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New Measurements of Photoneutron Spectra investigating specific signatures of Carbon, Nitrogen, and Oxygen

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ABSTRACT

We report new measurements on photoneutron spectra from graphite, glucose, and melamine, revealing distinct signatures corresponding to carbon, oxygen, and nitrogen individual elements. Using a 23-MV electron linear accelerator (LINAC) and EJ-309 liquid scintillators with advanced pulse shape discrimination and pile-up rejection algorithms, we successfully detected fast neutrons from photo-nuclear (γ, Xn) reactions within an intense pulsed photon field. Energy deposition from fast neutrons was unfolded using two well-known independent algorithms ML-EM and GRAVEL. Our findings indicate discrepancies between the experimental results and Monte-Carlo simulations performed with the widely-used code MCNP6, highlighting the need for new data in order to improve the models used for the simulation of photoneutron production. These results have significant implications for various nuclear physics applications, including electron accelerator facilities decommissioning, illicit material detection for homeland security, and global radiotherapy patient dosimetry including neutron dose.

KEYWORDS: Neutron Spectrometry, Organic Scintillator, LINAC, Giant Dipole Resonance, Monte-Carlo Simulations

I. INTRODUCTION

Photoneutron energy spectra, especially those produced in reactions on light elements such as carbon, oxygen and nitrogen, remain inadequately characterized, despite their critical importance in various applications as pointed out in a previous work related to Monte-Carlo codes benchmark [1]. Activation and decommissioning of electron accelerator facilities, detection of illicit materials for homeland security and the assessment of neutron doses in radiotherapy treatments are

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38 nowadays very actual applications in which the photo-nuclear interactions eventually leading to
39 neutron productions are the dominant process.

40

41 In the field of nuclear security, high-energy photon interrogation using linear electron accelerators
42 (LINACs) operating around 9 MeV has played a pivotal role in detecting special nuclear materials
43 and characterizing nuclear waste. However, recent advancements in active photon interrogation
44 techniques above 12 MeV underscore the pressing need for precise photoneutron spectra data [2].
45 Understanding these spectra—particularly the signatures of carbon, nitrogen, and oxygen—is
46 essential, as these elements are key components of materials such as explosives, narcotics, and
47 chemical agents representing significant security threats.

48

49 Also, in medical applications photo-nuclear reactions induced by Bremsstrahlung photons in
50 LINAC facilities not only contribute to patient global dosimetry and affect accelerator components
51 but also influence facility decommissioning and radioactive waste management [3]. Regulatory
52 authorities and waste-management operators increasingly demand accurate characterization of
53 generated radioactive waste to ensure appropriate management strategies.

54

55 Despite the crucial importance of photoneutron spectra, existing data are sparse and outdated,
56 limiting the accuracy of Monte-Carlo simulations in modelling these interactions. The absence of
57 precise experimental measurements hampers the development of reliable predictive models for
58 photoneutron production for applications simulations.

59

60 To address these challenges, this study presents novel measurements of photoneutron energy
61 spectra from light-element targets established for the first time by proton recoil detection. By
62 employing a 23-MV electron LINAC and EJ-309 liquid organic scintillators with advanced pulse
63 shape discrimination and pile-up rejection algorithms, we unfold and analyse the photoneutron
64 energy spectra from graphite (C), glucose (C₆H₁₂O₆), and melamine (C₃H₆N₆) targets. These
65 targets, chosen for their carbon, oxygen, and nitrogen content, serve as benchmark for investigating
66 photo-nuclear interactions, particularly within the giant dipole resonance (GDR) region.

67

68

II. EXPERIMENTAL PROCEDURE

69

A. Photon source based on a medical linear electron accelerator

70 The measurements were performed using a Varian TrueBeam medical linear electron accelerator
71 at the Doseo platform of CEA in Saclay (France). This accelerator primarily designed for
72 radiotherapy applications, operates with a maximal energy estimated at 22.9 ± 0.7 MeV.
73 Modifications detailed in Ref. [4] were applied to optimize the accelerator's operating regime to
74 fulfil our specific experimental needs. The accelerated electron beam interacts with an internal
75 electron-to-photon conversion target inside the accelerator head producing Bremsstrahlung
76 photons as shown on Figure 1. The photon field, characterized by a typical Bremsstrahlung
77 spectrum with a maximum energy of 23.6 MeV, spans an area of 40×40 cm² measured at one

78 meter from the exit of the accelerator's vacuum section. The accelerator produces electron pulses
79 lasting 3–4 μs , with a pulse frequency ranging from a few to 360 Hz.

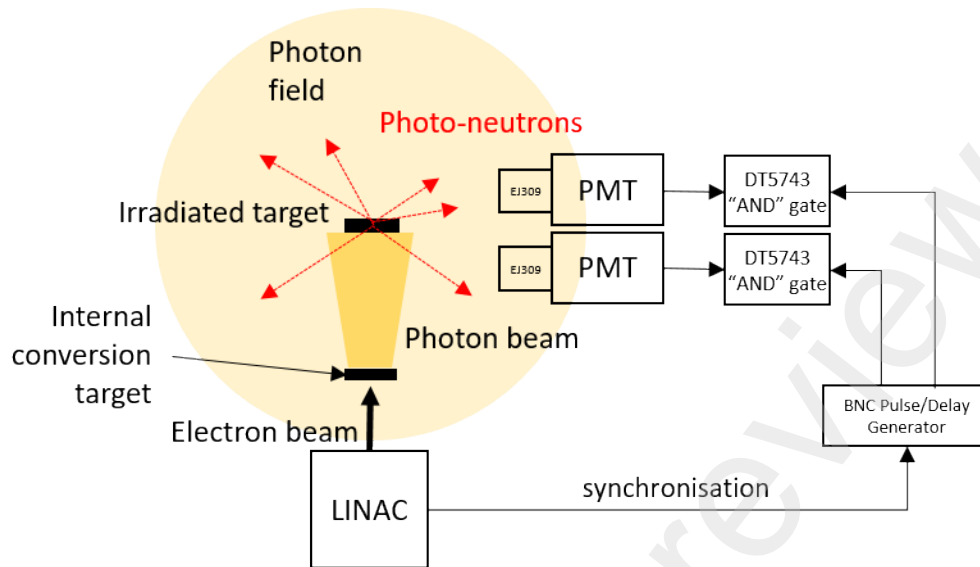
80 **B. Neutron detector set-up and data acquisition**

81 The neutron measurements were carried out using two organic liquid scintillators (EJ-309), housed
82 in cylindrical cells with a diameter and height of 5.08 cm. Each scintillator is mainly composed of
83 xylene (>90%) as the solvent and aromatic fluorine (<10%) as the solute, with a density of 0.964
84 g/cm^3 . The EJ-309 scintillators share similarities with well-established detectors such as BC501A,
85 NE213, and EJ-301, offering excellent neutron-photon pulse shape discrimination (PSD) in mixed
86 radiation fields. A key feature of EJ-309 is its fast decay time of 3.2 ns, which is crucial for
87 handling the high photon flux produced during LINAC pulses.

