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Incomplete energy deposition in long CsI(Tl) crystals

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Abstract We studied process of incomplete energy deposition in long CsI(Tl) crystals, caused by inelastic interactions of impinging nuclear fragment in the scintillating material. The secondary beam from the ACCULINNA fragment separator and the heavy-ion beam from the CELSIUS storage ring were used to measure the yield of this process as a function of the initial energy of incoming fragments. The functional fit to GEANT simulations will be used to correct the energy spectra from future experiments.

Key words nuclear interaction in solids • scintillation detectors

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Introduction

The Forward Wall Detector (FWD) [3], a part of a larger detection system [4, 9], was built at the Institute of Nuclear Physics in Cracow and successfully tested at the CELSIUS storage ring in Uppsala, Sweden. The aim of FWD is to register and identify projectile-like fragments from heavy-ion-induced reactions at beam energies of 50–450 MeV/nucleon.

The FWD detection module consists of a ΔE sensor, which is either a 750 μm silicon detector or a 10 mm fast plastic (BC408-Bicron) scintillator (in phoswich configuration), followed by a 80 mm thick CsI(Tl) scintillator (E). The thickness of the E detector was chosen to maximize the energy limit for particle identification, keeping incomplete energy deposition (IED) at a reasonably low level. A detailed description of the detectors and FWD performance can be found in [3].

Incomplete energy deposition is caused mainly by inelastic interaction in scintillator materials. This process can remove an initially interacting nucleus from the scintillator before it stops completely. As a consequence, the measured energy will be lower than the initial one and the nucleus will be removed from the identification line. The percentage of the removed particles depends strongly on their initial energy and can reach values as high as 30% for fully stopped alpha particles. Therefore, a good knowledge of its energy dependence is crucial for cross-section corrections.

Several authors [1, 5, 6, 11] have studied the IED process for protons. For heavier fragments only few measurements [1, 5] exist. According to Poggi *et al.* [7], the IED probability is highest for alpha particles and decreases with increasing charge. For particles with charges higher than three, the range decreases faster than the cross-section increases and, therefore the IED processes can be neglected.

In order to investigate the IED energy dependence, two simple experiments were performed: one at the U-400M cyclotron in Dubna, Russia, using monoenergetic secondary beams from the ACCULINNA separator, the other at the CELSIUS storage ring using the ^{17}O beam. The percentage of contribution of events with incomplete energy deposition was measured for energies up to 200 MeV/nucleon.

Experimental set-up and data analysis

ACCULINNA separator

In the experiment performed at the U-400M cyclotron in Dubna, beams of secondary particles were produced by the fragmentation of 33 MeV/nucleon ^{11}B beam on a ^{9}Be target. Secondary fragments were extracted using the ACCULINNA separator [8]. The variation of the secondary beam energy in the range of 10 up to 80 MeV/nucleon was obtained by varying spectrometer rigidity. Beam energy was determined with an accuracy better than 2.5%. The average beam intensity was kept below 10^4 particles per second to avoid a pile-up of impulses from the detector.

A telescope consisting of a square-shaped 500 μm thick silicon detector (ΔE) with a 10×10 mm active area and an 80 mm long CsI(Tl) cylindrical scintillator (E) of 12 mm diameter was positioned along the beam axis in a vacuum chamber [10]. The CsI(Tl) crystal, light guide and photomultiplier were located in an aluminium housing. The silicon detector was mounted in front of the CsI crystal. Two collimators, at a distance of 590 cm and 55 cm respectively before the telescope, were installed to reduce the beam spot at the telescope front to a circle of 8 mm in diameter. The CsI scintillator was thick enough to stop any incident particles. The response of the telescope to a variety, monoenergetic light particles: $^{1,2,3}H$ and $^{3,4}He$, was measured as a function of incident particle energy. An example of the identification matrix is presented in Fig. 1a, where three peaks corresponding to ^{2}H, ^{3}He and ^{4}He of energies 47, 125.3 and 94 MeV, respectively can be seen clearly.

