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**Citation for published version:**

Csedreki, L, Ciani, GF, Balibrea-Correa, J, Best, A, Aliotta, M, Barile, F, Bemmerer, D, Boeltzig, A, Broggini, C, Bruno, CG, Cacioli, A, Cavanna, F, Chillery, T, Colombetti, P, Corvisiero, P, Davinson, T, Depalo, R, Di Leva, A, Elekes, Z, Ferraro, F, Fiore, EM, Formicola, A, Fulop, Z, Gervino, G, Guglielmetti, A, Gustavino, C, Gyurky, G, Imbriani, G, Janas, Z, Junker, M, Kochanek, I, Lugaro, M, Marigo, P, Masha, E, Mazzocchi, C, Menegazzo, R, Mossa, V, Pantaleo, FR, Patichio, V, Perrino, R, Piatti, D, Prati, P, Schiavulli, L, Stockel, K, Straniero, O, Szucs, T, Takacs, MP, Terrasi, F & Zavatarelli, S 2021, 'Characterization of the LUNA neutron detector array for the measurement of the  $^{13}\text{C}(,n)^{16}\text{O}$  reaction', *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 994, 165081. <https://doi.org/10.1016/j.nima.2021.165081>

**Digital Object Identifier (DOI):**

[10.1016/j.nima.2021.165081](https://doi.org/10.1016/j.nima.2021.165081)

**Link:**

[Link to publication record in Edinburgh Research Explorer](#)

**Document Version:**

Peer reviewed version

**Published In:**

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

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# Characterization of the LUNA neutron detector array for the measurement of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction

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## Abstract

We introduce the LUNA neutron detector array developed for the investigation of the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  reaction towards its astrophysical  $s$ -process Gamow peak in the low-background environment of the Laboratori Nazionali del Gran Sasso (LNGS). Eighteen  $^3\text{He}$  counters are arranged in two different configurations (in a vertical and a horizontal orientation) to optimize neutron detection efficiency, target handling and target cooling over the investigated energy range  $E_{\alpha,\text{lab}} = 300 - 400$  keV ( $E_n = 2.2 - 2.6$  MeV in emitted neutron energy). As a result of the deep underground location, the passive shielding of the setup and active background suppression using pulse shape discrimination, we reached a total background rate of  $1.23 \pm 0.12$  counts/hour. This resulted in an improvement of two orders of magnitude over the state of the art allowing a direct measurement of the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  cross-section down to  $E_{\alpha,\text{lab}} = 300$  keV. The absolute neutron detection efficiency of the setup was determined using the  $^{51}\text{V}(p,n)^{51}\text{Cr}$  reaction and an AmBe radioactive source, and completed with a Geant4 simulation. We determined a  $(34 \pm 3)$  % and  $(38 \pm 3)$  % detection efficiency for the vertical and horizontal configurations, respectively, for  $E_n = 2.4$  MeV neutrons.

**Keywords:** Helium-3 counter, Low-background, Underground laboratory, Nuclear Astrophysics, Neutron

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## 1. Introduction

The  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  reaction is the dominant neutron source for the synthesis of the elements heavier than iron via slow neutron captures (the  $s$ -process) in thermally pulsing, low-mass AGB stars [1]. The relevance of this reaction for the synthesis of heavy elements and the most recent experimental studies are extensively illustrated in [2–6]. As underlined by [6], direct data in the low energy region are highly desirable to better constrain the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  astrophysical reaction rate. In order to measure the rapidly declining cross-sections in this energy region, a low neutron background and high neutron detection efficiency are needed.

Here, we introduce the LUNA neutron detector array, which has been developed for  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  reaction cross-section measurements at the underground LUNA 400kV accelerator [7] of the Laboratory for Underground Nuclear Astrophysics (LUNA) facility installed in the Laboratori Nazionali del Gran Sasso (LNGS), Italy.

The deep underground environment of the LNGS leads to a reduction of the natural neutron background by three orders of magnitude with respect to the surface [8, 9]. At this level, the intrinsic radioactivity of the detector and other nearby materials becomes the dominant source of background [10]. To constrain the astrophysical reaction rate, the measurement of the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  reaction cross-section ( $Q$  value = 2.216 MeV) needs to be performed at energies  $E_{\alpha,\text{lab}} < 400$  keV [6]. At these beam energies, emitted neutrons are in energy range  $E_n = 2.2 - 2.6$  MeV, given in laboratory coordinate system, considering also the counters position of the LUNA neutron array. Assuming a beam current of  $I_{\text{beam}} = 100 \mu\text{A}$ , the estimated neutron emission rate at these energies is as low as 1 neutron/hour. Therefore, our goal was to minimize the background counting rate and to optimize the absolute neutron detection efficiency ( $\eta_n$ ) of the LUNA neutron detector array in the neutron energy region of around 2.4 MeV.

In contrast to  $\gamma$ -ray spectroscopy, the determination of the neutron efficiency curve is challenging mainly due to the limited choices of sources with accurately known energy spectra and/or angular distributions (in the case of reactions) and in some cases the limited availability of accurately calibrated sources. A standard procedure is to employ radioactive sources ( $^{252}\text{Cf}$ , AmBe), which emit neutrons with a continuous energy spectrum, in combination with Monte Carlo simulations [2, 11, 12].