88
89 The two detectors were placed inside a detection cell with 30 cm thick walls, constructed from
90 high-density polyethylene (HDPE) to shield against contaminating neutrons from the accelerator.
91 A window facing the irradiated targets allows the detection of photoneutrons without obstruction.
92 Tungsten and lead bricks are included inside the cell to reduce photon flux reaching the detectors
93 in order to minimize their saturation related to the pulsed beam. Monte-Carlo simulations were
94 performed to confirm that the contribution of additional neutrons above 2 MeV produced in the
95 shielding materials was negligible compared to those emitted by the irradiated targets. The
96 detection cell was positioned at an angle of 90° relative to the beam direction to decrease as much
97 as possible its exposure to the main photon beam, which is mainly forward directed.

98
99 The detection system uses Hamamatsu R329-02 photomultiplier tubes (PMTs), operated at
100 -950 V, chosen for their fast response time with a 2.6 ns anode pulse rise time. Signal acquisition
101 was managed using a CAEN DT5743 digitizer for each detector, operating at a 3.2 GHz sampling
102 frequency, with an input range of ± 1.25 V and 12-bit resolution. The acquisition system was
103 synchronized with an external trigger signal generated by the Varian TrueBeam accelerator,
104 processed through a counter-timer module. This setup allowed precise control of the signal length
105 and delay, ensuring synchronization with the accelerator pulses. An AND gate was applied via
106 CAEN WaveCatcher software to select events occurring within a predefined time window. More
107 details can be found in the previous work described in Ref. [4].

108



109

110 Figure 1. Schematic view of the experimental set-up.

111 C. Detectors calibration, response function and unfolding methodology

112 The EJ-309 scintillators were calibrated using both photon sources and mono-energetic neutron
 113 beams. Photon calibration involved determining conversion factors from integrated pulses (in
 114 V·ns) to MeVee (mega-electron-volt electron equivalent) by analysing the Compton edges
 115 corresponding to various photon sources and it was performed twice: first under standard
 116 laboratory conditions and then at the Amade neutron beam facility [5]. This allowed to account
 117 for the attenuation effect due to the 50-meter cable used during calibration with neutrons and
 118 consequently associated correction to be applied.

119

120 Neutron calibration further allowed to convert the deposited energy (in MeV) to MeVee, ensuring
 121 accurate energy deposition measurements. Figure 2 presents the neutron calibration curve obtained
 122 for detectors exposure to mono-energetic neutron beams. Our calibration curve is compared to
 123 those for similar liquid scintillator detectors reported in Refs. [6] and [7] demonstrating
 124 consistency in the established calibration data.

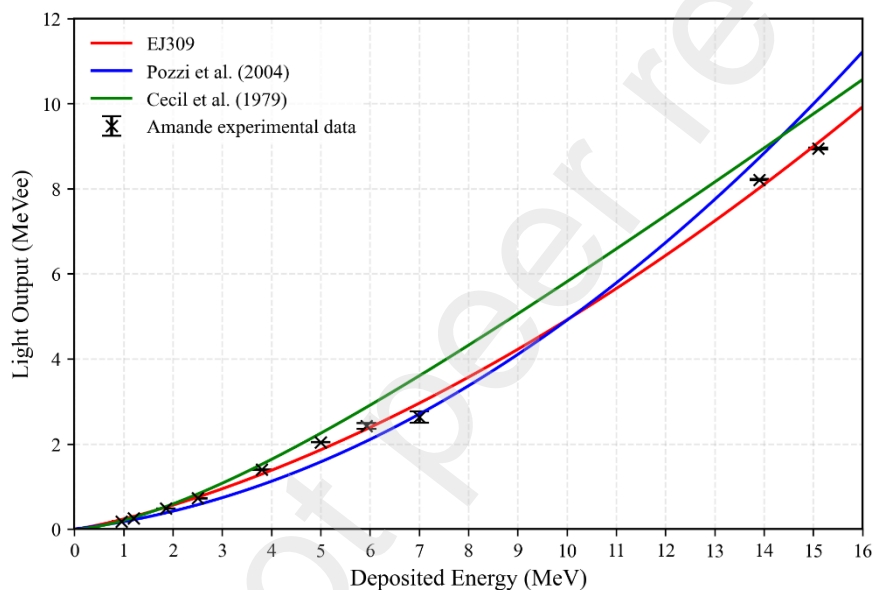
125

126 The response matrix of the detectors was simulated using the Monte-Carlo code Geant4 [8], with
 127 the NRESP7 option activated to include multi-step reactions in the scintillating material [9]. This
 128 response matrix played a key role in accurately unfolding the photoneutron spectra using two
 129 robust algorithms: Maximum Likelihood-Expectation Maximization (ML-EM) [10] and GRAVEL
 130 [11], the latter being based on a non-linear iterative least squares method. These algorithms were
 131 chosen for their proven effectiveness in extracting true neutron energy spectra from the measured
 132 data.

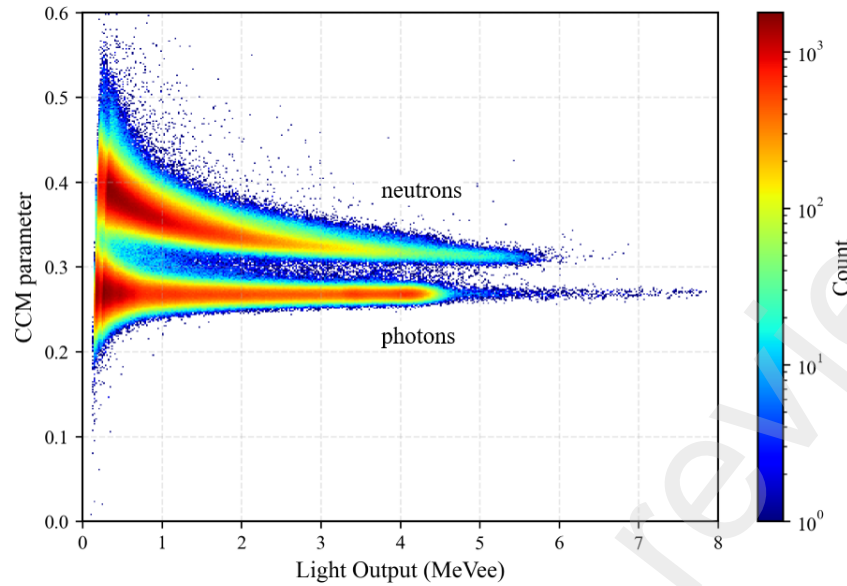
133

134 Classical pulse shape discrimination (PSD) techniques based on the charge comparison method
135 (CCM) were applied to distinguish between neutron and photon events. An example of the PSD
136 performance of our method is shown in Figure 3 for the Am-Be source. The FoM (Figure of Merit)
137 value for this example was 1.5 at 1 MeVee.
138

139 To further validate our unfolding methodology, we compared our unfolded neutron spectrum for
140 the Am-Be source with the reference one provided by the ISO-8529 standard [12]. Figure 4
141 illustrates this comparison, highlighting the close agreement and thus confirming both the accuracy
142 and global robustness of our method, particularly in the region of fast neutrons, and the accurate
143 calibration of our detector.