The contribution from IED events is seen as a tail extending on the left-hand side of the peak corresponding to the fully stopped particles. There is a small contribution of continuous spectrum coming from particles scattered on collimators. An example of alpha particle energy spectrum is shown in Fig. 1b. The percentage contribution of IED events was calculated as a ratio of the tail to the total yield of the identified particles, excluding the continuous part of the spectrum. The energy deposited in the CsI crystal was calculated from the exactly known beam energy and the energy loss in the ΔE detector calculated from its thickness with the TRIM code [12].

CELSIUS storage ring

In the experiment performed at the CELSIUS storage ring, the energy spectra of fragments produced by a ^{17}O beam of 250 MeV/nucleon energy on a ^{131}Xe target were measured with a $\Delta E1$–$\Delta E2$-E telescope. Energy loss was measured by two cylindrical semiconductor silicon detectors $\Delta E1$ and $\Delta E2$ of 16 mm in diameter, and 950 μm and 2008 μm in thickness, respectively. They were placed in front of the FWD second ring CsI scintillator at 6.8° [3]. The identification matrixes are presented in Fig. 2. The background extending to the left-hand side of projectile-like fragment peaks comes from the IED events. For $Z \leq 3$, identification of IED events is more complex for two reasons:

- light fragments have a continuous energy spectrum – this allows to measure the energy dependence of IED percentage contribution,
- the existence of a backbending part coming from fragments which did not stop in the CsI crystal – the punch-through points are at 210, 180 and 180 MeV/nucleon for the ^{7}Li ions, alpha particles and protons, respectively.

The amplification was chosen to allow the IED measurement of fragments with $Z \leq 3$. Unfortunately, only the IED of helium isotopes could be finally analysed. The p, d, t lines are too close to one another to allow proper background counting for each isotope and too far from one another to be handled together. For lithium nuclei there was not enough statistics in the continuous part of the spectrum.

For the IED calculation, a helium background (Bcg) was defined as a number of events in the region on the left-hand side of fully stopped $^{3,4}He$ fragments. The percentage contribution of the IED events was calculated as a ratio of Bcg to (N+Bcg), where N is the number of the ^{3}He and ^{4}He fragments with full energy deposition. The illustration of the IED calculations is shown in Fig. 3, where the experimentally obtained energy spectrum for 16 MeV<$\Delta E2$<18 MeV is

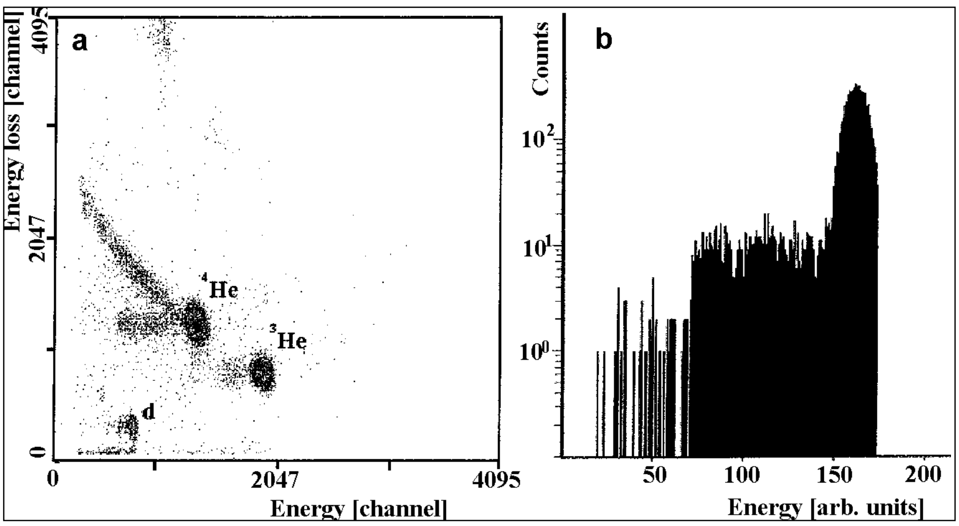

Fig. 1. Identification matrix from measurements on ACCULINNA separator (left-hand side). Energy spectrum of alpha particles at 94 MeV (right-hand side).

