Study of the identification efficiency of the FAZIA array CsI(Tl) crystals for energetic helium ions.

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Abstract

The identification efficiency of selected thallium-doped CsI crystals (100 mm thick) of the FAZIA array has been measured for helium ions with energies ranging from about 20 to 150 MeV/u exploiting the fragmentation of energetic ^{12}C

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beams delivered by the synchrotron of the CNAO medical facility in Pavia. Nuclear interactions of energetic He ions occurring within the crystal influence the energy deposition and the light response of the scintillator thus reducing its identification efficiency. As done in previous studies on protons, the measured efficiency is compared with dedicated GEANT4 simulations and a good agreement (within 2-4%) has been found, confirming the quality of the procedure and the model description. This study complements the rather scarce literature on systematic experimental investigations on the response of CsI(Tl) scintillators to ^{3}He and ^{4}He ions and thus is also valuable for heavy-ion experiments at intermediate energies where energetic light ions, which are important probes to study the details of nuclear interaction, are abundantly produced.

Keywords: `CsI(Tl)` detectors, particle identification techniques, light-energy response, heavy ion collisions

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1. Introduction

CsI(Tl) scintillators are widely employed in many radiation detectors and equipments for both fundamental and applied physics, thanks to their relatively low cost, high stopping power, large scintillation efficiency, and particle identification capability on the basis of the Pulse Shape Analysis (PSA). Limiting to fundamental nuclear physics, there are many detector arrays worldwide featuring CsI(Tl) crystals; they are often used as the final stage of telescope configurations, to extend the identification capability and the measured energy range for the most penetrating ejectiles produced in reactions [1] - [12] when the ΔE - E method is compromised by the very weak signals in the preceding (typically thin) telescope layers.

The importance of CsI(Tl) as residual energy stage in telescope arrays is based on the PSA allowing efficient identification of light particles [2, 4, 5, 6, 7, 13, 14]. When using thick detectors for experiments at high energy, where highly penetrating light fragments are produced, the identification ef-

ficiency (hereinafter referred to as id-efficiency) for them is blurred as clearly evidenced in various papers [6, 15] and also quantitatively assessed for protons [16, 17, 18, 19, 20] and in fewer cases for heavier species [18, 19, 20]. The origin of these effects reducing the id-efficiency for energetic particles in thick crystals lies in nuclear interactions. As explained also in [16], these interactions are of two types: elastic or inelastic scattering and other nuclear reactions of the incoming particles with the cesium and iodine nuclei in the bulk. The scattered particles can escape the crystal before being stopped, altering the whole ionization profile and, in turn, the luminescence characteristics (that rules the PSA). Similarly, the production of fragments and/or neutrons from nuclear reactions changes the deposited energy and the resulting light distribution in the crystal. In general, the particles undergoing significant nuclear interactions produce a diffuse background [6, 16, 21] in the identification spectra and they are referred to as IED (incomplete energy deposition) particles or events. Due to their origin, IED events are strongly related to the range of the particles within the bulk and to the geometry of the crystals. Therefore, they increase with particle energy and they decrease with increasing stopping power; for a given particle-energy combination, the IED events are modulated by the shape of the crystal because scattering effects are more pronounced for narrow detectors than for wider ones. IED effects have been evidenced and studied in the past also by the FAZIA collaboration [16, 17], which is involved in nuclear heavy-ion experiments with such telescope detectors. In agreement with other authors [19, 20] a significant decrease in the id-efficiency for energetic protons is observed. In the FAZIA CsI(Tl) case, the reduction for a given energy is larger than in other studies, due to their quite elongated shape (20.4×20.4 mm^2 entrance window versus 100 mm length [7, 22]), enhancing the scattering losses from lateral sides. On the other hand, the use of elongated crystals is a must when a precise direction measurement (and thus high granularity) is required. This is the case, for example, in experiments at intermediate energies aiming to determine the reaction plane for particle flow studies [23, 24] or for femtoscopic analyses where particle correlations [25, 26] are crucial up to high momenta. For this reason it

