University of Groningen

NE102A Plastic Scintillator Response to He-3 Ions

Jafari, Fatemeh; Mehmandoost-Khajeh-Dad, Ali Akbar; Mohammadi-Dadkan, Maysam; Ghal-Eh, Nima; Yazdandoust, Hamideh

Published in:
Physics of Particles and Nuclei Letters

DOI:
10.1134/S1547477119060219

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2019

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Jafari, F., Mehmandoost-Khajeh-Dad, A. A., Mohammadi-Dadkan, M., Ghal-Eh, N., & Yazdandoust, H. (2019). NE102A Plastic Scintillator Response to He-3 Ions. *Physics of Particles and Nuclei Letters*, *16*(6), 761-767. https://doi.org/10.1134/S1547477119060219

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 19-11-2022

ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2019, Vol. 16, No. 6, pp. 761–767. © Pleiades Publishing, Ltd., 2019.

PHYSICS OF ELEMENTARY PARTICLES
AND ATOMIC NUCLEI. EXPERIMENT

NE102A Plastic Scintillator Response to ^{3}He Ions

Fatemeh Jafari[a], **Ali Akbar Mehmandoost-Khajeh-Dad**[a, *], **Maysam Mohammadi-Dadkan**[a, b],
Nima Ghal-Eh[c], **and Hamideh Yazdandoust**[d]

[a]*Department of Physics, Faculty of Sciences, University of Sistan and Baluchestan, Zahedan, P.O. Box 98155-987, Iran*
[b]*KVI-CART, University of Groningen, Zernikelaan 25, 9747 AA Groningen, the Netherlands*
[c]*Department of Physics, Faculty of Sciences, Ferdowsi University of Mashhad, Mashhad, P.O. Box 91775-1436, Iran*
[d]*Department of Physics, Faculty of Sciences, University of Birjand, Birjand, P.O. Box 97175-615, Iran*
**e-mail: mehmandoost@phys.usb.ac.ir*

Received February 8, 2019; revised February 28, 2019; accepted February 28, 2019

Abstract—Plastic scintillators are widely used in detecting nuclear radiation due to their low construction cost, the ability to be produced in nearly any shape and size and relatively fast time response, among which NE102A (or its equivalents, BC400 and EJ-212) is one of the most famous and widely used scintillators in the focal plane of the particle magnetic spectrometers. In this study, the response of a large NE102A scintillator to ^{3}He ions was investigated in the energy range of 55–87 MeV. The experimental data were collected from the measurements carried out at the accelerator center of University of Groningen, the Netherlands (KVI-CART). The results of this research, acceptably consistent with previous published experimental data, confirmed that the response of the NE102A scintillator to ^{3}He ions with energies more than 10 MeV is approximately linear.

Keywords: ^{3}He, NE102A, BC400, EJ-212, plastic scintillator, non-linear response, optical photon transport

DOI: 10.1134/S1547477119060219

1. INTRODUCTION

The precise knowledge of the detector response is extremely important for the particle detection and spectroscopy. The response of inorganic scintillators such as thallium-doped cesium iodide crystal (Csl(Tl)) to heavy ions has been studied, which supported the scintillation light dependence on energy, electrical charge and mass of ions [1, 2].

In some experiments, it is necessary to register detector counts of order 10^7 counts per second, which imposes the use of a fast detector. In such situations, the use of organic scintillators with a fast time response is recommended. Organic scintillators such as NE102A have a fast decay time and therefore suitable for making phoswich detectors [3], which exhibit excellent pulse shape discrimination properties and are suitable for radiation monitoring [4, 5]. The old plastic scintillators NE102A produced by the Nuclear Enterprise Technology and the new brands BC400 and EJ-212 produced by the Saint Gobin Crystals and Eljen Technology respectively, have the same physical properties.