The efficiency curve can be complemented using nuclear reactions, e.g. the  $^{51}\text{V}(p,n)^{51}\text{Cr}$  reaction [13–16]. To constrain the uncertainty of efficiency determination, the design of neutron detection setup should be optimized to obtain an energy-efficiency relation as flat as possible along the energy range of interest [15].

This paper consists of the following sections: section 2 is devoted to the technical description of the neutron detector array; in section 3, the background characterization of the experimental setup is presented; section 4 describes the determination of the neutron detection efficiency, followed by an overview of the simulation in section 5; results are discussed in section 6.

## 2. Description of the neutron detector array

The detector array contains eighteen  $^3\text{He}$  filled proportional counters with stainless steel housing<sup>1</sup>. They are arranged in two concentric rings around the target chamber: twelve counters of 40 cm active length are located at a radius of 11 cm, and six counters of 25 cm active length are located at 6 cm radius. This configuration allows for a nearly  $4\pi$  solid angle coverage around the target. As  $^3\text{He}$  has a very high cross-section for capturing thermal neutrons through the  $^3\text{He}(n,p)^3\text{H}$  reaction ( $\sigma_{\text{Thermal}} = 5330$  barn,  $Q = 764$  keV), effective thermalisation of the emitted neutrons from the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  reaction is required. To achieve this, the counters are embedded in a high-density polyethylene (PE) moderator.

To measure the very low number of neutrons emitted at the lowest energies, the neutron detection efficiency, target handling, and active target cooling has to be optimized. Therefore, two detector geometries were designed for the experimental  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  campaign: in one configuration the counters positioned at 90 degrees to the beam axis and in the other the counters are positioned parallel to the beam (these two configurations are referred hereafter as “vertical” and “horizontal” setups, respectively, see figure 1) were used. Moreover, the distribution of the  $^3\text{He}$  counters was also optimized to maximize the efficiency at the energy of interest (around  $E_n = 2.4$  MeV).

The vertical setup was used with a “T”-shaped stainless steel target chamber composed of vertical and horizontal tubes with an outer diameter of 52 mm. The beam arrives along the horizontal tube of the chamber and impinges on the target mounted on a multi-stage,

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<sup>1</sup>Manufactured by GE Reuter-Stokes, Inc., model numbers RS-P4-0816-217 and RS-P4-0810-250. The nominal filling pressure is 10 atm.

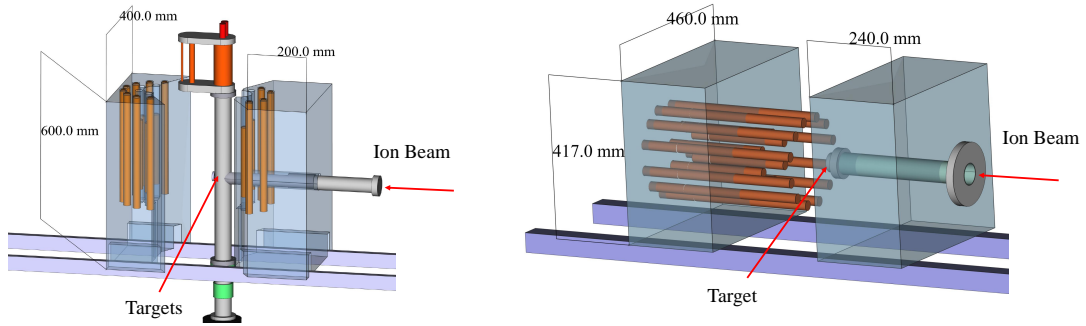


Figure 1: Vertical (left panel) and horizontal (right panel) setup of the LUNA neutron detector array. Dimensions of the moderators, target positions and beam direction are also indicated (see text for more details).

water cooled target holder with capacity for three targets installed in the vertical tube of the chamber. This minimizes possible contamination and simplifies the target changing procedure during the experiment. Moreover, the target holder could be extracted from the chamber without interfering with the moderator contributing to the stable condition of the setup.

In the horizontal setup, a single, water cooled target was mounted at the end of the horizontal tube (a diameter of 40 mm). This setup allows for a higher neutron detection efficiency and better cooling capacity, and was used for the low-energy measurements where detection efficiency was of particular importance. The moderator is divided vertically in two, movable section to allow for easy exchange of the target (see figure 1).

In addition, the moderator was surrounded with 25.4 mm (vertical configuration) and 50.8 mm (horizontal configuration) thick layer of 5 % borated polyethylene (BPE) to further reduce the environmental neutron background. The shape of the polyethylene shielding in the horizontal and the vertical setup was constrained by the arrangement of the  $^3\text{He}$  tubes, which was optimized taking into account the target changing procedure, efficiency and target cooling capacity. The neutron counters in the vertical setup was used to measure the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  reaction cross-section in the energy range  $E_{\alpha,\text{lab}} = 360 - 400$  keV, while higher neutron detection efficiency, further background suppression by more shielding material, and better cooling of the horizontal setup allowed for the low-energy measurements at  $E_{\alpha,\text{lab}} = 300 - 360$  keV.

In both setups, a cooling loop running deionised water at  $5^\circ\text{C}$  is integrated in the target holders for beam power dissipation (on the order of  $\sim 100$  W). Further descriptions of the setup can be found in previous publication [17].

