database. A rather surprising observation is that, where large differences exist, the 2017 database exhibits larger disagreements with the experimental results than the 2015 edition (see for example, Figs. 120 and 155). However, the readily available on-line predictions are in acceptable agreement with the overall shape of the measured and evaluated excitation functions, and are therefore useful for the estimation of other unmeasured nuclear processes. The main shortcomings observed in the TENDL libraries and related TALYS reaction modelling can be identified with the following behaviour:

1. Energy shift of high energy reactions with the emission of multiple particles.
2. Underestimation of the production of some isomeric states which is reflected in the underestimation of cumulative processes.
3. Poor quantification of the magnitude of alpha-particle induced reactions near their maximum and at higher energies.
4. Underestimation of the cross section for a single ^3He -induced reaction.
5. Underestimation of the cross section for deuteron induced reactions, especially from the threshold to the maximum of the excitation function.
6. Unexplained strange shapes within some (p,n) reactions (e.g., plateau near maximum).

Many of these shortcomings are related to known problems in the theoretical modelling that will be shared by results calculated using different reaction codes.

Additional improved experimental studies of particular production routes are clearly merited, as defined by the nature of some of the existing cross-section data to be found throughout Section [Results for charged-particle reactions](#). However, there are also other reactions that require consideration and analyses of the form undertaken above [327, 328], along with the need for better quantified studies of specific positron and X-ray emission probabilities [329].

New measurements and evaluations are required of the activation cross sections for proton-induced reactions with energies up to 250 MeV: ^{11}C , ^{13}N , $^{14,15}\text{O}$, ^{30}P and ^{38}K . More extensive cross-section studies would also be beneficial to achieve the optimum production of $^{34\text{m}}\text{Cl}$, ^{43}Sc , ^{45}Ti , ^{48}V , ^{49}Cr , ^{51}Mn , ^{57}Ni , ^{75}Br , ^{77}Kr , ^{81}Rb , ^{83}Sr , ^{95}Ru , ^{121}I and ^{152}Tb . Improved decay data are identified with the need for accurate absolute positron and X-ray emission probabilities for ^{57}Ni , ^{72}As , ^{73}Se , $^{75,76}\text{Br}$, ^{77}Kr , $^{81,82\text{m}}\text{Rb}$, ^{83}Sr , ^{86}Y , ^{89}Zr , $^{94\text{m}}\text{Tc}$ and ^{120}I . On balance, reviews of the nuclear data requirements in nuclear medicine would appear to be appropriate approximately every 10 years to ensure a continued and well-defined international focus on ensuring that the necessary technical information is immediately to hand when required.

Conclusions

Substantial extensions and significant improvements have been made to the IAEA-NDS recommended cross-section database for the production of PET radionuclides. Evaluations were performed on 69 reactions for direct, indirect or generator production of ^{44}Sc , ^{44}Ti , ^{52}Mn , $^{52\text{m}}\text{Mn}$, ^{52}Fe , ^{55}Co , ^{61}Cu , ^{62}Cu , ^{62}Zn , ^{66}Ga , ^{68}Ga , ^{68}Ge , ^{72}As , ^{72}Se , ^{73}Se , ^{76}Br , ^{82}Rb , $^{82\text{m}}\text{Rb}$, ^{82}Sr , ^{86}Y , ^{89}Zr , ^{90}Nb , $^{94\text{m}}\text{Tc}$, $^{110\text{m}}\text{In}$, ^{110}Sn , ^{118}Sb , ^{118}Te , ^{120}I , ^{122}I , ^{122}Xe , ^{128}Cs , ^{128}Ba , ^{140}Pr and ^{140}Nd . A Padé fitting method was applied to the evaluated datasets selected, and uncertainties for all of the recommended data were deduced. The experimental data were compared with theoretical predictions taken from both the TENDL-2015 and TENDL-2017 libraries, sometimes exhibiting significant disagreements in the magnitude and shape of the resulting excitation functions.

As well as a lack of published data for specific reactions, significant disagreements were also found to exist between various equivalent experimental data. All of the recommended cross-section data were used to derive integral or production thick target yields for direct practical application.

All of the numerical reference cross-section data with their corresponding uncertainties and deduced integral thick target yields are available on-line at the IAEA-NDS medical portal www-nds.iaea.org/medportal/ [2] and also at the IAEA-NDS web page www-nds.iaea.org/medical/positron_emitters.html.

These evaluated experimental data are important for existing and potential applications in nuclear medicine, and may also have useful roles in other fields of non-energy related nuclear studies.

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