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Development of a system for measuring the shape of β spectra using a semiconductor Si detector

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A system for the measurement of beta energy spectra has been developed. It is based on a silicon semi-conductor detector operating at liquid nitrogen temperatures, under ultra high-vacuum. Monte-Carlo simulations were made to optimize the detection chamber and the source holder. Descriptions of the electronic and mechanical systems are included, as well as the first measured spectra.

I. INTRODUCTION

The study of the shape of β spectra is experiencing a resurgence of interest having been little studied since the late 1970s. Precise knowledge of the shape of energy spectra, coupled with well established uncertainties, are sought by users from the nuclear power industry (decay heat calculations), medical care sector (dose calculations) or ionizing radiation metrology (reduction of uncertainties in activity measurements using the liquid scintillation counting technique). As the primary laboratory for measurements of radioactivity in France, the Laboratoire National Henri Becquerel (LNHB) is developing a computer code, BETASHAPE [1], to meet the demands of users. BETASHAPE calculates analytically the beta spectra for allowed and forbidden unique transitions and takes into account the screening effect due to the electron cloud, the finite nuclear size effect with regard to the electron Compton wavelength, and the radiative corrections. This program must be tested and validated by experiments. Hence, an operational device using a semiconductor Si detector (easy to implement, linear response function, good energy resolution) has been developed in order to measure spectral shapes and to quantify uncertainties.

II. REQUIREMENTS OF THE SYSTEM

The main difficulties in beta spectrometry arise because the spectra may be distorted by the detection system. Specific requirements are necessary to limit the

sources of deformation and to maximize the signal-to-noise ratio [2]. Silicon detectors are operable at room temperature, however, thermally-generated leakage currents contribute heavily to the noise level. Operation at liquid nitrogen temperature offers marked improvements in resolution and to the signal-to-noise ratio, especially for low energies. Operation at low temperature, in turn, dictates a further design criterion: the detector must be kept under vacuum to prevent atmospheric moisture from condensing and freezing on the detector's surface [3]. However, the vacuum pump induces microphonics which have to be attenuated. Otherwise, physical phenomena like self-absorption in the source, detector dead zones, angle of incidence, scattering and backscattering or bremsstrahlung have also a great influence on the measured spectral shape. A high-vacuum provides another advantage, namely a low scattering environment. However, we must also carefully choose the materials and define the geometry of the detection chamber and source holder. Finally, for each radionuclide, a chemical study must be undertaken to determine the best method for preparing thin and homogeneous sources [4].

III. GEANT4 SIMULATIONS

We performed Monte Carlo simulations to study the impact of materials and geometry on the spectral shape. The model of the detector, the detection chamber and the source holder are relatively simple because here we are just interested in qualitative results. We have implemented in GEANT4 [5] a new class based on our BETASHAPE [1] code. We use it rather than the *G4RadioactiveDecay* class for simulating beta sources since it is more reliable. Our simulations were carried out using an isotropic ⁹⁰Y source.

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A. Study of the detection chamber

The detection chamber is a cube milled on its six faces. Clearly the bigger the cube, the lower the scattering, but we must also avoid a cumbersome system. We tested various sizes of the detection chamber between 150 to 250 mm for two materials: stainless steel and aluminum. The source position from the detector was varied from 10 to 40 mm. Close to the detector the scattering effect is almost negligible but another source of deformation is induced due to the detector thickness. Fig. 1 shows that aluminum is to be preferred to stainless steel. Thus the dimensions of the cube could be reduced. The best trade-off found is a cube with 170 mm sides made from aluminum.