## 2.1. Data acquisition system

Signals from the counters were shaped in CAEN A1422 charge sensitive preamplifiers with a gain of 90 mV/MeV. Each module has 8 channels plus a common test input, for a total of 3 modules used. The signal is fed to a CAEN V1724 100 MS/s 14-bit digitizers, which are read out through a common USB connection. The 18 signals (one from each  $^3\text{He}$  counter) are distributed to three digitizers occupying 6 channels/module.

A pulse height analysis firmware implementing a trapezoidal shaping algorithm (CAEN Dpp-PHA) [18] was used for the efficiency measurements (see Section 4.1 and 4.2). To estimate the system dead time, a reference pulse generated with a BNC DB-2 random pulse generator was fed into the test input of each preamplifier and one of the free channels in each digitizer.

For the underground measurements, the signals of each counter were read out and digitized for off-line analysis using a custom Labview interface [19]. This configuration allows to perform pulse-shape discrimination [20], which is of particular importance for the low-energy measurements at  $E_{\alpha,\text{lab}} < 340$  keV (see Section 3). Due to the low event rates ( $< 1$  Hz), the underground measurements were considered dead-time free.

## 3. Internal and external backgrounds

As already pointed out, both high detection efficiency and low background are crucial to achieve the required sensitivity for a low energy measurement of the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  reaction. In our case, the location of the experimental apparatus and the properly selected material of the enclosure of the  $^3\text{He}$  counters imply an unique low-natural background. The comparison of the experimental background in the signal region of interest is presented in figure 2: showing data taken on the Earth's

162 surface (dashed line), in the underground laboratory of  
 163 the LNGS (dash-dotted line) using single counter made  
 164 of aluminium, and in the underground laboratory using  
 165 counter made from stainless steel – part of the setup we  
 166 are describing here (solid line).

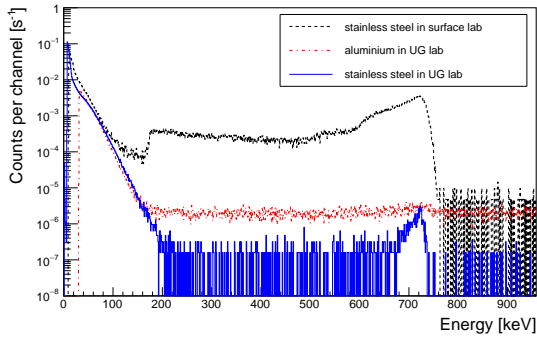


Figure 2: Comparison of background spectra of bare  $^3\text{He}$  counters acquired on the surface and in the underground laboratory (UG lab) using single counters made from aluminium (dash-dotted line) and from stainless steel (dashed and solid lines).

167 The signals from the  $^3\text{He}(n,p)^3\text{H}$  products (proton and  
 168 triton) appear between 150 and 800 keV including the  
 169 full-energy deposition (764 keV) and the cases when one  
 170 of the product is absorbed in the wall of the counters,  
 171 so called wall-effect. All three measurements were per-  
 172 formed without any moderator or shielding around the  
 173 detector.

174 The alpha activity of radioactive contaminants (from  
 175 the decay chain of uranium and thorium) inside the en-  
 176 closure of the counters leads to an intrinsic background.  
 177 From the count rate in the energy region above the ther-  
 178 mal neutron peak and assuming a flat alpha spectrum  
 179 [8], the alpha activity<sup>2</sup> of the enclosure material was  
 180 evaluated to be  $(2.71 \pm 0.07) \cdot 10^{-6} \alpha \text{ cm}^{-2}\text{s}^{-1}$  (to be  
 181 compared to  $6 \cdot 10^{-5} \alpha \text{ cm}^{-2}\text{s}^{-1}$  for the Al counters [8]).  
 182 The average alpha background rate integrated over the  
 183 neutron signal region was about  $1.50 \pm 0.04 \alpha \text{ hour}^{-1}$  for  
 184 the entire array.

185 For the entire setup, the total background rate inside  
 186 the neutron signal region (between 200 keV and 800  
 187 keV in figure 2) is  $3.34 \pm 0.11$  (vertical) and  $3.08 \pm 0.09$   
 188 (horizontal) counts/hour. This is the sum of the intrinsic  
 189 alpha and the extrinsic neutron backgrounds.

190 However, going towards the  $s$ -process Gamow peak,  
 191 the reaction yield of the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  reaction drops to the

<sup>2</sup>Calculated as the total alpha yield, assuming a flat alpha spectrum also in the neutron signal region, measured for the entire setup divided with the total surface area (in  $\text{cm}^2$ ) of the  $^3\text{He}$  counters.

192 1 event/hour level. Therefore, even the achieved very low  
 193 background severely limits the sensitivity towards the  
 194 lowest energies and needs to be further suppressed. For  
 195 this, we applied the pulse-shape discrimination method  
 196 described in ref. [20] to the signals from the detectors,  
 197 removing practically all  $\alpha$ -particle signals and lowering  
 198 the total background to  $1.23 \pm 0.12$  counts/hour. It is  
 199 worth noting that this number is affected by the efficiency  
 200 of PSD method as it is described in ref. [20], which we  
 201 will consider in the cross-section determination. The  
 202 achieved background rate represents an improvement of  
 203 two orders of magnitude over similar setups [2, 11].