An ideal scintillation material should convert the kinetic energy of charged particles into detectable light with a high scintillation efficiency. This conversion should be linear so that the light yield should be proportional to deposited energy over as wide a range as possible. An important challenge ahead of using organic scintillator is their relatively non-linear response to heavy ionizing particles [6, 7]. NE102A is one of the most famous, low cost and commonly used organic scintillators. The response of this scintillator has been measured and studied for low-energy neutrons [8] as well as different ions in various energy ranges [9]. However, its response to ^{3}He ions with kinetic energies in the range of 55–100 MeV has not been studied and reported yet, which is accounted as the main purpose of this research.

Detection of ^{3}He ions is important in many ways. ^{3}He is the first bound nucleus comprised of more than one proton which makes it interesting to study the combination of a short-range and a long-range interaction [10]. It is the lightest bound three-body system forming a bridge between the simple two-body nucleon-nucleon interacting case and heavier nuclei [11]. More ever, detection of ^{3}He ions is important to study the ^{10}He exotic nuclei with largest neutron-to-proton ratio [12].

2. MATERIALS AND METHODS

2.1. Experimental Apparatus

The collected data in the experiments carried out at the KVI-CART accelerator affiliated with Groningen University of the Netherlands were used in the present research. Here, 133 and 180 MeV deuteron beams were

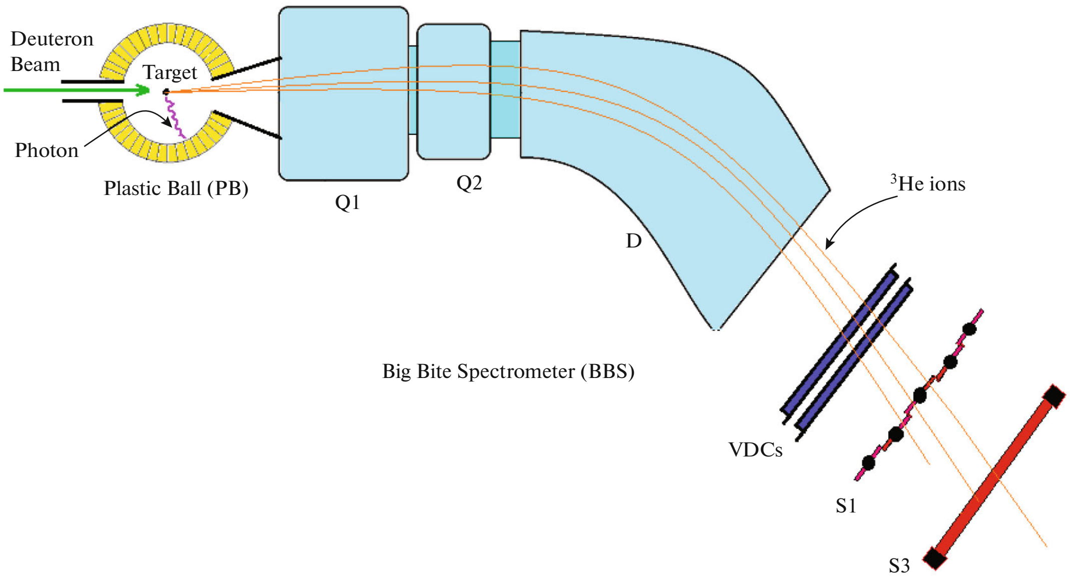

Fig. 1. An overview of the position of the detectors used in the experiment.

incident on a liquid hydrogen target, located at the center of the Plastic Ball (PB) detector which consists of 575 plastic phoswitch detectors and approximately covers 4π steradians solid angle surrounding the hydrogen target.

In these experiments, a variety of interactions may occur and subsequently different particles may be produced. The detection system is so adjusted that as much proton-deuteron radiative capture interaction data as possible are to register. The products of this interaction are photon and ^{3}He. According to the interaction kinematics, photons are emitted at polar angles of zero to 180 degrees whilst ^{3}He is emitted at small forward angles. The energies, the momenta of the photons and ^{3}He ions are determined by the PB detector as well as a Big Bite Spectrometer (BBS), respectively. Figure 1 shows an overview of the apparatus used in the experiments [13].