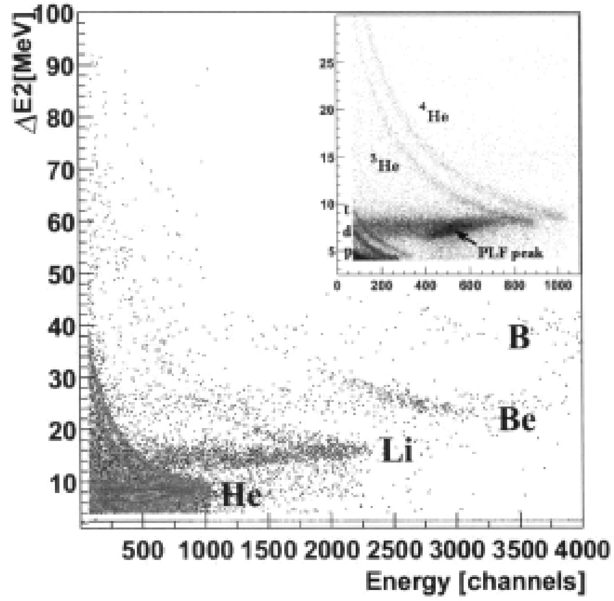

Fig. 2. Identification matrix for $^{17}O+^{131}Xe$ reaction at 250 MeV/nucleon taken with Si-Si-CsI telescope at 6.8°. Insert shows $^{3,4}He$ resolution and Z=1 region.

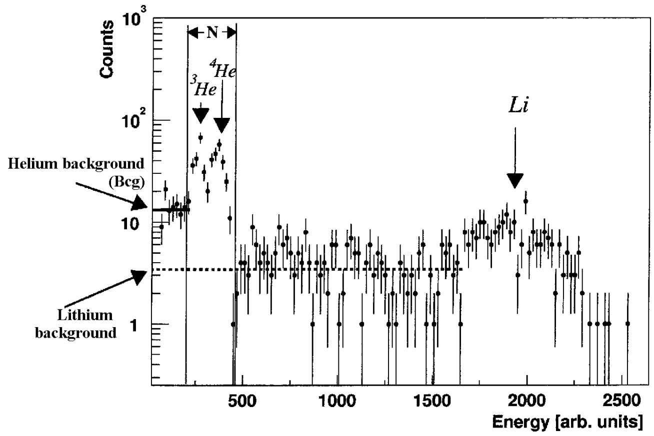

Fig. 3. Experimentally obtained energy spectrum for 16 MeV<Δ*E*2<18 MeV with marked helium and lithium backgrounds.

presented. The contribution of the IED is shown in Fig. 4 (left-hand side) as a function of energy loss in the Δ*E*2 detector. The initial energy was calculated afterwards with the TRIM code from the energy loss in the detector with known thickness as if all fragments were alpha particles. The corresponding range in the CsI scintillator was obtained from the Energy-Range relation calculated with the TRIM code.

There is a visible enhancement of the background to the total ratio at around 14 MeV, which can be ascribed to the additional background produced by lithium PLF's (see Fig. 3). An attempt to subtract this contribution was made in the following way: the lithium background was defined as the events from the region between the He and Li identification lines. The energy spectra for the lithium background were produced for specified intervals in Δ*E*2. An average count number per channel was calculated and subtracted from all helium spectra (Bcg, N). The procedure of the energy and range calculation described above was applied. This simplified procedure of lithium background subtraction assumes that the intensity of the "tail" produced by the IED events is independent of the deposited energy. The available experimental data show that the tail intensity decreases with decreasing deposited energy. Consequently, in some cases our procedure can overestimate the Li contribution.

The results of the percentage contribution with and without lithium background subtraction are shown in Fig. 4 (right-hand side).