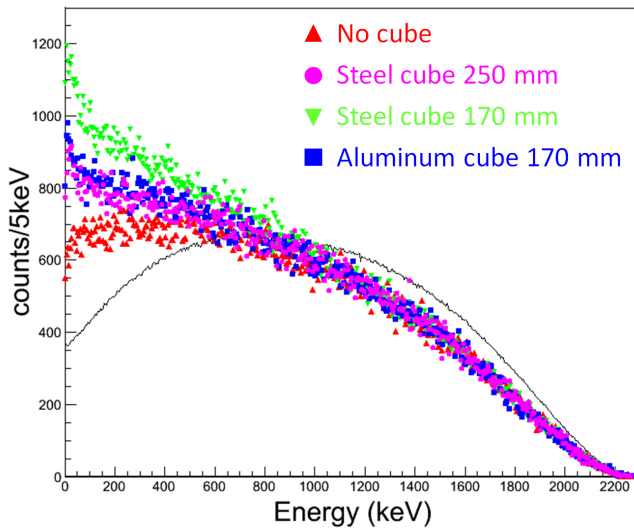


FIG. 1. Study of the spectrum deformation as a function of the material and dimensions of the detection chamber. The simulation was performed with a 5 mm thick detector. The curve in black is the theoretical spectrum calculated with BE-TAShape [1].

B. Study of the source holder

We want to avoid, as far as possible, the detection of backscattered electrons coming from the source holder. Backscattering is more pronounced for electrons of low energy and absorbers with high atomic number [6]. GEANT4 simulations were conducted from the GEANT4 benchmark *TestEm5* adapted to our application. We tested two materials for the source holder: aluminium and PEEK (polyether ether ketone) which is an organic polymer thermoplastic. PEEK is the best plastic to use for vacuum applications because it does not outgas. A 500 keV mono-energetic beam was simulated, impinging on a full block of material and then, conserving the same geometry, with a 1 cm recess milled into the block. Results are shown in Table I. Finally, the geometry adopted

for the source holder is shown in Fig. 2. The notches on the side allow pressure equalization across the source.

TABLE I. Backscattered electrons depending on the material and geometry of the source holder.

	Fraction reflected in full source holder	Fraction reflected in recessed source holder
Aluminium	11.4 %	5.1 %
PEEK	2.7 %	1.3 %

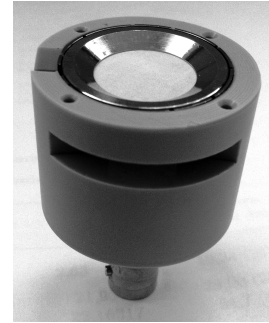


FIG. 2. View of the source holder.

IV. DESIGN OF SI ELECTRON SPECTROMETER

A. Physical description

As we can see in Fig. 3 and Fig. 4 there are three gate valves, hence the detector chamber remains under constant vacuum. When the experimental setup is cooled we readily reach an ultra high vacuum of about 10^{-7} mbar. During the change of the source, the gate valves of the cross are closed and the linear feed-through, below the cross, can be removed. On its top, the source holder (Fig. 2) is attached which can be easily removed in order to use another source. Two vacuum gauges, one behind the detection chamber and the other at the cross, permanently monitor the vacuum. The linear feed-through has a range of 152 mm, thus one can study spectral deformation as a function of the source-detector distance. A detector holder in copper, attached to the cold finger from the dewar, is used to uniformly cool the detector. Two basic electrical wires - one to carry information and to polarise the detector, the second one to ground the detector - are connected from the detector to an electrical feed-through located on top of the detection chamber. This electrical feed-through uses a microdot-BNC connector. On the other side, a preamplifier is directly plugged to this connector, which ensures a minimum distance between the detector and the preamplifier, hence minimizing the capacitance.

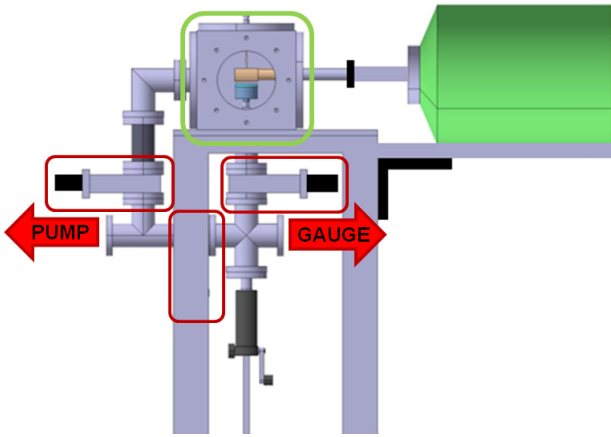


FIG. 3. Technical drawing of the beta spectrometer. Gate valves are indicated by the red circles and the detection chamber is indicated by the green circle.