The BBS magnetic spectrometer consists of two Quadruple and one Dipole magnet. This device was designed to form a point image from a point target in the focal plane of the spectrometer, consisting of two VDCs (Vertical Drift Chambers) that can measure the ion trajectory. Having known the charge and mass of the ion and the incorporated optics of the spectrometer, the ion kinetic energy is determined with high precision.

Passed through the VDCs, the ^{3}He ion collides with an array of five NE102A plastic scintillators, each with 2 × 280 × 1020 mm^3 dimensions, which are vertically arranged. This array of scintillators is called S1 detector. If the ion has enough energy to cross the S1 detector, it could hit another large plastic scintillator of the same material with a size of 6 × 280 × 1020 mm^3, which is horizontally installed in about 40 cm after the S1 detector. This scintillator is called S3 detector. ^{3}He ions, either stop or cross over the S3 detector depending on their kinetic energies.

Through a light guide, every scintillator is coupled from both sides with two Philips XP2262 photomultiplier tubes (PMTs). The outputs of the photomultipliers are shaped and sent to modified ORTEC CCF8200 constant-fraction discriminators (CFDs), which produce logical output signals proportional in length to the time-over-threshold of the incoming pulses. Because the time-over-threshold is related to the energy deposited in the scintillator, one can obtain energy-loss information by measuring the length of the CFD signals using time-to-digital converter (TDC, LeCroy 4298) and thereby avoiding long conversion times needed for charge integration. This has been tested reading out the photo-multiplier signals with a charge-to-digital converter (QDC, LeCroy 2280) in parallel to the above described setup

The trigger in these experiments is set differently according to the energy of ^{3}He ions. In a test with 180 MeV deuteron beam, the ^{3}He ions, have enough energy to reach both S1 and S3 detectors, and hence the trigger is constructed through the logical combination of both detector signals [14, 15].

When the energy of the deuteron beam is 133 MeV, the BBS magnetic spectrometer is re-adjusted by selecting a new kinematical settings and the trigger is performed only by the S1 detector, which is because assumed that all ^{3}He ions have no chance to reach the S3 detector. In this study, we only use information from the mid plate of the S1 detector. This plate is also