Monte Carlo simulations

The Monte Carlo simulations were done using the GEANT3 code [2]. A bunch of monoenergetic fragments coming from the realistically estimated interaction region impinging on the detector surface was traced. Calculations were made for protons and alpha particles from 50 up to 450 MeV/nucleon of the incident energy in 50 MeV/nucleon steps. The number of inelastic interactions induced by incident particles in the scintillator material was counted. The results are shown in Fig. 5.

In order to obtain real energy spectra from the experimentally measured energy distribution of fully identified fragments, one has to correct experimental yields with the formula:

$$Y_{tot} = Y_{exp}/(1-f(E))$$

where: $f(E)$ is the percentage contribution of the IED events. In order to obtain the $f(E)$ function, the results of the GEANT

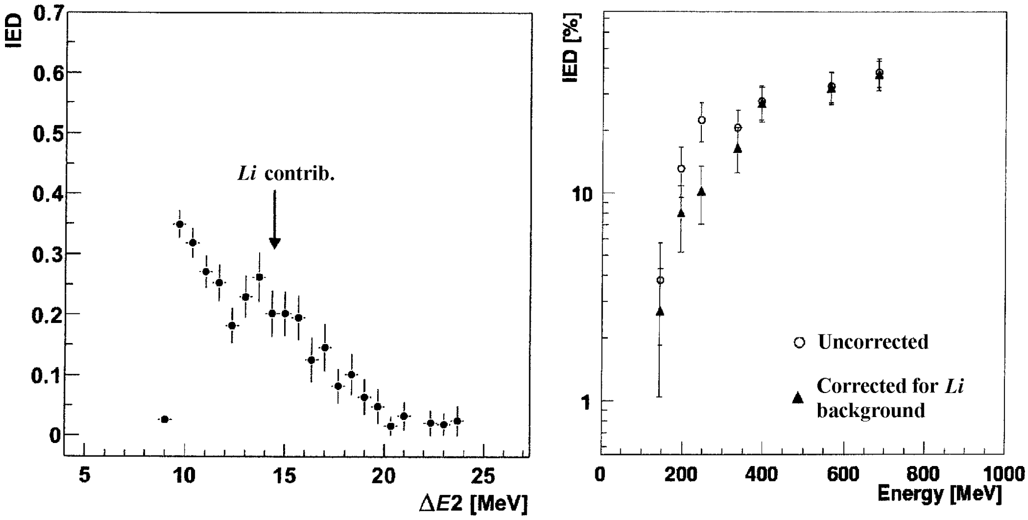

Fig. 4. Contribution of helium IED events as a function of energy loss in 2008 μm Δ*E*2 detector (left-hand side) The Li background contribution is marked with an arrow. Energy dependence of the percentage contribution of helium IED events of the energy loss in CsI(Tl) scintillator with (solid triangles) and without (empty circle) lithium background subtraction (right-hand side).

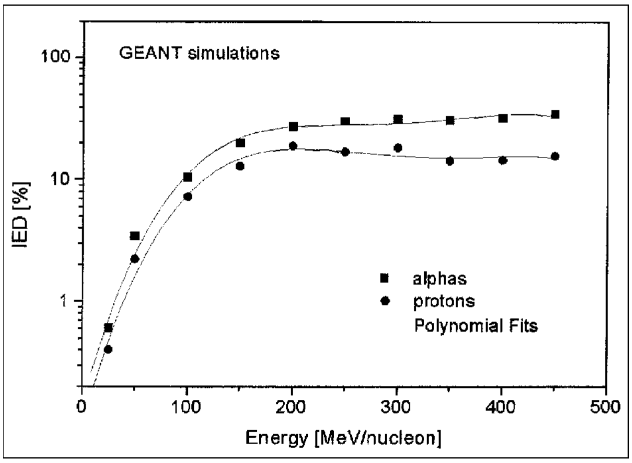

Fig. 5. Energy dependence of the percentage contribution of IED events for protons (circles) and alpha particles (squares) simulated with GEANT (points) and fitted with 4th order polynomial (solid line).