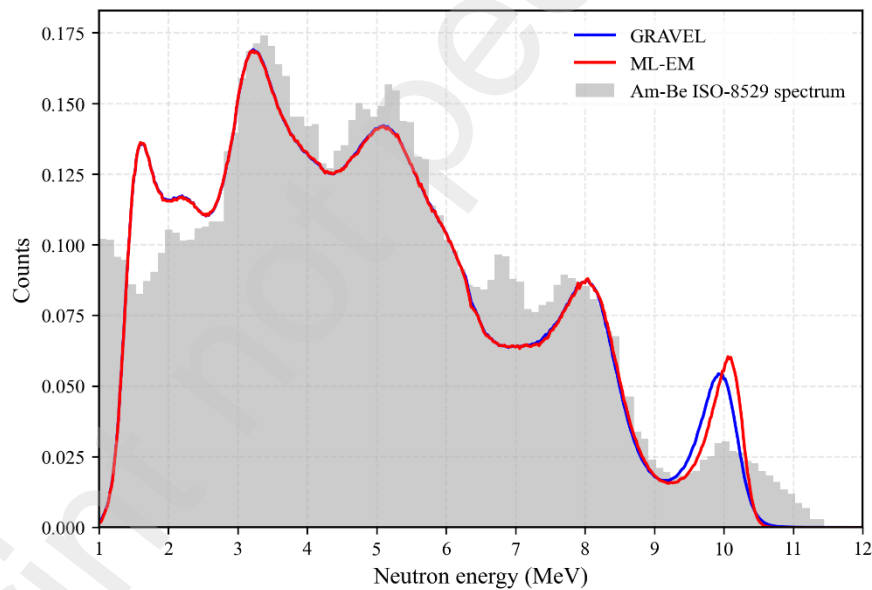


144
145 Figure 2: EJ-309 detector calibration curve obtained in this work using mono-energetic neutrons
146 (in red) compared with data from the literature.



147

148 Figure 3: Pulse shape discrimination scatter-density plot for neutrons and photons obtained with
 149 the Am-Be source.



150

151 Figure 4: Comparison between the unfolded Am-Be neutron spectrum obtained in this work using
 152 two algorithms (300 iterations each) and the reference values from the ISO-8529 standard
 153 (histogram).

154 **D. Target materials**

155 To investigate the photoneutron energy spectra and individual elements signatures, we selected
 156 graphite, glucose, and melamine as target materials. Each target was chosen for its elemental
 157 composition allowing to provide distinct signatures for carbon, oxygen, and nitrogen. All targets

158 were irradiated at a distance of 1 meter from the accelerator's exit point, fully exposed to the $40 \times$
159 40 cm^2 photon field.

160 **1. Graphite target**

161 The graphite target, with the chemical formula C, was used to study carbon signatures. It consisted
162 of a solid block with dimensions of $30 \times 30 \times 30 \text{ cm}^3$. The homogeneous, high-density nature of
163 graphite makes it an ideal candidate for photoneutron studies involving carbon.

164 **2. Glucose target**

165 The glucose target, with the chemical formula $\text{C}_6\text{H}_{12}\text{O}_6$ was chosen to explore oxygen signatures.
166 This target was in powder form with a total mass of 10 kg contained by a bucket with 1 mm-thick
167 plastic walls, enough to ensure uniform irradiation and target integrity during the experiment while
168 minimizing any additional photoneutron production.

169
170 **3. Melamine target**

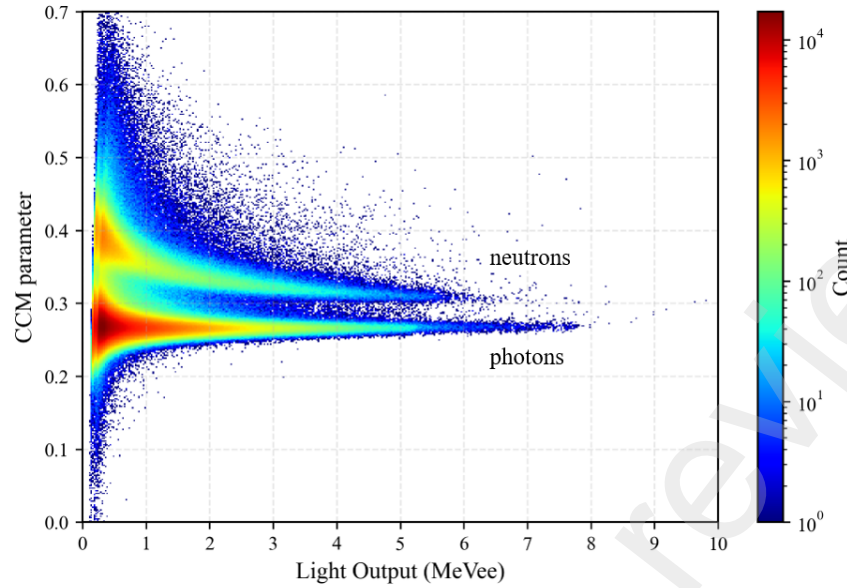
171 The melamine target, with the chemical formula $\text{C}_3\text{H}_6\text{N}_6$, was selected to investigate nitrogen
172 signatures. As for the glucose target, melamine in powder form with a total mass of 10 kg was
173 housed in a bucket of the same type.

174
175 **III. RESULTS AND DISCUSSION**

176 **A. Photoneutron spectra from irradiation of graphite, glucose, and melamine**
177 **targets**

178 PSD results for both detectors are cumulated in a single scatter density plot after applying the
179 appropriate calibration to both individual detectors. The method for selecting neutron pulses to
180 construct the recoil proton spectrum and unfold it to obtain the neutron spectrum was the one
181 previously described in the subsection II.C. An example of scatter density plot for the melamine
182 target is given in Figure 5. The FoM value achieved here was 1.25 at 1 MeVee demonstrating the
183 effectiveness of traditional PSD methods even when dealing with complex experimental
184 conditions specific to electron accelerators, characterized by pulsed and mixed neutron/photon
185 radiation fields with high photon fluxes. The corresponding photoneutron spectra obtained from
186 the graphite, glucose, and melamine targets are presented in Figures 6, 7, and 8, respectively.