is necessary to undergo detailed investigations of the behavior of FAZIA crystals irradiated with energetic light species. Moreover, it will permit to stringently benchmark the prediction of interaction simulation codes as GEANT4, increasing the reliability of further extrapolations to broader phase space regions or to new detector configurations. The results concerning id-efficiency for protons have been published in Refs. [16, 17]; here the results for He ions up to about 150 MeV/u (slightly lower than 190 MeV/u, maximum energy for stopped He ions in 10 cm of CsI(Tl), just to have a clean identification) are discussed profiting of the carbon beams available at the CNAO synchrotron facility (Pavia). The paper is organized as follows: in Section 2 the experimental conditions are recalled while in Section 3, the analysis method to scan the He ions energy range and the details to evaluate the id-efficiency are discussed. Finally, in Section 4, the results and the comparison with those predicted by GEANT4 tool that replicates the crystal geometry and the measurement conditions are shown.

2. Experimental details

The measurements were performed at the Centro Nazionale di Adroterapia Oncologica (CNAO) in Pavia (Italy), with exactly the same apparatus and setup already described in [17]. A simple top view sketch not to scale of the experimental apparatus is shown in the upper part of Fig.1: the target is located in air at the end of the beam pipe, while a complete FAZIA block is mounted 1 m far from the target on a horizontal plane at the height of the beam axis. The FAZIA block structure is shown in the lower part of Fig.1, where the 16 three-layer (Silicon 1 - Silicon 2 - CsI(Tl) crystal) telescopes organized into 4 quartets corresponding to different colors can be recognized. A full description of these telescopes can be found in [7, 16, 22]. The length of each CsI/Tl) crystal is 100 mm, while their active area is 20.4×20.4 mm^2, as defined by the presence of a thick brass collimator in front of the silicon detectors.

The CsI(Tl) readout is performed using photo-diodes (PD), and the crystal entrance face is protected with a reflective and dark metalized mylar foil (2.5 µm

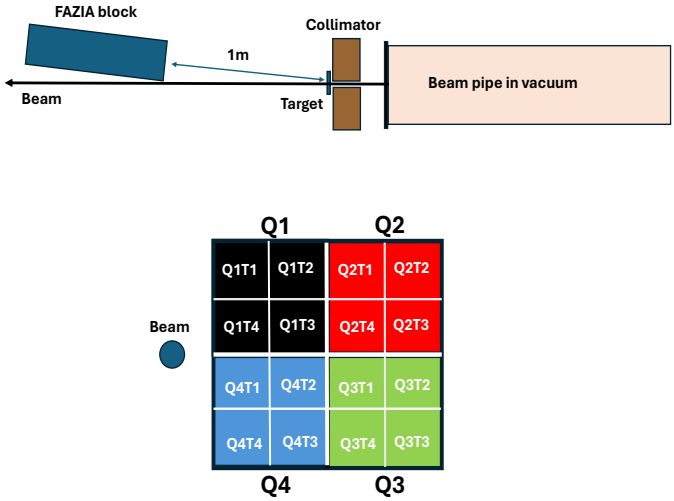


Figure 1: Upper part: top view not to scale of the experimental apparatus, where the ^{nat}C 2 μm thick target, the beam collimator and the FAZIA block position are indicated. Lower part: front layout of the FAZIA block to label the different quartets and telescopes.