#### 204 4. Efficiency measurement

205 To determine the neutron detection efficiency ( $\eta_n$ ) of  
 206 both configurations of the LUNA neutron detector array,  
 207 we performed measurements using the  $^{51}\text{V}(p,n)^{51}\text{Cr}$  re-  
 208 action at the Van de Graaff Laboratory of Institute for  
 209 Nuclear Research (Atomki) in Debrecen, Hungary. To  
 210 further extend the investigated neutron energy region, we  
 211 also performed an efficiency campaign using an AmBe  
 212 neutron source (described in Section 4.2) at the Univer-  
 213 sity of Naples “Federico II”. The experimental arrange-  
 214 ment of the neutron arrays in both efficiency campaigns  
 215 was identical with one of the underground measurements,  
 216 unless indicated otherwise in the respective section.

##### 217 4.1. The $^{51}\text{V}(p,n)^{51}\text{Cr}$ reaction

218 The measurements were performed at the  $30^\circ$   
 219 beamline of the 5 MV Van de Graaff accelerator of  
 220 Atomki[21]. The beam was transported through a series  
 221 of tantalum collimators resulting in a  $\approx 5$  mm diameter  
 222 beamspot on the target surface. The closest collimator  
 223 was located 50 cm from the target outside the volume  
 224 of the moderator. The accumulated beam charge was  
 225 measured by an ORTEC 439 Digital Current Integrator.

226 The  $^{51}\text{V}(p,n)^{51}\text{Cr}$  reaction ( $Q = -1534.8$  keV) was  
 227 used to produce monoenergetic neutrons in the energy  
 228 range below 1 MeV. Due to the slow variation of neu-  
 229 tron intensity and energy with angle, combined with  
 230 the well-known target preparation and utilization, the  
 231  $^{51}\text{V}(p,n)^{51}\text{Cr}$  reaction is widely used for calibration of  
 232 neutron detectors [13–15, 22, 23]. However, its appli-  
 233 cation is limited by the opening of additional neutron  
 234 channels above  $E_{p,\text{lab}} = 2330$  keV, which corresponds  
 235 to the first excited state of  $^{51}\text{Cr}$  at  $E_x = 749$  keV. Above  
 236 this energy, neutrons of different energies ( $n_0$  for ground  
 237 state transition,  $n_1$  for the first excited state, etc.) might  
 238 be mixed in the emitted neutron spectrum of the re-  
 239 action. In spite of the  $n_1$  neutron channel opening at

240  $E_{p,lab} = 2330$  keV, the work of [13] indicates a negligible 280  
 241 contribution of this neutron group to the total flux up to 281  
 242  $E_{p,lab} = 2600$  keV. Therefore, we performed the measure- 282  
 243 ments at  $E_{p,lab} = 1700, 2000, 2300, 2600$  keV assuming  
 244 monoenergetic  $n_0$  neutrons emitted at 130, 420, 710 and  
 245 990 keV energy, respectively.

246 The targets for these measurements were made by  
 247 evaporating natural vanadium with nominal thicknesses  
 248 of 60 - 200  $\mu\text{g}/\text{cm}^2$  (typically 7 – 17 keV proton energy  
 249 loss at  $E_{p,lab} = 1700 - 2600$  keV) onto 0.3 mm thick  
 250 tantalum backings. The beam intensity was limited to  
 251 minimize the dead time of the data acquisition system.  
 252 The average beam intensity varied between 20 nA and  
 253 500 nA. A blank tantalum target was also irradiated  
 254 before each vanadium target run in order to investigate  
 255 the possible contribution of beam induced background  
 256 to the measured neutron yield. It was always found to be  
 257 less than 0.1 %.

258 The determination of the total number of emitted neu-  
 259 trons was based on the activation technique [24]. The  
 260  $^{51}\text{V}(p,n)^{51}\text{Cr}$  reaction emits neutrons and produces an  
 261 equivalent number of  $^{51}\text{Cr}$  radioactive nuclei. These  
 262 nuclei decay via electron capture with a half-life of  
 263  $t_{1/2} = 27.7025(24)$  days. With a branching ratio  $B$  of  
 264 9.91(1) %, the decay leads to the first excited state in  
 265  $^{51}\text{V}$  and is followed by the emission of a 320 keV  $\gamma$  ray  
 266 [25]. The detection of this  $\gamma$  ray provides the possibility  
 267 of determining the number of reactions and hence the  
 268 number of neutrons produced.

269 After irradiation, off-line  $\gamma$ -ray measurements of the  
 270 activated targets were performed at Atomki using a 100  
 271 % relative efficiency HPGe detector placed in a complete  
 272  $4\pi$  lead shielding [26]. The absolute efficiency ( $\eta_{320}$ ) of  
 273 the HPGe detector was  $(13.4 \pm 0.4)$  % at  $E_\gamma = 320$  keV, as  
 274 determined with calibrated radioactive sources of  $^{137}\text{Cs}$ ,  
 275  $^{60}\text{Co}$ ,  $^{133}\text{Ba}$  and  $^{152}\text{Eu}$ . The efficiency curve of this partic-  
 276 ular detector and the method of the efficiency calibration  
 277 is presented in [24] Section 3.1.