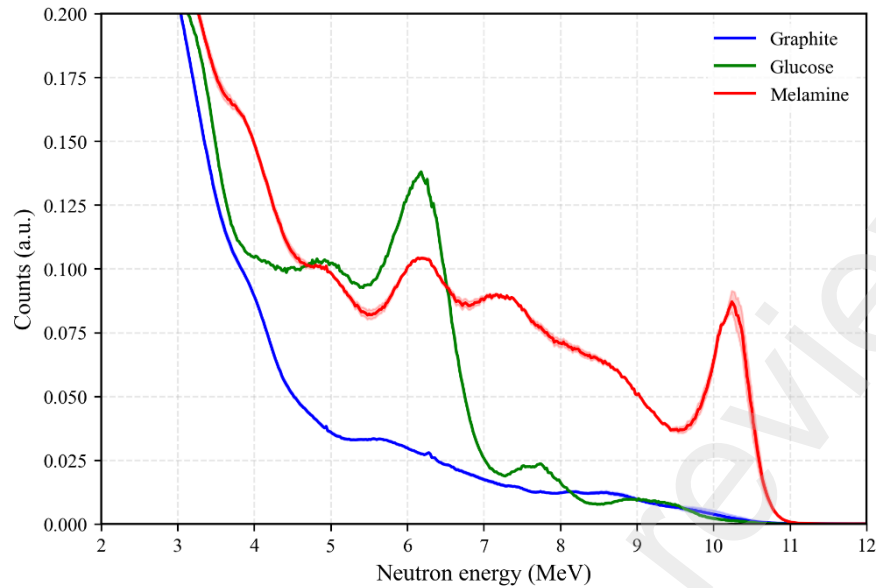
187



188
 189 Figure 5: Pulse shape discrimination scatter-density plot for neutrons and photons for the
 190 melamine target irradiation.

191
 192 The solid lines shown in these figures correspond to the average values of the spectra unfolded
 193 with the two algorithms ML-EM and GRAVEL. The shaded area, mainly visible at high energies
 194 in the spectrum from the melamine target, is determined as the difference between these two
 195 spectra.

196 Neutron energy distributions resulting from (γ, Xn) reactions on each target material were so
 197 determined experimentally. As it will be discussed in the next section, their detailed analysis
 198 subsequently allows the identification of specific signatures corresponding to the individual
 199 elements carbon, oxygen, and nitrogen. As expected according to the composition of the respective
 200 target materials irradiated, the graphite target primarily highlights the carbon specific signatures,
 201 while the glucose target reveals oxygen signatures and the melamine target exhibits signatures
 202 from nitrogen.



203
 204 Figure 6: Experimental photoneutron spectra from the irradiation of the graphite, glucose and
 205 melamine targets.

206 **B. Carbon specific signature in the photoneutron spectrum from graphite**
 207 **target**

208 The neutron spectrum measured with the carbon target (blue curve in Figure 6) is not background-
 209 subtracted, as it almost corresponds to the photoneutron background from the surrounding
 210 environment (including contributions from the accelerator, detector shielding, and the bunker).
 211 This is due to the fact that carbon from the target emits very few photoneutrons since the Q-value
 212 of the $^{12}\text{C}(\gamma, n)^{11}\text{C}$ reaction is very high at -18.7217 MeV and so its threshold is only slightly below
 213 the highest energy (23.6 MeV) of photons produced by the accelerator during our experiments.

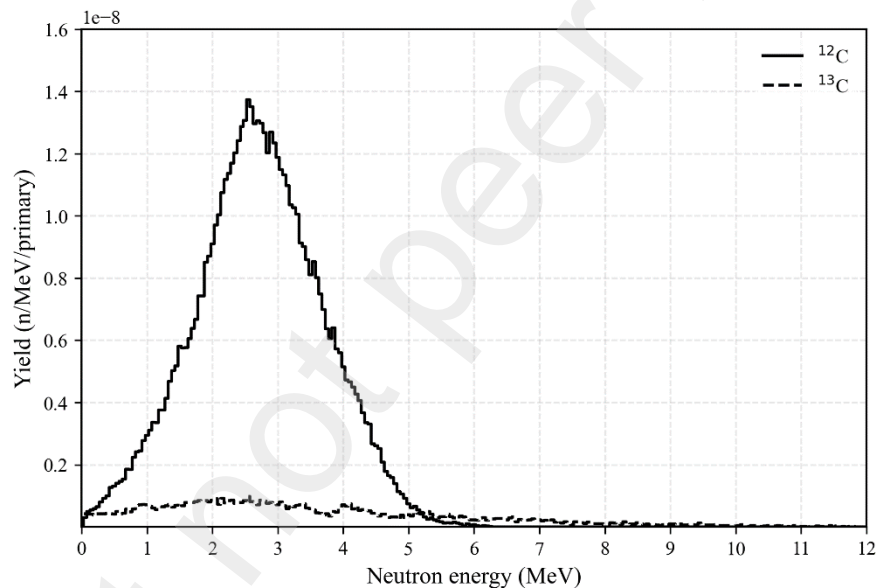
214
 215 Monte-Carlo simulations using the MCNP6.2 code reproducing the experimental configuration
 216 were performed allowing to calculate the contributions from photo-nuclear reactions on ^{12}C and
 217 ^{13}C separately as shown in the resulting spectra given in Figure 7. It must be reminded that ^{13}C
 218 accounts for approximately 1.1% in the graphite natural composition which explains its lower
 219 contribution to the total photoneutron production. The contribution from ^{12}C has a maximum
 220 slightly below 3 MeV, the photoneutron emission probability rapidly decreasing afterwards.
 221 Around 5 MeV the contribution from ^{13}C becomes dominant, resulting in a noticeable change in
 222 the spectral slope. This change is consistent with the experimental spectrum for the carbon target
 223 from Figure 6, where a similar change in the shape of the photoneutron energy distribution is
 224 observed around the same energy.

225
 226 This behaviour is explained by the reaction kinematics, since the maximum electron energy from
 227 our accelerator is 23.6 MeV and so is the maximum energy of the photons it produces and being
 228 used for the irradiations performed in this work. This limits the maximum possible photoneutron

229 energy from $^{12}\text{C}(\gamma,n)^{11}\text{C}$ reaction to 4.9 MeV, considering the photo-nuclear reaction threshold as
230 discussed above. This corresponds to the energy value at which the slope change is observed in
231 the measured photoneutron spectrum. The more energetic neutrons can thus only be produced by
232 photo-nuclear reactions on ^{13}C , since in this case the Q-value is much lower at -4.9463 MeV. The
233 photoneutron distribution from this later reaction extends up to 10 MeV, although even more
234 energetic neutrons can theoretically be emitted but they were not evidenced experimentally by our
235 measurements.