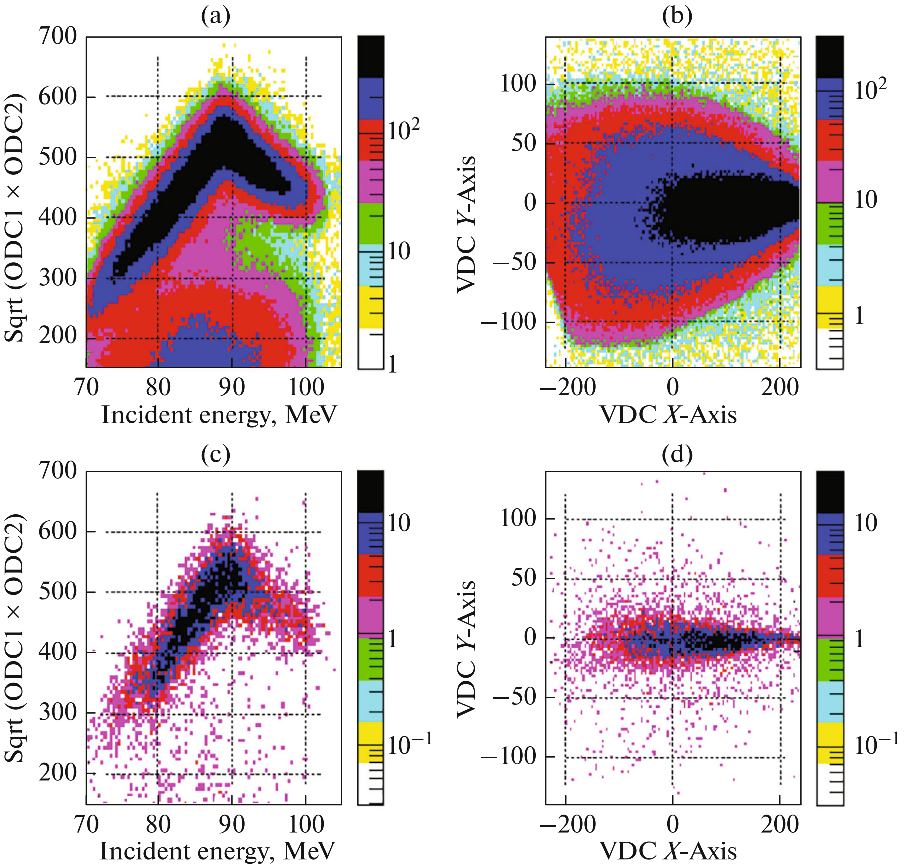

Fig. 2. A sample measurement data used in this study. (a) The square root taken over the product of QDC values of PMTs, located at the two ends of the S3 detector, as a function of incident ion energy. (b) The vertical and horizontal coordinates of the ion interaction location at the first VDC. (c) and (d) are similar to (a) and (b) but a coincidence with a photon detected by the PB is required.

coupled from both sides with the same Philips XP2262 PMTs.

As already mentioned, the energy and emission angle of the gamma rays generated in the proton-deuteron radiative capture reaction is recorded by the PB detector and stored in a so-called event file. Therefore, by taking into account a coincidence condition, the ^{3}He ions emitted at a specific polar and azimuthal angles are determined by conditioning the emission angles of photons through the data reduction process.

The experimental data are presented in Fig. 2 for 180 MeV incident deuteron beam. In this case, the ^{3}He energy is so that the trigger is constructed by both S1 and S3 detectors. The BBS is also set for a distinct kinematical setting. In Fig. 2a, the square root taken over the product of QDC values of PMTs located at the two ends of the detector S3, are plotted as a function of incident ion's energy. The energy of the incident ion is calculated through the spectrometer optics, however, since the ^{3}He ions lose some of their energies before reaching the S3 detector, one has to estimate the energy losses by simulation.

The vertical and horizontal coordinates of the ion interaction locations inside the first VDC are plotted in Fig. 2b. By considering the fact that the ions move along the straight line after leaving the spectrometer, the location of the ion incident on the VDCs determines the interaction points inside detectors S1 and S3.

Figures 2c and 2d are similar to those of Figs. 2a and 2b, but with two additional limitations; (1) A coincidence with a photon detected by the PB detector is required, (2) the photon's azimuthal angles are limited in the range of −10 to +10 degrees. Having restricted the photon azimuthal angles, the ^{3}He ions only hit the mid-height of the VDCs and subsequently the middle regions of S1 and S3 detectors.

As shown in Fig. 1, the ^{3}He ions move through the air and different materials (including the reflective shielding layer and the dead layer on front surface of the S1 and S3 detectors) after passing through the VDCs, hence lose some energy before entering the scintillators.

In this study, the Geant4 toolkit was used to calculate the precise ^{3}He energies while hitting the scintillator surface. Figure 3 shows the deposition energy of