thick) while the other surfaces are wrapped first with a highly reflecting polymer (ESR Vikuiti, 3M) and then tightened with an opaque tape. The thicknesses of the two silicon detectors used in this experiment were 500-500 µm or 300-750 µm, depending on the quartet. The block was mounted at very forward angles, from around 1.1° to 5.3° with respect to the beam axis. For all details, one can refer to Tab.1 of [17]. The detector irradiation was done exploiting a carbon beam at energies ranging from 150 to 350 MeV/u (in steps of 50 MeV/u) reacting with a $^{\mathrm{nat}}$C target 4.7 µm thick. To maximize the statistics for the helium particles, the data of the different beam energies have been summed up. Since the synchrotron of CNAO is mainly devoted to medical applications, the beam spot was relatively large (up to few cm) and, therefore, to better control the impact point on the target, a collimation stage was mandatory. For such a reason, a 5 cm thick brass block, with 10 mm diameter aperture, was introduced just before the carbon target. Moreover, to reduce possible contamination of beam particles not passing through the target, additional massive shields (made of copper and lead) were arranged around the brass collimator. Data acquisition

was triggered by a threshold applied to a fast trapezoidal filter synthesized from the three detector signals (put in logic OR). The beam intensity was not directly measurable but tuned in order to keep the acquisition rate lower than 1 kHz. The measurement was performed in normal atmosphere, but the energy losses and straggling in the air layers crossed by the particles before reaching the telescopes were rather small (a few MeV), without any significant effects for the analysis.

3. Experimental Results

In the following analysis some detectors are missing. In fact, Q1T3 was not working, Q3T2 is not used for missing energy calibrations, and Q2T2 and Q4T3 are discarded due to their low isotopic resolution for Z=2 isotopes. The aim of the present work is to measure the id-efficiency η of the FAZIA telescopes, defined as the fraction of particles passing through the two silicon detectors still identified as the same particle in the following CsI(Tl) crystal exploiting the PSA. Therefore η is defined as η=N_{CED}/N_{tot}, where N_{CED} is the total number of Complete Energy Deposition events, which correspond to correctly identified events in PSA, while N_{tot} is the total amount of particles of such a species impinging on the crystal, i.e. punching-through the silicon detectors. The CsI(Tl) PSA in the FAZIA apparatus is obtained by differently shaping the digital signals, producing the so called fast component (cs_f) and the total energy component (cs_t). By means of their correlation, the particle identification can be achieved, while from the cs_t component it is possible to extract the deposited energy. In this experiment, the use of the C+C collisions at different beam energies allows to generate particles from Z=1 to Z=5 in a large energetic domain, producing the well known ΔE - E matrix and CsI(Tl) PSA plot shown in Fig.2 as panel a) and b), respectively, for a specific telescope. In particular, for the ΔE - E correlation, the sum of the energy deposited into the first and the second silicon after a linear calibration procedure is plotted with respect to the CsI(Tl) collected light, expressed in ADC units. The CsI(Tl) PSA is

performed through the correlation of the ratio $\frac{cs_f}{cs_t}$ vs cs_t , as already used in previous works [16, 17]. In both panels a) and b), the different fragments can be easily recognized.