236

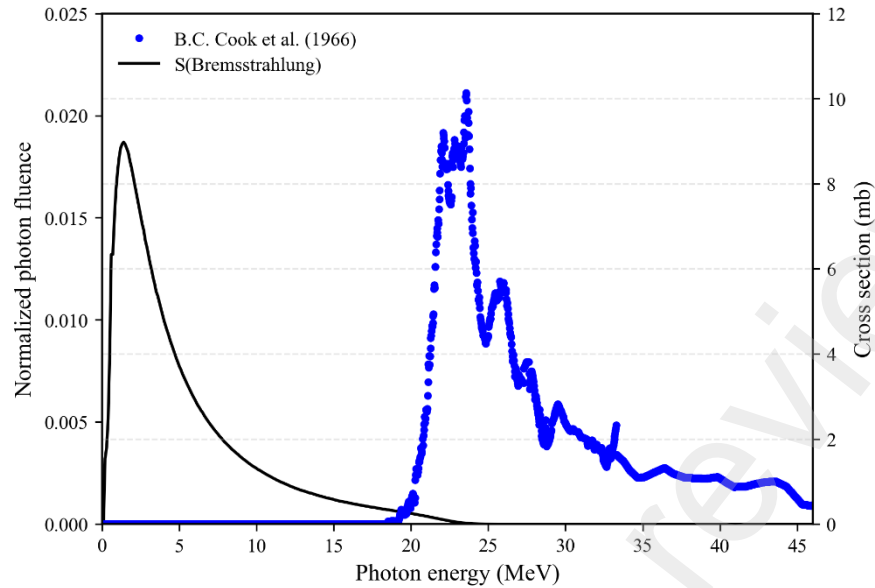
237 The overall shape of the simulated spectrum is in agreement with the theoretical one $\sigma(\gamma,n)I(E_\gamma)$
238 , 23) shown in Figure 9. The later was deduced by folding the Bremsstrahlung spectrum $I(E_\gamma, 23)$
239 for a 23 MeV electron beam corresponding to our accelerator with the experimental $\sigma(\gamma,n)$ cross-
240 section values from Cook et al. [13]. The agreement found confirm that the photoneutron emission
241 process is occurring as expected, predominantly leaving the ^{11}C residual nucleus in its ground state
242 (Figure 8).



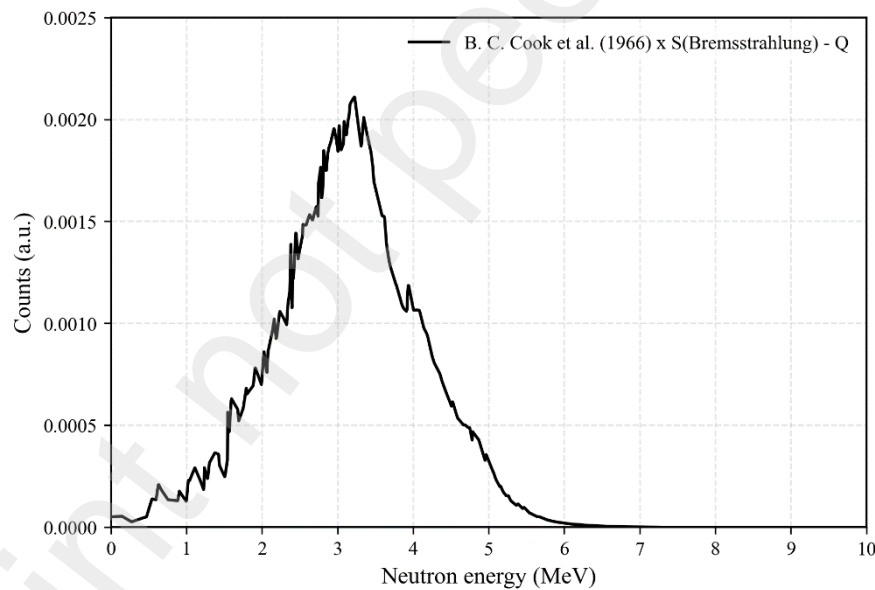
243

244 Figure 7: MCNP6.2 simulated photoneutron spectrum for graphite irradiation with the

245 Bremsstrahlung photons corresponding to our accelerator.



246
 247 Figure 8: Experimental cross-sections from Cook et al. [13] and the Bremsstrahlung spectrum $I(E_\gamma, 23)$
 248
 249



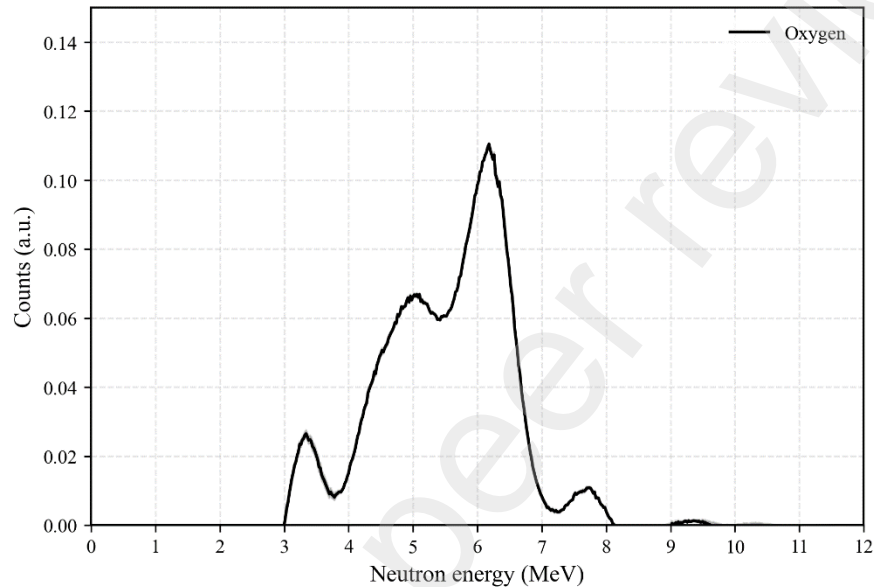
250
 251 Figure 9: Calculated theoretical photoneutron spectrum $\sigma(\gamma, n)I(E_\gamma, 23)$ corresponding to ^{11}C
 252 residual nucleus in its ground state.