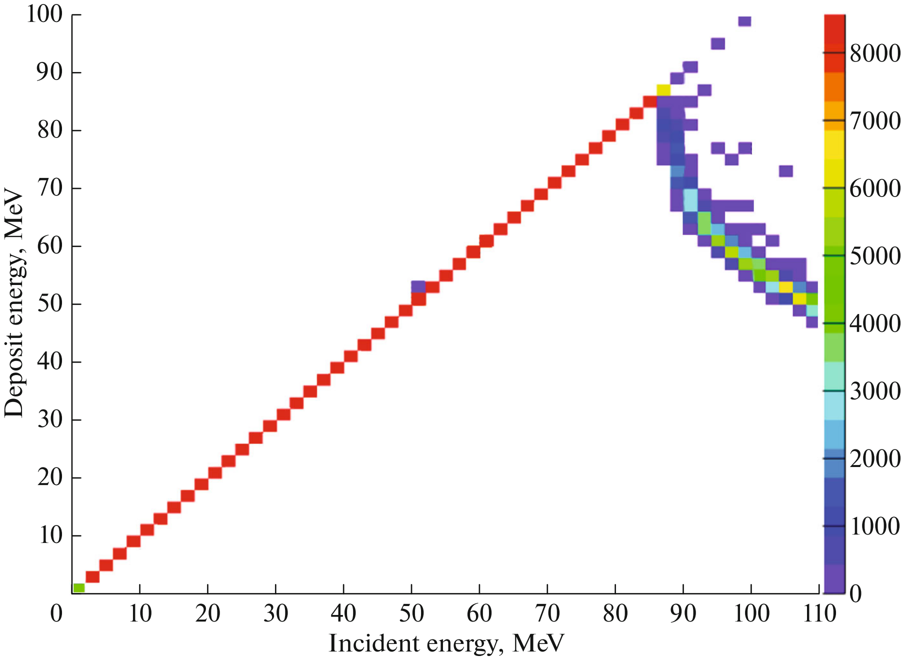

Fig. 3. The deposition energy calculated through Geant4 simulations of ^{3}He ion collisions with NE102A plastic scintillator.

^{3}He ions in a 6 mm thick NE102A scintillator. It should be noted that only ^{3}He ions with energies more than 87 MeV have the chance to penetrate the scintillator. Therefore, it was decided to shift the ^{3}He ion energy calculated with the spectrometer optics until the punch-through point of the experimental data shown in Fig. 2 would become consistent with the corresponding simulation results of Fig. 3.

2.2. Modeling and Measurement of Scintillator Response

In order to obtain the response of the plastic scintillator used in this study, one should also take into account the factors influencing the non-linear behavior of the PMTs. One advantage of the present study, compared to measurements that have been done so far, is that the ^{3}He ions with different energies simultaneously enter the scintillator to experience similar PMT behavior. On the other hand, since it is possible to record and study the time signals of the PMTs and to compare them with the accelerator radio frequency pulses, one can select the coincident events which minimize the space-charge effects at the PMTs.

The schematic of a 6 mm thick NE102A scintillator of the S3 detector is shown in Fig. 4. The scintillator light yield depends strongly on the position where the ^{3}He ions intersect the scintillator. Since VDCs can determine the ion trajectories, one can calculate the ion interaction position inside the scintillator in an extrapolation procedure.

In order to calculate the light collection efficiency of different points of the scintillator, its volume was divided into 175 equal-sized voxels. Then a large number of optical photons were generated at center of each voxel whose wavelengths were sampled from the NE102A scintillator emission curve. Then, the Monte Carlo light transport simulation with PHOTRACK was performed to track the scintillation lights generated at each voxel until either they reached the light guides, absorbed in the scintillator, or escaped from the scintillator. The number of scintillation lights arrived at PMTs divided by those produced in each voxel, known as the light collection efficiency or relative light yield of the voxel, is illustrated in Fig. 5. In order to calculate the scintillator response, it is necessary to correct the QDC values of the PMTs using the light collection efficiency of the voxel where the ^{3}He ion is incident on [16].

Our simulation results show that the light collection efficiency is almost independent of the vertical position of the scintillator (Y-axis). The maximum variation in Y direction was observed at both ends of the scintillator which are less than 15%. The light collection efficiency strongly depends on the horizontal position of the scintillator (X-axis). Therefore, here it was decided (1) to study the ^{3}He ions incident around the central area of the scintillator by restricting the azimuthal angles of the gamma rays in the PB detector (from −10 to +10 degrees), and (2) to correct the QDC values of the PMTs according to the scintillator light collection efficiency. The areas in which the ^{3}He ions collide with the detector were marked schemati-