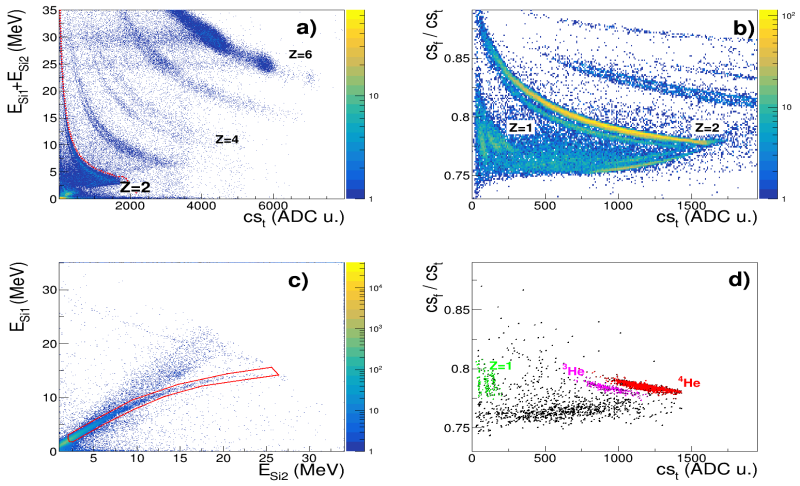


Figure 2: Panel a): an example of FAZIA ΔE - E matrix obtained correlating the energy released in the two silicon detectors calibrated in MeV and the cs_t component of the CsI(Tl) in ADC units. The dashed red curve sets an upper limit for the identification of helium ions (see text). Panel b): corresponding CsI(Tl) PSA plot (with a zoomed-in view on x-axis). Panel c): Si_1 vs. Si_2 correlation: the red outline identifies helium ions punching-through the two silicon detectors (see text). Panel d): CsI(Tl) PSA plot for a selected bin in $E_{Si1} + E_{Si2}$ (see text), allowing to disentangle the different contributions, i.e. ^{4}He (red points), ^{3}He (magenta points), the corresponding IED events (black points) and a residual Z=1 contribution (green points).

The impinging particles of interest (Z=2 in this case) can be identified applying two different conditions. As the first step, in the ΔE - E matrix a line (red dotted line in panel a) of Fig.2) is traced to define an upper limit in Z identification for helium isotopes. In addition, in the Si_1 vs. Si_2 matrix of Fig.2 panel c) a graphical selection (red line) is performed to improve the event selection cutting away some H isotopes and ensuring that events are compatible with Z=2 punching-through isotopes. In this plot, the ridge corresponding to

He particles is clearly identifiable and fully consistent with the nominal thickness of the silicon detectors, indicating that the particles are incident on them at a near-perpendicular angle (and also implying their source is located in the immediate vicinity of the target). Applying these conditions, the events corresponding to selected intervals of $E_{Si1} + E_{Si2}$ (for example 4.0 ± 0.1 MeV in panel d) of Fig.2) are obtained, highlighting some aspects: first of all, while it is easy to identify the ^{4}He (red points) and ^{3}He (magenta points) CED events, He isotopes cannot instead be separated at all for IED cases. For such a reason, the results of this paper concern the id-efficiency determination of the FAZIA crystals for Z=2 particles. Furthermore, within the selected events, there is a residual contribution of Z=1 particles (green points in Fig.2 panel d)). The CsI(Tl) id-efficiency as a function of the impinging Z=2 particles energy is then obtained using a dedicated graphical cut in the CsI(Tl) PSA plot for each selected bin of Si_1+Si_2 energy. Depending on the telescope and the selected energy, the number of events in each bin ranged from few 10^3 to 10^2. It is therefore possible obtain the N_{CED} events as the sum of the well identified ^{4}He and ^{3}He ions, while the estimation of the N_{tot} events is obtained subtracting the Z=1 isotopes. Despite the imposed conditions, the background of IED events coming from heavier ions punching-through the two silicon layers cannot be totally excluded, producing a possible systematic error in the estimation of the N_{tot} events.

For each bin of energy deposited in silicon detectors, the corresponding energy deposited in the CsI(Tl) crystal is obtained by calibrating the Light Output (LO) starting from the energy loss tables. Using also the data of elastically scattered protons, the standard method used in the FAZIA collaboration is applied, using the LO formula described in [27] and fitting the 4 parameters present in the formula for each crystal. Once the CsI(Tl) are calibrated, the average values of the id-efficiency distributions of well identified ^{4}He and ^{3}He are weighted to consider their relative statistics and the final helium isotopes energy for each selection is assigned.