The neutron detection efficiency,  $\eta_n$ , of the detector  
 array at a given incident proton energy<sup>3</sup> can be calculated  
 using the standard formula of activation [24]. The num-  
 ber of reactions ( $N_R$ ) that take place during the activation  
 time  $t_i$  can be obtained as:

$$N_R = \frac{N_\gamma}{B \cdot \eta_{320}} \cdot \frac{e^{\lambda t_w}}{1 - e^{-\lambda t_c}} \cdot \frac{\lambda \cdot t_i}{1 - e^{-\lambda t_i}}, \quad (1)$$

278 where  $N_\gamma$  is the number of detected 320 keV  $\gamma$  rays (after  
 279 dead time correction),  $t_c$  is the counting time,  $t_w$  is the

<sup>3</sup>The energy of the emitted neutrons as a function of emission angle relative to the incident beam direction is calculated based on the equation C.5. in ref. [27] and the arithmetic mean is used as an average neutron energy assigned to the incident proton energy.

waiting time elapsed between the end of the irradiation  
 and the start of the counting, and  $\lambda = \ln(2)/t_{1/2}$  is the  
 decay constant of  $^{51}\text{Cr}$ .

Then  $\eta_n$  can simply be calculated as:

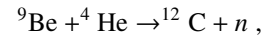
$$\eta_n = \frac{N_n}{N_R}, \quad (2)$$

283 where  $N_n$  is the number of the detected neutron events.  
 284 For the determination of  $N_n$ , dead time correction is  
 285 applied using the signal of a pulser with a rate of 20  
 286 pulses/sec.

#### 4.2. Measurement with an AmBe source

287 To extend the efficiency towards higher neutron ener-  
 288 gies, another campaign of measurements was performed  
 289 using an AmBe neutron source (manufactured by Eckert  
 290 & Ziegler). As only a nominal activity was known, we  
 291 performed the calibration campaign as follows.

The combination of  $^9\text{Be}$  and the  $\alpha$ -emitter  $^{241}\text{Am}$  leads  
 to the production of neutrons with energies up to 12 MeV  
 via the reaction



293 leaving  $^{12}\text{C}$  in either the ground or the excited state. For  
 294  $n_1$  emission, a  $\gamma$  ray of  $E_\gamma = 4.4$  MeV is emitted from  
 295 the de-excitation of the first excited state in  $^{12}\text{C}$ . The  
 296 probability of  $n_1$  emission, or the  $\gamma(4.4\text{MeV})/n_{total}$  ratio  
 297 is  $R = 0.575 \pm 0.028$  (see [28] and references therein).  
 298 Therefore, by measuring the  $\gamma$ -activity we can determine  
 299 the total activity of the source.

300 To better constrain the systematic uncertainty of the  
 301  $\gamma$ -ray measurements, three different types of detectors  
 302 ( $\text{LaBr}_3:\text{Ce}$ , NaI, HPGe) were used simultaneously. The  
 303 detectors were arranged at  $\theta = 30^\circ, 330^\circ$  and  $180^\circ$  with  
 304 respect to the surface of the neutron source. The source  
 305 was placed on a target holder in the center, at a distance  
 306 of 10 cm from the detectors. To suppress the low-energy  
 307 gammas emitted by the source, lead plates with 1 mm  
 308 thickness were inserted between the source and the  $\gamma$ -  
 309 detectors. The absolute efficiency ( $\eta_\gamma$ ) curve of the dif-  
 310 ferent detectors was determined using  $^{60}\text{Co}$  and  $^{56}\text{Co}$   
 311 radioactive sources (activities  $A_\gamma$  are known at a preci-  
 312 sion of  $\leq 1$  % and 3 %, respectively) and extended to  
 313 higher energies using an extrapolation that was cross-  
 314 checked with a Geant4 simulation. Overall a relative  
 315 uncertainty of the extrapolated efficiency of  $\sim 3\%$  was  
 316 reached at  $E_\gamma = 4.4$  MeV.

The activity  $A_n$  of the source can be determined  
 through

$$A_n = \frac{N_\gamma}{\eta_{4.4} R t}, \quad (3)$$



317 where  $N_\gamma$  is the number of net counts in the full-energy 346  
 318 peak. The measurement time is defined by  $t$  and  $\eta_{4.4}$  347  
 319 is the photo-peak efficiency of the  $\gamma$ -ray detectors at 348  
 320  $E_\gamma = 4.4$  MeV. The  $A_n$  values and their weighted mean 349  
 321 activity determined through the different  $\gamma$ -ray detectors 350  
 are presented in figure 3. The activities measured with 351

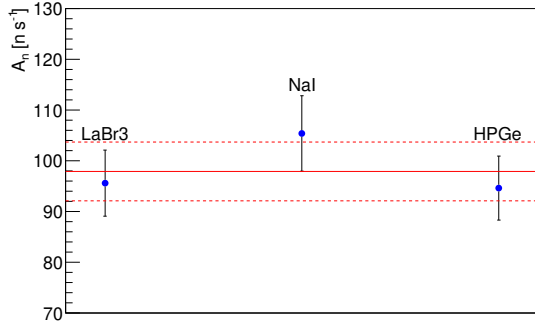


Figure 3: Comparison of the neutron activities evaluated with the three different  $\gamma$ -ray detectors. The solid and the two dashed lines represent the weighted average and the associated one sigma uncertainty range.

322 the three different  $\gamma$ -ray detection setups agree within 323  
 324 one sigma. We obtained a  $A_n = 97.9 \pm 5.8$  n/s as a 325  
 326 weighted average of the values. The indicated value 327  
 takes also into account the uncertainty of the branching 328  
 ratio R (4.8 %).