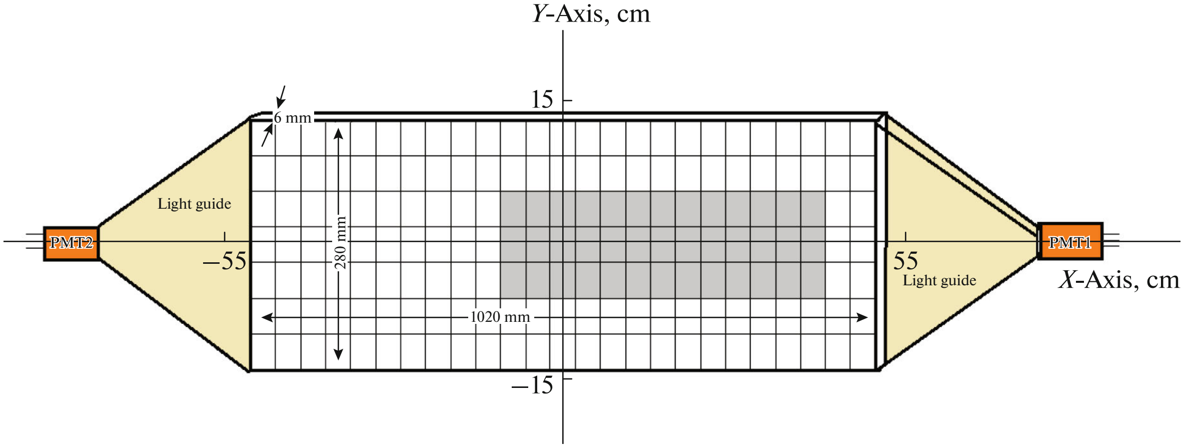

Fig. 4. The schematic of a rectangular NE102A scintillator coupled to light guides and PMTs on both sides.

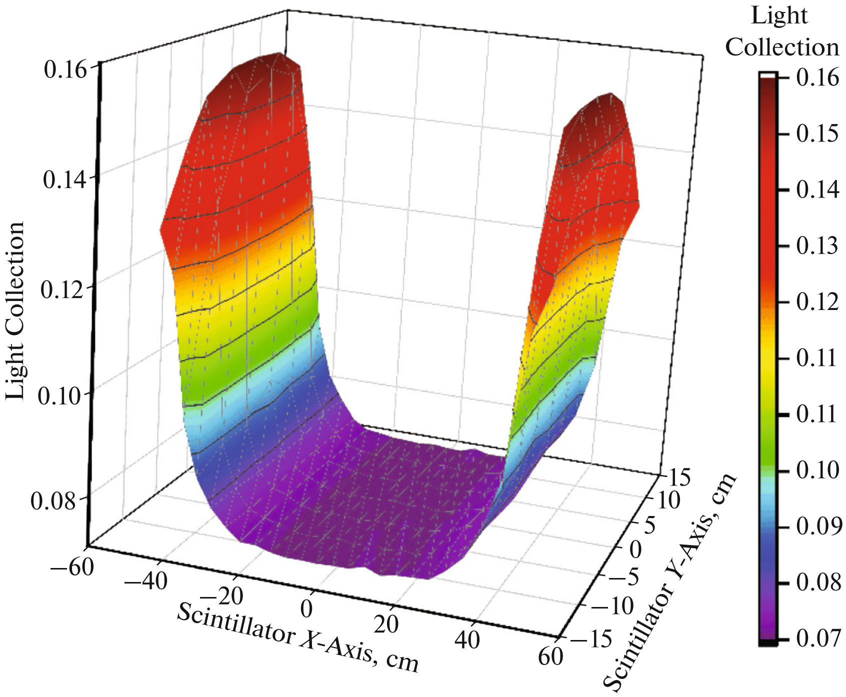

Fig. 5. The light collection efficiency or relative light yield of the scintillator for different voxels shown in Fig. 4.

cally with dark color in Fig. 4. After the necessary corrections, the results of the NE102A scintillator response to the incident ^{3}He ions in the range of 73 to 87 MeV are shown in Fig. 6. The results show that the linear behavior of data in Fig. 2c did not change significantly, but its slope almost doubled.