253 C. Oxygen specific signature in the photoneutron spectrum from glucose target

254 The level density of ^{16}O is relatively low because it is a doubly magic nucleus. In the $^{16}\text{O}(\gamma, n)$
 255 reaction, the residual nucleus ^{15}O also has a low level density, with its first excited state appearing
 256 at 5.183 MeV [14]. The emission of one neutron in the (γ, n) photo-nuclear reaction will leave the
 257 resulting residual nucleus ^{15}O either in its ground state or in an excited state.

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To isolate the contribution of photo-nuclear reactions on oxygen from the total spectrum measured during glucose irradiation, we subtracted from it the spectrum obtained from the irradiation of the graphite target presented in the previous section. As it has been discussed, few neutrons from this spectrum are produced by photo-nuclear reactions on carbon but most of them are representing the background present in the experimental hall during the irradiations. The resulting spectrum is given in Figure 10 and allows to reveal the distinct signatures of the oxygen present in glucose, namely 3 peaks at 3.5, 5 and 6 MeV respectively.



266
267
268

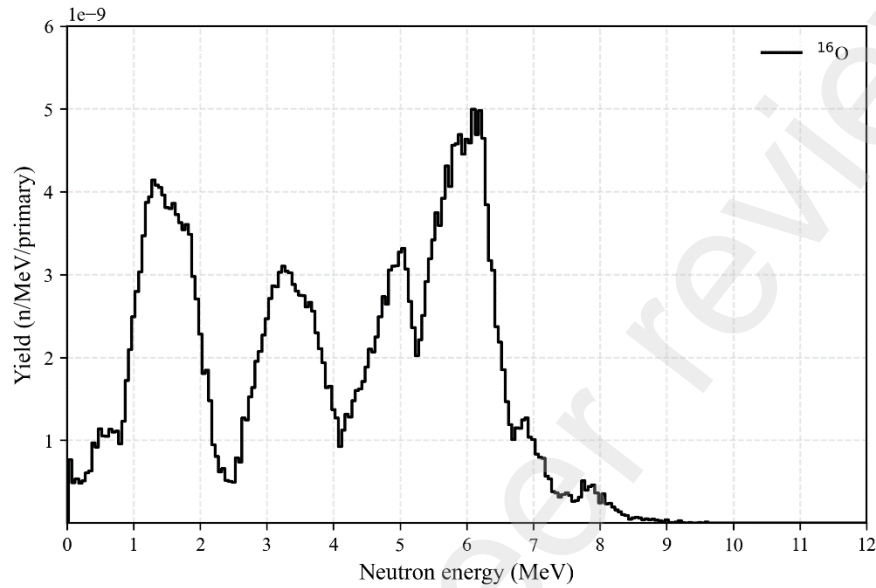
Figure 10: Experimental photoneutron spectrum from photo-nuclear reactions on oxygen.

269 Previous measurements of photoneutron spectra from ^{16}O were conducted in 1970 as described in
270 Ref. [15] using time-of-flight technique. One of the irradiations, performed with a Bremsstrahlung
271 spectrum with endpoint energy of 22.6 MeV, is sufficiently close to our experimental conditions
272 to allow a direct comparison. The previously measured neutron spectrum at an angle of 82°
273 exhibits notable structures between 3 and 4 MeV and pronounced peaks at 5 MeV and 6 MeV,
274 features that align closely with the experimental results reported in this work obtained using a
275 completely different detection technique based on proton recoil in scintillators. However, an
276 additional peak just below 2 MeV has also been reported but it is not confirmed by our data. This
277 discrepancy is likely due to the challenges associated with background subtraction in our
278 experimental set-up.

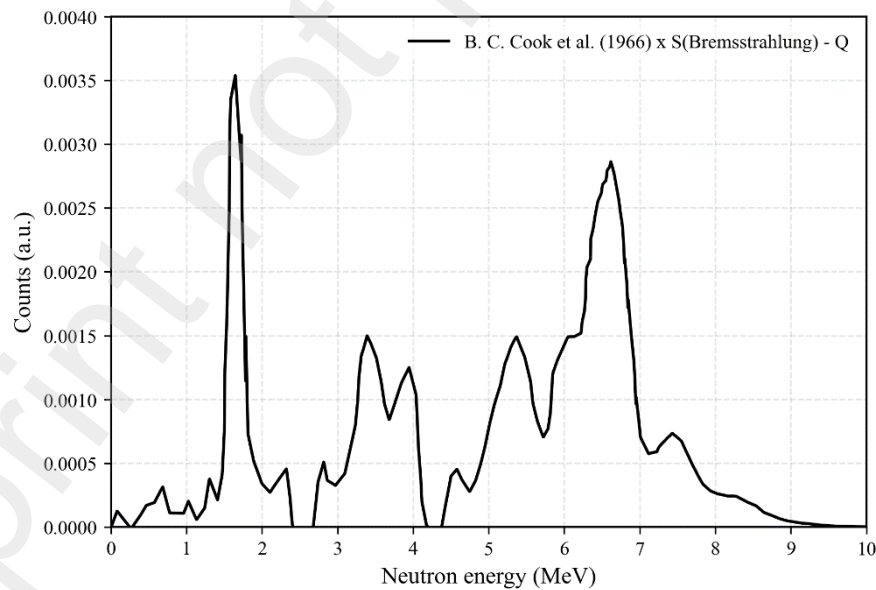
279

280 The MCNP6.2 simulated photoneutron spectrum for natural oxygen is shown in Figure 11. The
281 photoneutron production is almost exclusively associated to reactions on ^{16}O representing 99.7%
282 in oxygen natural isotopic composition. As in the case of carbon, the simulations agree well with
283 the theoretical spectrum $\sigma(\gamma, n)I(E_\gamma, 23)$ shown in Figure 12 and determined based on the
284 experimental $\sigma(\gamma, n)$ cross-sections from B.C. Cook et al. [16]. This agreement indicates that the

285 photoneutron emission predominantly leave the ^{15}O residual nucleus in its ground state. It is worth
286 noting that the structures present in the simulated spectrum are also globally confirmed by the
287 measurements reported in this work, except for the peak in the simulated spectrum below 2 MeV
288 which is not observed in our data due to background subtraction limitations.
289