329 Since the AmBe neutron spectrum has a wide energy 330  
 331 range ( $E_n = 0$  to 12 MeV), the effective (or weighted 332  
 333 average) neutron energy  $E_{n-AmBe}$  was determined using 334  
 the neutron emission probability at a given energy  $E_n$  335  
 and the energy dependence of the efficiency. This effi- 336  
 ciency trend was calculated using Geant4 simulation 337  
 (see in Section 5) and the reference neutron spectrum 338  
 was taken from ISO 8529-2 [29, 30]. The resulting value 339  
 was  $E_{n-AmBe} = 4.0 \pm 0.3$  MeV.

340 The physical quantities, parameters and their uncer- 341  
 342 tainties in the experimental efficiency calculation using 343  
 the  $^{51}\text{V}(p,n)^{51}\text{Cr}$  reaction and the radioactive source are 344  
 reported in table 1. The total uncertainties are obtained 345  
 from the quadratic sum of partial uncertainties unless 346  
 indicated otherwise in the respective section.

## 343 5. Simulation of the detector response

344 We used the Geant4 toolkit [31, 32]<sup>4</sup> to simulate the 345  
 detector response. All materials in the detector region

<sup>4</sup>Geant4 version 10.03, with “neutron high precision” physics and thermal scattering corrections enabled for water and polyethylene.

were included according to the technical drawings of 346  
 the various components (moderator, shielding, detectors, 347  
 target chamber, water cooling). The simulation was used 348  
 to calculate the relative distribution of counting rates 349  
 between the counters, the ratio between total yields of 350  
 the outer and inner ring, and the energy dependence of 351  
 the neutron detection efficiency. The energy broadening 352  
 and angular distribution effects due to the transformation 353  
 from the center-of-mass frame to the laboratory frame 354  
 were taken into account for the nuclear reaction measure- 355  
 ments. The neutron emission of the AmBe source was 356  
 assumed to be isotropic. 357

358 Simulations of the hit patterns in the vertical config- 359  
 360 uration were carried out for the  $^{51}\text{V}(p,n)^{51}\text{Cr}$  reaction 361  
 at  $E_{p,lab} = 1700, 2000, 2300$  and  $2600$  keV, correspond- 362  
 ing to average neutron energies of  $E_n = 130, 420, 710$  363  
 and  $990$  keV; and for the AmBe neutron source, corre- 364  
 sponding to  $E_n = 4000 \pm 300$  keV, respectively. The 365  
 comparison between measurements and simulation at 366  
 $E_{p,lab} = 1700$  keV and using the AmBe source is shown 367  
 in figure 4, with the beam axis at 0 degree.

368 It is worth noting that the total number of detected 369  
 370 neutrons from the simulation was normalized to that 371  
 obtained in the experimental measurements for the compar- 372  
 373 ison. Due to the small statistical uncertainties, the 374  
 error bars are not visible in the figure.

375 There is a fair agreement between simulation and ex- 376  
 377 perimental measurements. The not-uniform distribution 378  
 of the yields for the counters at different positions is also 379  
 well reproduced by the simulation. This anisotropy is 380  
 attributed to geometrical effect, the distribution of con- 381  
 struction materials (e.g., the water in the cooling loop), 382  
 and the kinematics of the nuclear reaction.

383 Therefore, we consider our simulation model suitable 384  
 to obtain  $\eta_n$  in the LUNA energy range.

## 385 6. Results and discussion

386 To determine the neutron detection efficiency  $\eta_n$  at the 387  
 388 neutron energy region of interest for the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  389  
 390 measurement ( $E_n \sim 2.4$  MeV), the experimental effi- 391  
 392 ciency data were compared with the simulated results 393  
 (including the kinematic energy distribution effect, see 394  
 section 5). The measured and simulated  $\eta_n$  obtained from 395  
 the  $^{51}\text{V}(p,n)^{51}\text{Cr}$  reaction and AmBe neutron source, 396  
 and the energy of bombarding particle and emitted neu- 397  
 trons in keV are summarized in table 2. A notable dis- 398  
 crepancy is present between the experimental and simu- 399  
 lated data. Therefore, we determined a scaling factor 400  
 $L_{scal} = 0.77 \pm 0.01$  between the simulated and the mea- 401  
 sured efficiency using the least squares method. The 402  
 application of such a scaling factor is commonly used

Table 1: Physical quantities, parameters and their uncertainties applied in the experimental neutron detection efficiency calculations.

Neutron emitters	Parameters	Value	Uncertainty (%)
$^{51}\text{V}(p,n)^{51}\text{Cr}$	$T_{1/2}$ (day)	27.703	0.01
	B	0.0991	1
	$\eta_{320}$	0.134	3
	$N_{\gamma-AA}$	-	$\leq 2$
AmBe	$\eta_{4.4}$	-	3
	$A_{\gamma}$ ( $^{60}\text{Co}$ )	-	$\leq 1$
	$A_{\gamma}$ ( $^{56}\text{Co}$ )	-	3
	R	0.576	4.8