The final result is reported in Fig.3, where the helium id-efficiency of the FAZIA CsI(Tl) crystal is shown for all the well-working telescopes as a function of the

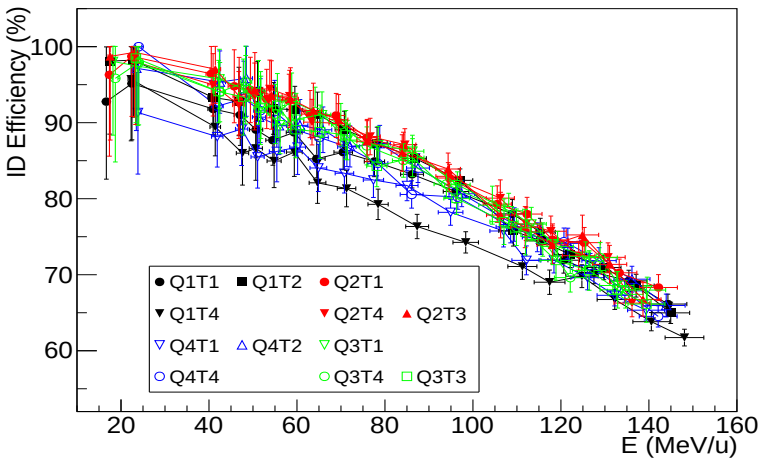


Figure 3: Experimental identification efficiency for Z=2 particles detected in the FAZIA CsI(Tl) crystals. Different colors and symbols correspond to different telescopes.

energy (expressed in MeV/u). A different color is used for each quartet (as already shown in Fig.1), while different symbols correspond to different telescopes. Open and full symbols correspond to detectors that, from the point of view of the particle kinematics, should behave equally. Concerning the error bars, for the impinging energy the statistical uncertainties are negligible and only a systematic error of $\pm 3\%$ mainly due to the energy calibration is considered. Instead, for the experimental id-efficiencies, only statistical uncertainties are considered, obtaining values between 1 and 10 %, depending on the energy. It is worth noting that almost all the detectors show very similar trends except for the two nearest to the beam Q1T4 and Q4T1, where the background produced by heavier ions is important, systematically reducing the id-efficiency. Thanks to the reaction kinematics, this background gradually becomes less important with increasing laboratory angles and its systematic contribution will be evaluated in the following analysis.

4. Simulations and comparison with experimental results

To compare with the experimental data, a dedicated GEANT4 simulation has been used. Unlike in [17], the complete interaction between beam and target in this case has not been reproduced. In fact, while in ref. [17] the reaction was an elastic scattering of protons on target with a very large cross section, in this case we are looking at the fragmentation of the beam/target nuclei to produce ^{4}He and ^{3}He of various energies, with a cross section much smaller than that of the C+C elastic scattering. For such a reason, helium ions in the GEANT4 simulation are produced directly after the target, using the experimental data as a reference for the energy and angular distributions. The origin of these particles is from nuclear reactions, producing a rather uniform rate of impinging particles on the detector surface, different from the strong angular gradient measured in [17], where the protons were elastically scattered by a gold target. By generating the particles directly at the target position, it is possible to implement the location and geometry of the different telescopes of the FAZIA block using the same three-dimensional CAD models as in [17], with still reasonable computing time.

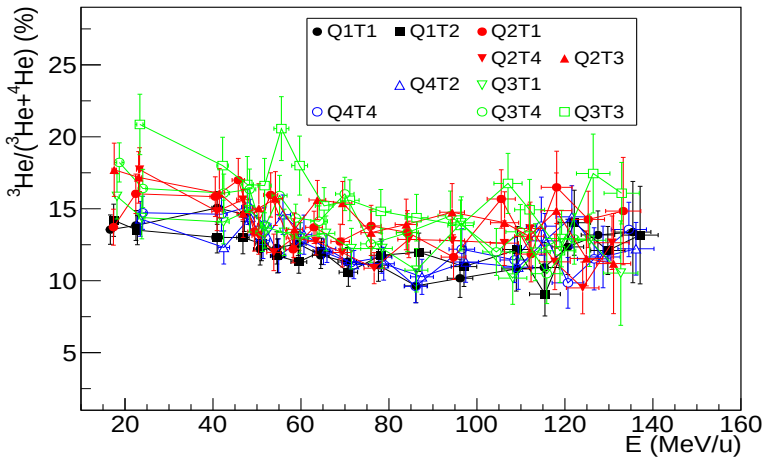


Figure 4: Experimental ^{3}He / (^{3}He + ^{4}He) ratio for the different FAZIA telescopes.