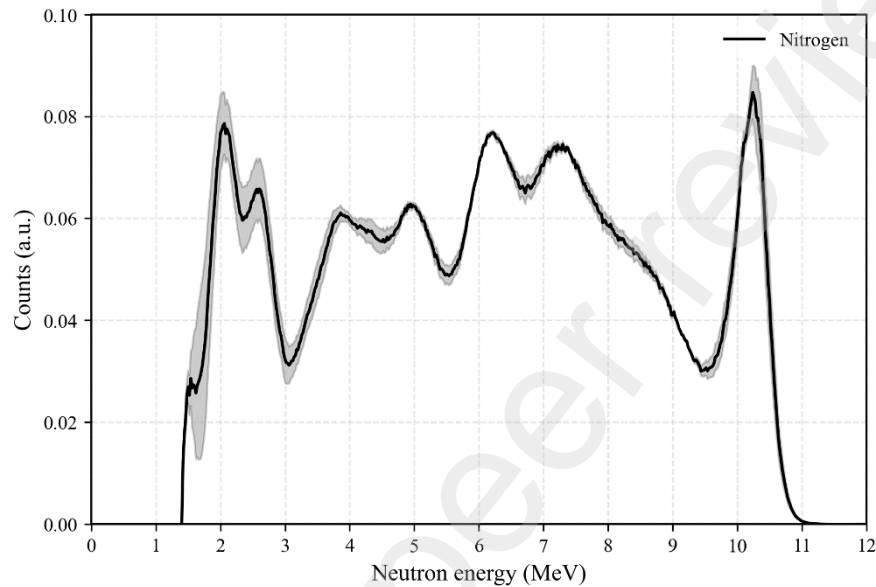
290
291 Figure 11: MCNP6.2 simulated photoneutron spectrum for oxygen irradiation with the
292 Bremsstrahlung photons corresponding to our accelerator.
293



294
295 Figure 12: Calculated theoretical photoneutron spectrum $\sigma(\gamma,n)I(E_\gamma, 23)$ corresponding to ^{15}O
296 residual nucleus in its ground state.
297
298

299 **D Nitrogen specific signature in the photoneutron spectrum from melamine**
300 **target**

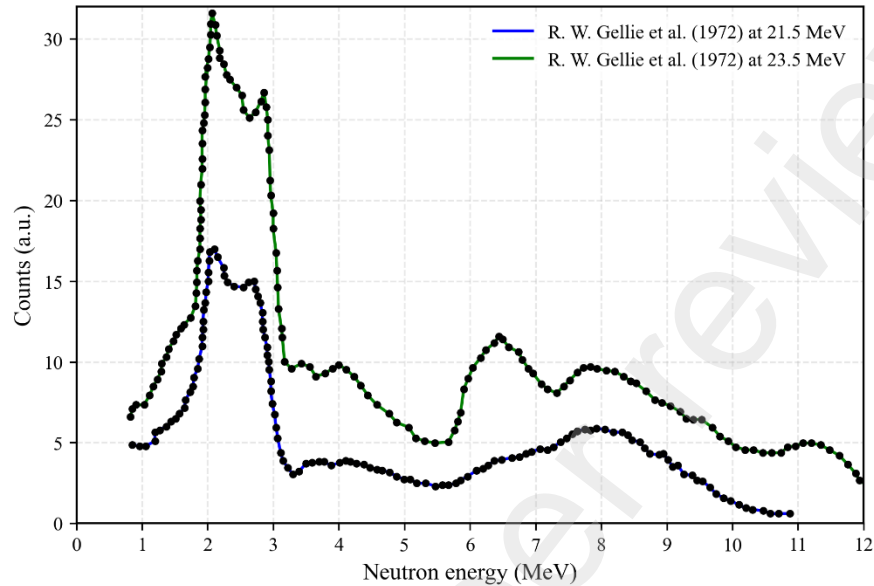
301
302 Melamine being made of hydrogen, carbon and nitrogen, the nitrogen specific signature in the total
303 measured photoneutron spectrum can also be isolated by subtracting the carbon contribution. The
304 results presented in Figure 13 reveal distinctive features in the spectrum, several peaks being
305 observed at energies of 1.9, 2.6, 4, 5, 6.3, 7.5 and 10.5 MeV respectively.



306
307 Figure 13: Experimental photoneutron spectrum from photo-nuclear reactions on nitrogen.

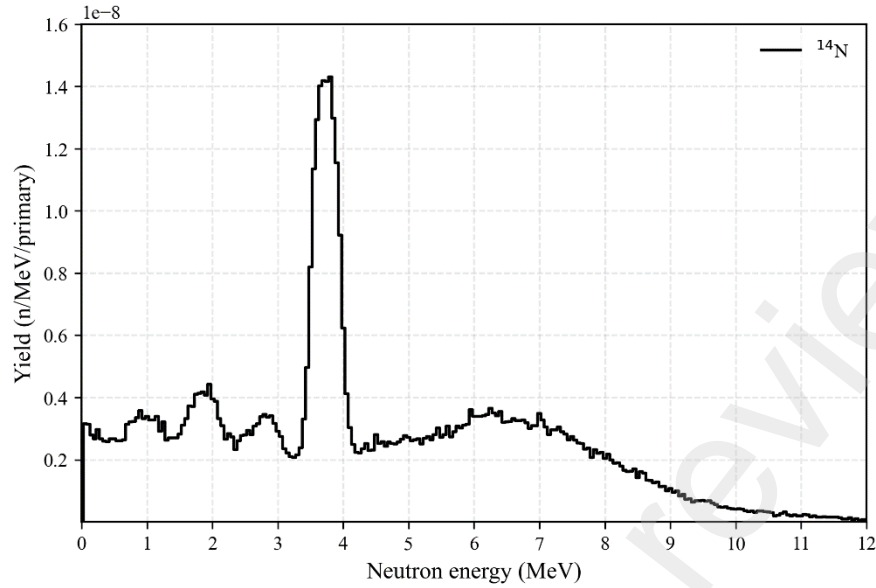
308
309 Historically, there have been very limited measurements of the photoneutron spectrum for
310 nitrogen. One notable study conducted by the National Research Council of Canada in the 1970s
311 used the time-of-flight method, as described in Refs. [17] and [18]. The reported results shown in
312 Figure 14 involved irradiating liquid nitrogen with Bremsstrahlung photons at endpoint energies
313 of 29.5, 27.5, 23.5, and 21.5 MeV. Despite the very different experimental approach used for the
314 photoneutron measurements, our results confirm most of the previously reported structures in the
315 nitrogen spectrum including peaks at 1.9 MeV and 2.6 MeV and a broader structure at 6.3 MeV.
316 Moreover, these structures were explained by the authors as being associated to a particular two-
317 step photo-nuclear reaction namely $^{14}\text{N}(\gamma, p)^{13}\text{C}^* \rightarrow ^{12}\text{C} + n$, leading first to the excitation by the
318 incident photons of the ^{14}N nucleus and the emission of a proton, followed by the deexcitation of
319 the remaining ^{13}C left in an excited state (at 7.55 MeV or 11.8 MeV) by the emission of a neutron.
320 Energy conservation allows to calculate the energy of photoneutrons emitted through these
321 mechanisms at around 3 and 4 MeV respectively for the two excited states of ^{13}C . This assessment
322 implies that the photoneutron energy is not influenced by the spectrum of the primary incident
323 photons, which can be assumed to be true as the reactions involved occur through an excitation-
324 deexcitation process in which the memory of the entry channel is typically almost completely lost.