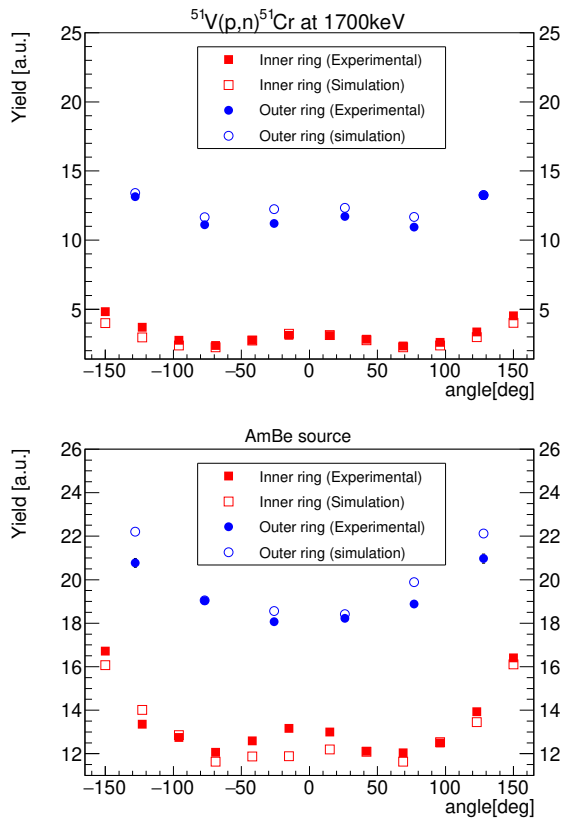


Figure 4: Comparison between the experimental (filled symbols) and the simulated (empty symbols) yields as a function of counters position. Circles (squares) refer to the inner (outer) ring of  $^3\text{He}$  counters in vertical configuration. Experimental data are obtained by exploiting the reaction  $^{51}\text{V}(p,n)^{51}\text{Cr}$  at  $E_{p,\text{lab}} = 1700$  keV (top panel) and by using the AmBe source (bottom panel).

to compensate the deficiencies of the simulation model [33–35] and the absolute scale is consistent with those found with similar neutron detection setups [14, 15]. The rescaled simulated data are also presented in table 2.

$L_{\text{scal}}$  can be used to calculate the nominal efficiency

curve<sup>5</sup>. This is presented in figure 5 (dashed line) together with the experimental results (filled symbols), where the plotted experimental data were corrected with the kinematic energy distribution effect to obtain the nominal efficiency values. To cross-check the consistencies of our model, the results for the inner (dotted line) and outer (dash-dotted line) rings of the detector array are shown separately.

A general agreement was obtained between the simulated and the experimental data. However, there is a slightly different energy dependence of the efficiency curve between the experimental and simulated data set, which may be attributed to various sources of uncertainty in the simulation Monte Carlo code, such as geometry, multiple-scattering of neutrons on the construction materials, elastic, inelastic scattering and nuclear reaction cross sections, molecular vibrational and rotational excitation modes in the moderator material.

Because the relevant energy range of this measurement is relatively narrow and well defined compared to the energy range where the efficiency is measured and simulated, with the quoted uncertainties the determined efficiency seems robust, regardless the possibly energy dependent scaling factor (see below). Moreover, in the next future the installation of LUNA MV facility at LNGS will allow to extend the efficiency measurements adding more high energy calibration points by other reaction or by a calibrated  $^{252}\text{Cf}$  source. This will permit to better constrain energy dependence.

The simulation results in efficiencies of  $(35 \pm 1)\%$  (horizontal) and  $(32 \pm 1)\%$  (vertical) for the two configurations of the neutron detector array in the LUNA energy range ( $E_{\alpha,\text{lab}} = 300 - 400$  keV,  $E_n \sim 2.4$  MeV).

To obtain a more robust  $\eta_n$  in the LUNA energy range, we also used another approach to interpolate the  $\eta_n$  from the low- and high-energy data points. The experimental

<sup>5</sup>This is the efficiency curve assuming monoenergetic, isotropically distributed neutron emission in the laboratory frame.



Table 2: Experimental and simulated neutron efficiencies for the different detector geometries given in %. The presented simulated results are already corrected for reaction kinematics and angular distribution. “Simulated-rescaled” represents the calculated efficiency (“Simulated”) by the Geant4 code is scaled to the “Experimental” data using the least squares method.

Reaction	$E_p$ (keV)	$E_n$ (keV)*	Experimental		Simulated		Simulated-rescaled	
			vert.	hor.	vert.	hor.	vert.	hor.
$^{51}\text{V}(p,n)^{51}\text{Cr}$	1700	$130\pm 20$	$42.3\pm 1.4$	$46.6\pm 2.3$	56.4	63.0	43.7	48.1
	2000	$420\pm 30$	$41.2\pm 1.3$	$45.4\pm 2.3$	54.2	61.0	42.0	46.6
	2300	$710\pm 50$	$40.4\pm 1.3$	$44.0\pm 2.2$	52.6	58.2	40.8	44.5
	2600	$990\pm 60$	$38.5\pm 1.2$		50.3		39.0	
AmBe		$4000\pm 300^{**}$	$32.4\pm 1.6$	$35.5\pm 1.7$	35.8	40.6	27.7	31.2

\* Due to the reaction kinematics and finite target thickness, neutrons are not strictly monoenergetic. Here, the average energy and the minimum and maximum energies are given.

\*\* The AmBe source emits neutrons with energies between  $E_n = 0 - 12$  MeV. The indicated value is the effective neutron energy (see Section 4.2).