The GEANT4 simulation has been performed using the same prescriptions of the previous ones [16], [17], namely the *FTFP_BERT_EMZ* physics list to mimic the interaction in the CsI(Tl), including also the *option4* for optimized low-energy electromagnetic interaction. The fragments impinging on the detectors are created with a very large gaussian energy distribution with mean at 500 MeV and σ of 250 MeV and with an almost flat angular distribution. Slightly different combinations of energy and angular distributions have been tested with negligible impact on the analysis. As already discussed, the IED events produced by ^{4}He and ^{3}He can not be separated in the experimental data thus a realistic GEANT4 simulation should include both isotopes. The simplest approach is to consider them separately, creating two different simulations. Then, they are analyzed in the same way as for the experimental data to obtain an id-efficiency curve separated for the ^{4}He and ^{3}He ions. Finally, those simulated curves are mixed to reproduce the experimental relative abundances.

In the details, for both helium isotopes, in each bin of energy released in the Si layers it is possible to count the total number of impinging particles (N_{tot}), while the number of events with complete energy deposition (N_{CED}) can be directly obtained from the tracks of the simulated particles. Of course, no contribution from Z=1 particles is present in the GEANT4 simulation. Finally, the relative abundances of ^{3}He with respect to the total number of ions with Z=2 are fixed, starting from the experimental values shown in Fig.4. For the ^{3}He / (^{3}He + ^{4}He) ratios only statistical uncertainties are considered, while for the energy deposited in the CsI(Tl) the $\pm$3% of uncertainty is considered. Looking at Fig.4, despite about 5% fluctuations, the percentage of ^{3}He is almost constant for all FAZIA telescopes, without showing an evident trend as a function of the energy. For such a reason, a fixed value of 15% is considered. Note that a variation in this percentage of $\pm$5% has been tested, without any relevant impact.

The final result of the GEANT4 simulation is shown in Fig.5, where the four telescopes for each quartet are averaged to obtain a unique trend to be compared with the experimental data.

As already discussed, effects connected to the different impinging rate along

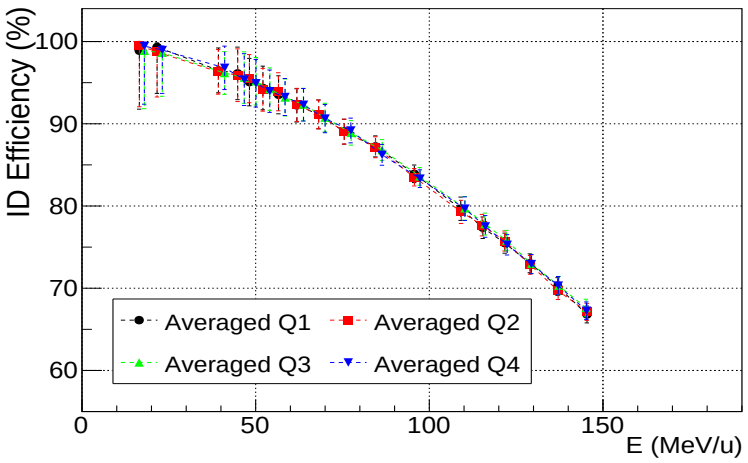


Figure 5: Averaged GEANT4 helium id-efficiencies for the telescopes of each quartet of the FAZIA block.

the detector surface are negligible, so a very similar trend between the different detectors for each quartet in the GEANT4 simulation is found. Moreover, the Q1-Q2 and Q4-Q3 quartet pairs are symmetric with respect to the beam axis, so from the point of view of the GEANT4 simulation, they should provide the same id-efficiency. This is evident in Fig.5 where the four quartets show the same behavior within the uncertainties as a function of the impinging energy. The error bars are purely due to statistics for both id-efficiency and energy.