When the energy of the deuteron beam is 133 MeV, the BBS magnetic spectrometer is re-adjusted by selecting a new kinematical setting and the trigger is performed only by the S1 detector. Here it is assumed that all ^{3}He ions have no chance to reach the S3 detector. In order to study the NE102A scintillator response, a 2 mm-thick vertical scintillator used in the S1 detector is taken into consideration. The Geant4 simulations show that the minimum ^{3}He ion energy to penetrate a 2 mm thick NE102A scintillator is 68 MeV. The necessary light transport simulation has been also performed. After the necessary corrections, the results of the NE102A scintillator response to the incident ^{3}He ions in the range of 57 to 68 MeV are shown in Fig. 6.

Since the measurements have been performed in two configurations, more ever, the PMTs at both ends of S1 are different with those of S3, the results are

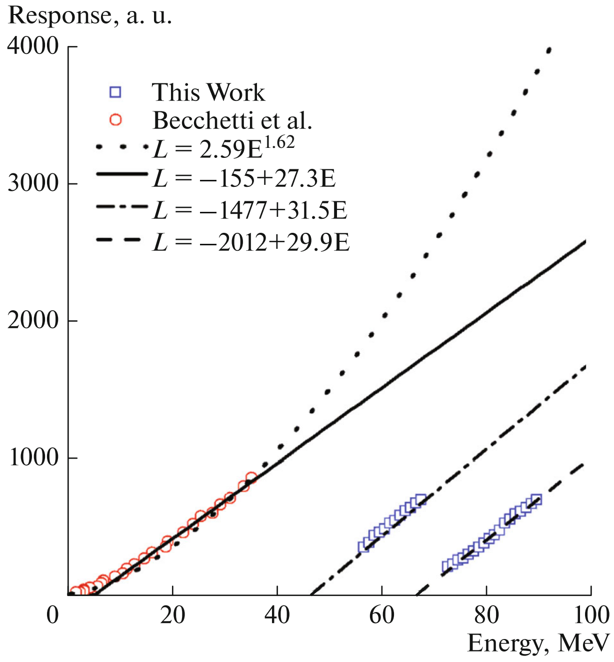

Fig. 6. The NE102A scintillator response to incident ^{3}He ions. Open circles and open squares are the experimental data of [9] and the present study, respectively. The full-line, dot-line and dashed-line are of the fitting models which are all first order in energy with almost the same slopes, whilst the dotted line is nonlinear in energy.

shown separately with two independent series. Unfortunately, in this experiment it was impossible to normalize the two sets of responses to each other.

3. RESULTS AND DISCUSSION

The data shown in Fig. 6 represent three sets of measurements undertaken with three NE102A scintillators at two different laboratories. Open circles show the absolute response values of [9], whilst open squares illustrate the relative response values of the present study.

Following a set of comprehensive and systematic studies, Becchetti et al. reported the response of some scintillators, including NE102A for different ions. They normalized their results to a ThC' α-particles ($E = 8.78$ MeV). Finally, they concluded that the response of NE102A scintillator follows a nonlinear relation, $L = 4(ZA)^{-0.63}E^{1.62}$, for all ion types with incident energies in the range of $0.5\ \text{MeV} < E/A < 15$ MeV. They tried to show that the NE102A scintillator response for ^{3}He ions up to 45 MeV is nonlinear, which is not entirely consistent with our research results.

As it can be seen in Fig. 6, a straight-line can be precisely fitted to the experimental data obtained in the present study. The line slopes are 29.9 ± 0.5 and 31.5 ± 0.6 for the energy ranges of $57 < E < 68$ MeV and $73 < E < 87$ MeV, respectively. The reduced χ^2 is 0.99 for both fittings. The 5% difference between the slopes can be explained by a small nonlinear behavior of the different PMTs.

Our data does not show a nonlinearity dependence of the form $E^{1.62}$. If we fit a quadratic polynomial function of energy to our results, the ratio of the nonlinear term to the linear term is of the order of 0.005E. On the other hand, fitting a straight line to Becchetti et al.'s data for the energies more than 10 MeV, results in a very good accuracy ($\chi^2 = 0.99$) with a slope of 27.3 ± 0.7.

The results of our research along with those of Becchetti et al. confirm that the response of the NE102A scintillator when exposed to ^{3}He ions is linear for energies greater than 10 MeV with an overall error of less than 10%.