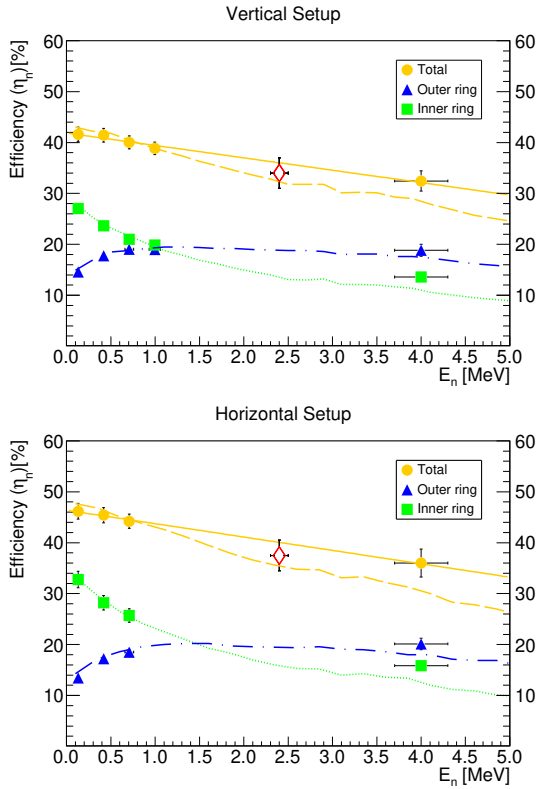


Figure 5: Experimental efficiencies (filled symbols) and the rescaled-nominal efficiency curve (dashed line) obtained using the vertical (upper panel) and horizontal (lower panel) setups, respectively. The simulated and the experimental efficiencies related to the inner (squares and dotted lines) and outer (triangles and dash-dotted lines) ring of the setups are also presented. The linear fit of the experimental data (solid lines) and the proposed efficiency value at  $E_n = 2.4$  MeV (empty diamonds) are also presented.

efficiencies as a function of neutron energy (corrected with the kinematics energy distribution) were fitted with a linear function, as shown the solid lines in figure 5. The uncertainty of the interpolated data was estimated using random sampling of the measured data assuming Gaussian distribution of the assigned uncertainties and considering also the uncertainty of the AmBe effective neutron energy. The  $\eta_n$  was interpolated to be  $(40\pm 1)$  % (horizontal) and  $(36\pm 1)$  % (vertical). A relative  $\approx 15$  % discrepancy is present between the interpolated and the simulated values. Therefore, we adopt the average of efficiency between the two methods with an assigned uncertainty to cover both the simulated and the interpolated value,  $(38\pm 3)$  % and  $(34\pm 3)$  %<sup>6</sup> (indicated the red empty diamonds in figure 5) for the two setups in the LUNA energy range. It is worth noting that the values indicated above assume an isotropic distribution of the emitted neutrons. An energy-dependent correction should be applied to take into account the effect of the angular distribution of the neutrons emitted in the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  reaction when calculating the reaction cross-section. This will be presented in forthcoming publication.

## 7. Summary

A new LUNA neutron detector array has been commissioned for the investigation of the  $^{13}\text{C}(\alpha,n)^{16}\text{O}$  reaction towards its astrophysical *s*-process Gamow peak in the low-background environment of the LUNA experiment at the Laboratori Nazionali del Gran Sasso.

<sup>6</sup>The systematic uncertainties attributed to possible geometrical effect, such as the not point like- and off centered- beamsport, and asymmetrically located counters along the horizontal and vertical axis were controlled using Geant4 simulation and experimental measurement using AmBe source. A relative  $\leq 1$  % was obtained on the  $\eta_n$ .

As a result of the low intrinsic activity of the  $^3\text{He}$  counters, the passive shielding of the experimental apparatus, the applied pulse shape discrimination technique and the deep underground location of the experiment, we achieved a total background rate  $1.23 \pm 0.12$  counts/hour.

Due to the large reduction of the reaction yield of the  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  reaction over the energy range  $E_{\alpha, \text{lab}} = 300 - 400$  keV investigated by the LUNA experiment, two different configurations of the setup were used with vertically and horizontally arranged  $^3\text{He}$  counters. This provided an optimized neutron detection efficiency, target handling and active target cooling.

We determined the neutron detection efficiency in a wide neutron energy range (0.1 – 4.0 MeV) experimentally using the  $^{51}\text{V}(p, n)^{51}\text{Cr}$  reaction and an AmBe neutron source combined with a robust simulation based on Geant4 code. A  $(38 \pm 3)\%$  (horizontal) and a  $(34 \pm 3)\%$  (vertical) absolute neutron detection efficiency of the setup were obtained as averages in the  $E_n = 2.2 - 2.6$  MeV range corresponding to the neutron emission of the  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  reaction in the LUNA experiment.

We conclude that the total environmental neutron background of the LUNA neutron detector array in the deep underground location of the LNGS, combined with high neutron detection efficiency, creates a unique possibility to measure the cross-section of the  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  reaction approaching its *s*-process Gamow peak.

## Acknowledgement

The authors would like to thank the mechanical workshops of LNGS and INFN Naples for technical support. D. Ciccotti greatly helped during all aspects of the execution of this work. Support from the National Research, Development and Innovation Office NKFIH (contract numbers PD129060, K120666 and NN128072), the University of Naples - Compagnia di San Paolo Program “STAR”, STFC-UK, DFG (BE 4100/4-1) and COST (ChETEC CA16117) is also acknowledged. This work was also supported by the Polish National Science Centre under Contract No. 2014/14/M/ST2/00738 (COPIN-INFN Collaboration).

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