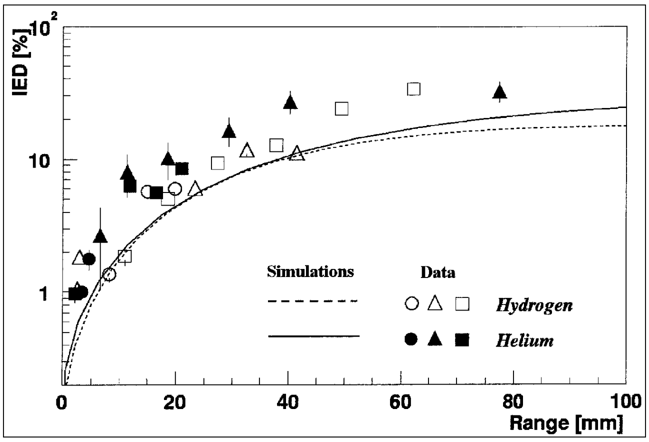

Fig. 7. The percentage contribution of IED events as a function of particle range in CsI(Tl) scintillator. Points and lines have the same meaning as in Fig. 6.

simulations were fitted with the 4th order polynomial (Fig. 5) with parameters given in Table 1. The experimentally measured energy dependence of the percentage contribution of IED events and the polynomial fits are presented in Fig. 6a) for Z=1 and in Fig. 6b) for Z=2 particles.

The agreement with the MC simulations is satisfactory. It is even better when the experimental data are plotted against the particle range of incident particles (Fig. 7). There is a kind of universal (charge- and mass-independent) behaviour of the percentage contribution of the IED events. This is confirmed by the almost identical shape of the MC simulations for protons and alpha particles.

Summary

Measurements of the percentage contribution of IED for hydrogen and helium isotopes in the CsI(Tl) scintillator were made in the 25–180 MeV/nucleon energy range. The Monte Carlo simulations with the GEANT code were made for protons and alpha particles. The energy dependence was fitted with the 4th order polynomial. The obtained fits describe well the experimental data. The percentage contribution as a function of the projectile range seems to be independent of the charge and mass of the incident particles.

The results obtained in this work should prove useful for the calculation of the necessary corrections of energy spectra obtained with the 80 mm CsI scintillator used in the Forward Wall Detector.

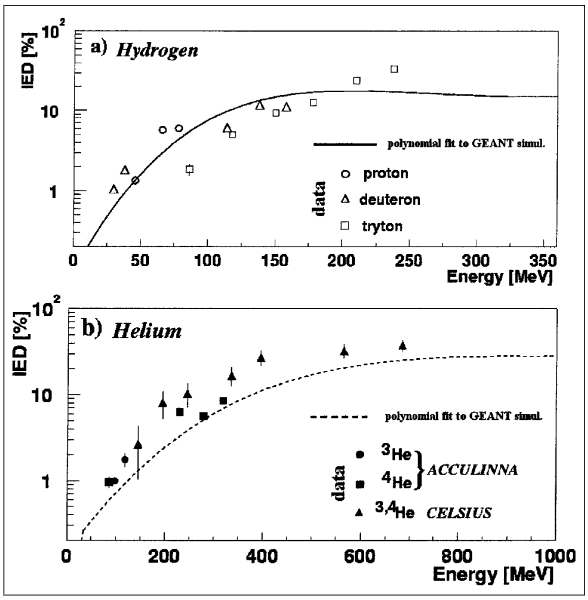

Fig. 6. Comparison of experimental data with MC simulations for hydrogen – a), and helium – b) as a function of their initial energy. Points represent experimental data, lines are polynomial fits to GEANT simulation.

Table 1. Parameters of fit with 4th order polynominal for protons and alpha particles.

Proton	Alpha
-1.02688	-0.8508
0.03205	0.00809
-1.61434×10^{-4}	-1.0507×10^{-5}
3.43562×10^{-7}	5.93635×10^{-9}
-2.64268×10^{-10}	-1.21644×10^{-12}

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