325 Finally, the two remaining structures observed at the highest photoneutron energies (7.5 and 10.5
326 MeV) can be attributed to the direct photo-nuclear $^{14}\text{N}(\gamma,n)$ reactions leaving the residual ^{13}N in
327 the 3.51 MeV excited state and the ground state respectively.
328

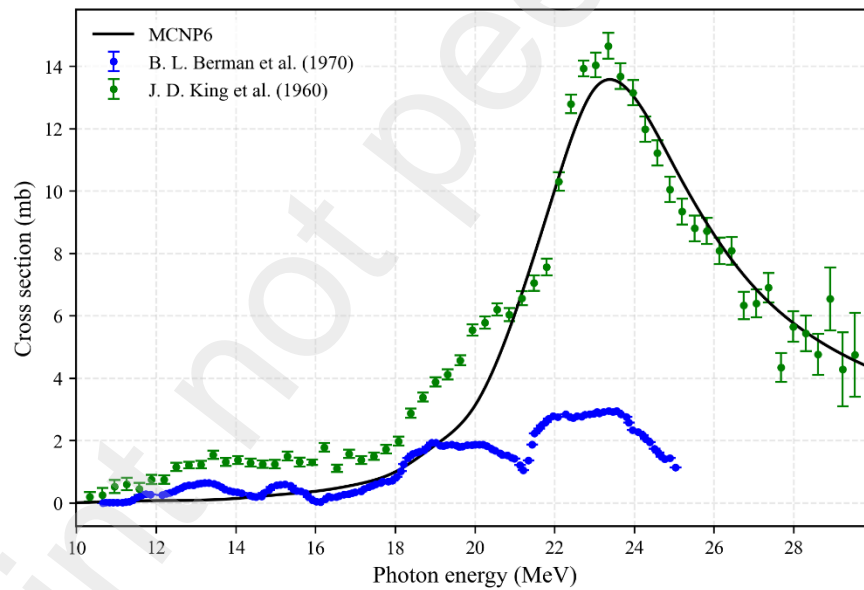


329
330 Figure 14: Photoneutron energy distributions from reactions on ^{14}N measured by R. W. Gellie et
331 al. [17] by time-of-flight.
332

333 Monte-Carlo simulations were performed using MCNP6.2 with a target of natural nitrogen (99.6%
334 ^{14}N and 0.4% ^{15}N). The simulation results, shown in Figure 15, reveal some similarities to the
335 measured spectrum, including a peak at 3.8 MeV, a broader structure between 6 and 7 MeV and
336 some others at lower energies. However, discrepancies are observed between the simulated and
337 experimental spectra suggesting the inaccuracy of the simulation, particularly consisting in
338 energies of the structures being shifted. This could be explained by an artificial inclusion in the
339 cross-section libraries used by MCNP6 of the photo-nuclear reactions, considering both direct (γ,n)
340 and wo-step (γ,pn) channels, probably based only on better fitting the experimental cross-section
341 values. Indeed, as it can be seen in Figure 16, MCNP6 simulations are able to reproduce accurately
342 the total photoneutron production cross-section showing a very good agreement with the data from
343 Ref. [19] concerning inclusive (γ,Xn) reactions, while being significantly higher than the data from
344 Ref. [20] which are limited to the single contribution of the (γ,n) reaction. The disagreement found
345 however when comparing the simulated energy distribution with the data reported in this work and
346 in Ref. [17] suggest that the above-discussed physics related to the (γ,pn) reaction is not properly
347 implemented in the code.
348



349
 350 Figure 15: MCNP6.2 simulated photoneutron spectrum for nitrogen irradiation with the
 351 Bremsstrahlung photons corresponding to our accelerator.
 352



353
 354
 355 Figure 16: Neutron production cross-sections for photo-nuclear reactions on ^{14}N calculated by
 356 MCNP6.2 and compared to the data from References [19] and [20] for (γ, X_n) and (γ, n) reactions
 357 respectively.
 358

359 IV. CONCLUSIONS

360
 361 We report in this paper the first measurements of neutron spectra from photo-nuclear reactions on
 362 graphite, glucose, and melamine performed using proton recoil scintillators, as opposed to former

363 studies based on time-of-flight methods. By employing a photon source based on a 23-MV linear
364 electron accelerator and advanced EJ-309 liquid scintillators, we successfully detected and
365 analysed fast neutrons from (γ, Xn) reactions on materials of interest for several actual applications
366 such as detection of illicit materials, radiotherapy treatments and induced activation for
367 decommissioning of electron accelerator facilities. This approach allowed the identification in the
368 detailed spectra of distinct signatures of carbon, oxygen, and nitrogen from the photo-nuclear
369 reactions in the giant dipole resonance energy region.

370
371 Our experimental results reveal unambiguous photoneutron signatures for each target material.
372 The graphite spectrum predominantly highlight carbon signatures, with contributions from both
373 ^{12}C and ^{13}C . The glucose and melamine photoneutron spectra exhibit in addition respectively the
374 oxygen and nitrogen signatures. These measurements provide valuable insights into the
375 photoneutron emission characteristics from reactions on light elements and represent a significant
376 advancement in improving the experimental techniques in this field.

377
378 The comparison between our experimental data and Monte-Carlo simulations with MCNP6.2 code
379 highlighted notable discrepancies in the case of nitrogen, indicating limitations in current cross-
380 section libraries used by the code. This emphasizes the need for improved models and data libraries
381 to enhance the accuracy of simulations for photoneutron production in the reactions on light
382 elements. This work allowed the identification of specific areas to be addressed for further
383 investigation and refinement in simulation practices, aiming to ensure more consistent agreement
384 with experimental data across different elements and conditions.

385
386 In the case of oxygen on the other hand the simulations are in good agreement with our data and
387 with measurements from previous studies, providing evidence for the reliability of our
388 experimental approach.

389
390 Overall, this study marks a significant advancement by providing new data on photoneutron
391 spectra measured with an original method using proton recoil scintillators. The improved
392 characterization of these spectra from the point of view of photo-nuclear reactions physics is
393 crucial for their better implementation in simulation tools, and by such and through specific
394 applications, for the refinement of nuclear security measures, for the optimization of radiotherapy
395 procedures and more generally for the increase of the reliability of simulations involving
396 photoneutrons. Future work should focus on addressing the identified discrepancies and expanding
397 experimental data to further advancements in this field.

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400
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