4. ACKNOWLEDGMENTS

The authors would like to sincerely thank Professor Nasser Kalantar-Neyestanaki and Professor Johan Messchendorp at the KVI-CART Accelerator Center affiliated with the University of Groningen, the Netherlands, for their precious supports.

REFERENCES

1. D. Horn, G. C. Ball, A. Galindo-Uribarri, E. Hagberg, R. B. Walker, R. Laforest, and J. Pouliot, “The mass dependence of CsI (Tl) scintillation response to heavy ions,” Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 273–276 (1992).
2. I. Gasparic, L. Joulaeizadeh, J. C. S. Bacelar, A. M. van den Berg, R. Caplar, and H. Löhner, “Design, instrumentation, and the light response of the heavy-ion detector array inside the big-bite spectrometer,” Nucl. Instrum. Methods Phys. Res., Sect. A **631**, 62–67 (2011).
3. D. Fluhs et al., “Dosimetry and design of radioactive eye plaques, radiotherapy of ocular diseases,” in *Proceedings of the 1st International Symposium on Special Aspects of Radiotherapy, Berlin, May 1996*; Front Radiat. Ther. Oncol. **30**, 26–38 (1997).
4. S. Usuda, H. Abe, and A. Mihara, “Phoswich detectors combining doubly or triply ZnS(Ag), and No. E102A, BGO and/or NaI(Tl) scintillators for simultaneous counting of α, β and γ rays,” Nucl. Instrum. Methods Phys. Res., Sect. A **340**, 540–545 (1994).
5. E. D. Filippo, R. Fonte, G. Lanzano, and A. Pagano, “The response of a NE102A-BaF2 phoswich detector to low energy heavy ions,” Nuovo Cim. A **107**, 775–782 (1994).
6. T. J. Gooding and H. G. Pugh, “The response of plastic scintillators to high-energy particles,” Nucl. Instrum. Methods Phys. Res. **7**, 189–192 (1960).
7. G. F. Knoll, *Radiation Detection and Measurement* (Wiley, Chichester, 2010).
8. A. A. Naqvi et al., “Response function measurements of an NE102A organic scintillator using an 241Am-Be source,” Nucl. Instrum. Methods Phys. Res., Sect. A **345**, 514–519 (1994).

9. F. D. Becchetti, C. E. Thorn, and M. J. Levine, “Response of plastic scintillator detectors to heavy ions, $Z \leq 35$, $E \leq 170$ MeV,” Nucl. Instrum. Methods Phys. Res., Sect. A **138**, 93–104 (1976).
10. J. Kirscher and D. Gazit, “The Couloumb interaction in helium-3 interplay of strong short-range and weak long-range potentials,” Phys. Lett. B **755**, 253–260 (2016).
11. N. Kalantar-Nayestanaki, E. Epelbaum, J. G. Messchendorp, and A. Nogga, “Signatures of three-nucleon interactions in few-nucleon systems,” Rep. Prog. Phys. **75**, 1–41 (2012).
12. A. Matta et al., “New finding on structure and production of ^{10}He from ^{11}Li with the (d, ^{3}He) reaction,” Phys. Rev. C **92** (4), 1–6 (2015).
13. A. A. Mehmandoost-Khajeh-Dad et al., “Proton-deuteron radiative capture cross-sections at intermediate energies,” Eur. Phys. J. A **47**, 59–64 (2011).
14. H. J. Wortche et al., “Instrumentation for and first results on nuclear responses for supernova explosions,” Nucl. Phys. A **687**, 321–328 (2001).
15. A. M. van den Berg, “The big-bite spectrometer for AGOR,” Nucl. Instrum. Methods Phys. Res., Sect. B **99**, 637–640 (1995).
16. N. Ghal-Eh, M. C. Scott, R. Koohi-Fayegh, and M. F. Rahimi, “A photon transport model code for use in scintillation detectors,” Nucl. Instrum. Methods Phys. Res., Sect. A **516**, 116–121 (2004).