In Fig. 6, the final result of the comparison between experimental data and GEANT4 simulation is presented: the experimental id-efficiencies are reported as black dots which correspond to the experimental averaged values with the error bars representing the maximum deviations between the different telescopes, producing an interval drawn by the shadowed area. For the GEANT4 simulation, the average over the four quartets is shown as blue points. Experimental data and simulation are consistent within the considered uncertainties, globally confirming the simulation in terms of the physics assumptions and its possibility to be used to reproduce the id-efficiency drop of the FAZIA CsI(Tl) crystals, as already shown in [17]. It is worth noting that the simulation is systematically

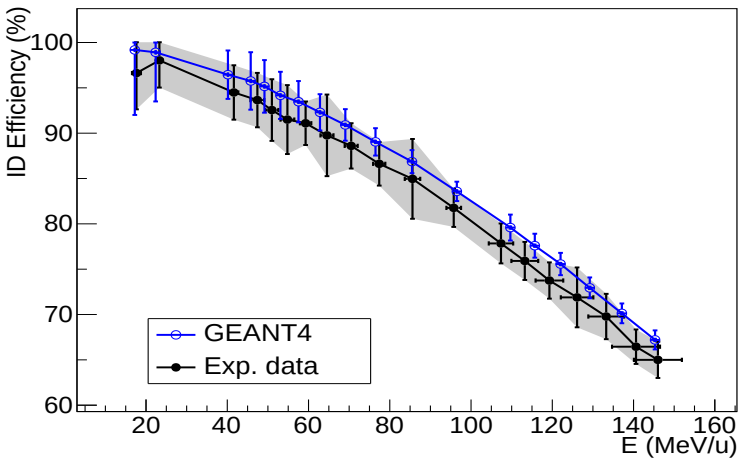


Figure 6: Averaged GEANT4 helium id-efficiencies compared with the experimental confidence zone.

above the experimental values. This systematic difference of about 2-4 % can be a consequence of two main effects. Looking to the GEANT4simulation, the interaction occurs in the target, as in the standard FAZIA measurements under vacuum. In this experiment, the largest fraction of particles are coming from a source located (see Si_1 vs. Si_2 matrix) in a region near the target. By shifting the source position by 0.5 m along the beam direction in the GEANT4 simulation, a reduction in efficiency of approximately 2 % is observed, remaining fully consistent with the experimental data. On the other hand, also a possible systematic underestimation in the experimental data due to a residual contamination of IED events coming from other particles heavier than helium can be taken into account. By considering the region in the ΔE - E matrix just above the Z=2 ridge, a first estimation of this effect has been obtained with a result consistent with the hypothesis. Depending on the angular position of the telescope which affects the relative population of the heavier ions, the background is evaluated to be around 2-6 %, a value compatible with the observed systematic effect.

5. Summary

A standard FAZIA block in realistic experimental conditions (mounting and geometry) has been irradiated with the $^{12}C+^{nat}C$ reaction products at beam energies ranging from 150 to 350 MeV/u. A measurement of the id-efficiency for helium ^{4}He and ^{3}He isotopes has been performed, following the methods already used in [17]. Experimental data show that the id-efficiency for helium ions continuously drops with their increasing energy and it results to be around 65 % at the highest probed energy of 150 MeV/u. As previously discussed for protons in Ref. [17], this is a demonstration that IED effect must be taken into account when studying nuclear reactions at Fermi energies, because the LCP yields are affected and their energy spectra are deformed towards high kinetic energies. Finally, a realistic GEANT4 simulation, where the interaction is considered in the target and the set-up and the geometry of the detector have been taken into account, can reproduce fairly well the observed trend (i.e. within 2-4%, with a systematic overestimation of the id-efficiency probably due to a possible shift of the source respect to the target position or a contamination by heavier ions, candidating it to be a powerful tool to simulate the id-efficiency for the FAZIA apparatus also for other impinging particles or not yet studied configurations.

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