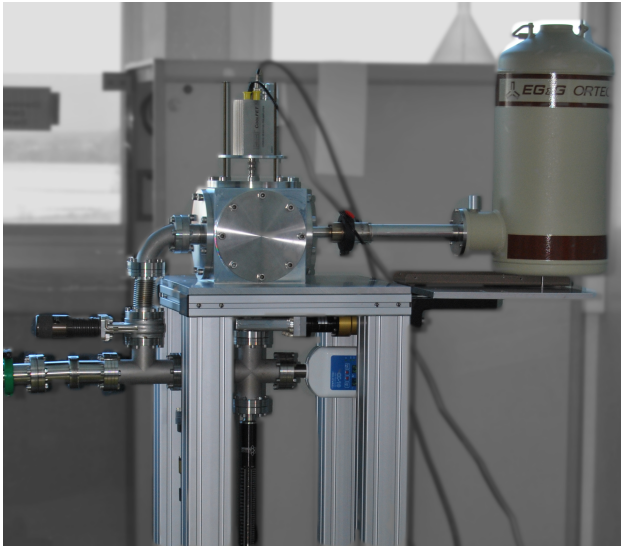


FIG. 4. Picture of the experimental setup.

B. Electronics

The electronics system is a classic spectrometry chain composed of a preamplifier connected to a high voltage device, an amplifier and a multichannel analyzer. The detector is a PIPS (Passivated Implanted Planar Silicon) manufactured by Canberra. The main advantages of this technology for our application are a very thin entrance window of 50 nm Si equivalent and a low leakage current. The energy-loss of electrons in 50 nm of silicon is about 1.2 keV (see e.g. range tables in PENELOPE [7]). Given the dead layer, the electronic noise and the resolution, the cutoff in energy of the PIPS detector is about 10 keV. The detector is 500 μm thick and has an active surface area of 450 mm^2 . Electrons having an energy of 320 keV have a range of 500 μm in silicon. Hence with the PIPS detector, we plan to measure spectra with an

end-point lower than 350 keV. The first stage of the electronics system, as close as possible to the detector, is an Amptek “CoolFET” charge sensitive preamplifier cooled by the Peltier effect. The preamplifier must be kept stable, and we observed a significant decrease in the signal-to-noise ratio when it was not positioned correctly. There are then two NIM ORTEC modules; a linear amplifier and an ADC for pulse processing and shaping. The settings (gain, shaping time, P/Z Cancellation, ADC LLD and zero ADC) of the NIM modules must be such as to find the best trade-off between the counting rate and the resolution. Finally, we use the MAESTRO spectrometry software for recording and analyzing our spectra.

V. MEASUREMENTS

A. ^{109}Cd source calibration

As an initial test we have measured the spectrum of a ^{109}Cd source, which emits mono-energetic conversion electrons (Table II) that appear as sharp peaks in the spectrum (Fig. 5). To check the influence of the temperature of the detector, two spectra were acquired with and without liquid nitrogen cooling. As expected, the energy resolution increases with temperature. At 300 K, the full width at half maximum (FWHM) is about 8 keV, while at 77 K it is about 5 keV. We believe the resolution may yet improve, compared to these preliminary spectra, if we can further optimize our electronics system settings. The response function for this energy range seems to be approximately linear. Monte Carlo calculations are still in progress in order to complete the analysis.

TABLE II. Evaluated data for the emitted electrons that follow the electronic capture (EC) in the ^{109}Cd decay [8].

$^{109}_{48}\text{Cd}$		$T_{1/2}$	\rightarrow	$^{109}_{47}\text{Ag}$	
Electrons					
Energy (keV)	Intensity (%)			Type	Origin
21.7	20.6			Auger K	Ag-109
62.52	40.8			ec K	Ag-109
84.46	44.8			ec L	Ag-109
87.67	9.28			ec M	Ag-109

B. ^{36}Cl

A preliminary measurement of a ^{36}Cl source was carried out. The radioactive material was deposited on an ion-exchange resin. As expected, the electrons of high energy that go through of our 500 μm thickness detector induce a folding of the spectrum, *i.e.* only a fraction of the energy of the electrons is deposited in the active volume of the detector resulting in an overcounting at low energy and an undercounting at high energy. The realistic geometry of the experimental

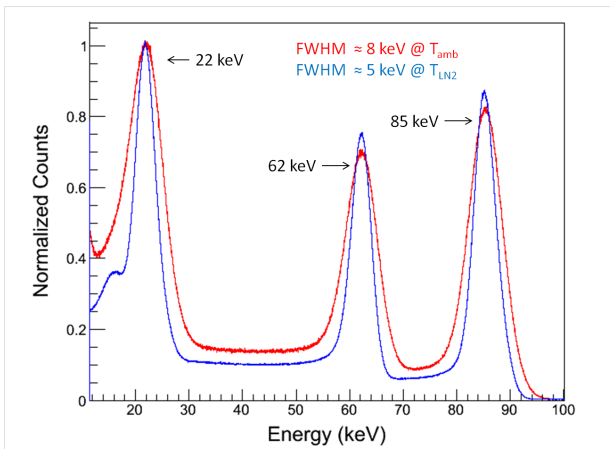


FIG. 5. Measured conversion electron spectrum following the EC decay of ^{109}Cd . Spectra were measured with the PIPS detector at room temperature (red curve) and liquid nitrogen temperature (blue curve). The 85 keV peak is a mixture of the L and M conversion electrons (see Table II).

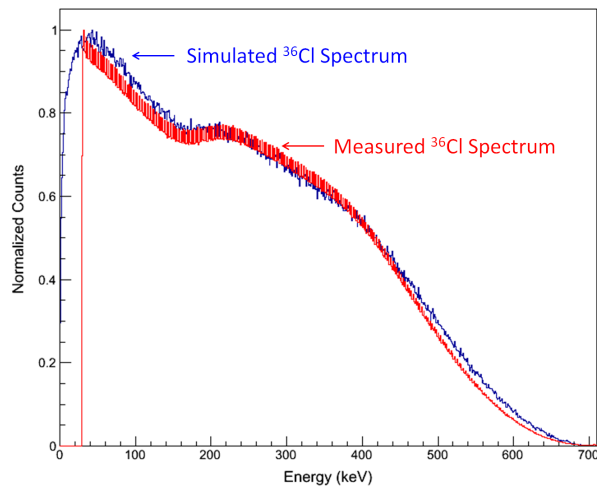


FIG. 6. Comparison between the ^{36}Cl measured and simulated beta spectra. The data were adjusted using an approximate linear energy calibration.

setup was implemented in our simulations. We used the

experimental shape factor extracted from the measurement of Rotzinger *et al.* [9] for the primary emitted beta spectrum. The data were adjusted using an approximate linear energy calibration. As shown in Fig. 6, our simulation reproduces well the main distortion of the measured spectrum. A complete and careful study of the detector response function will provide a precise energy calibration and should improve the agreement with our simulation.

VI. CONCLUSION

Our experimental setup, dedicated to measuring the shape of beta spectra, is finalized and initial measurements have been carried out with success. Some distortion, due to the detection system, persists in the measured spectra but owing to the important development and simulation work, we should be able to characterize and quantify this with our Monte Carlo simulations. The next step will be to precisely study the response function of the detector in order to determine an experimental distortion function. Then we will carry out a series of measurements of well-known spectra to validate our benchmark. Finally, we will focus on unique and non-unique forbidden beta spectra to validate our code BETASHAPE. This particular setup is well suited for measuring beta spectra with a maximum energy of about 350 keV. It is also easily adjustable to a 5 mm thick Si(Li) detector, for measuring beta spectra up to about 2.5 MeV.

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