Response of GAGG(Ce) scintillators to different charged particles

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Abstract

Studies of nuclear clustering rely on charged-particle telescopes to detect breakup fragments and typically require high-resolution scintillators for precise total-energy determination. GAGG(Ce) is a promising scintillator for charged-particle detection at high counting rates because of its high light yield, fast response, and non-hygroscopic nature. However, systematic data on its light-output response to different charged particles remain scarce. In this work, we present a systematic study of the scintillation light-output response of GAGG(Ce) crystals to various charged particles and quantify the associated quenching behavior. The relationship between the scintillation light output and the deposited energy is established over a broad range of particle species and energies, providing essential experimental input for response modeling and energy calibration of GAGG(Ce)-based charged-particle detector systems.

Full Text

Preamble

Response of GAGG(Ce) scintillators to different charged particles Kai-Jie Zhou,1 Zai-Hong Yang,1, ∗ Hooi-Jin Ong,2, 3, 4, 5, 6 Qi-Te Li,1 Ze-Yu Du,1 Jia-Wei Bian,1 Cheng Wang,1 Jin-Ning Li,1 Satoru Terashima,2, 5, 6 Bing-Feng Lv,2, 3 Xuan Wang,7 Zhi-Chao Zhang,2 Hong-Na Liu,8 Yu-Yang Yu,8 Peng-Jie Li,9 and Ye-Lei Sun7 1School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China 2State Key Laboratory of Heavy Ion Science and Technology, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China 3School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing

100049, China 4Joint Department for Nuclear Physics, Lanzhou University and Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China 5Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan 6Nishina Center for Accelerator-Based Science, RIKEN, 2-1 Hirosawa, Wako, 351-0198 Saitama, Japan 7School of Physics, Beihang University, Beijing 100191, China 8School of Physics and Astronomy, Beijing Normal University, Beijing 100875, China 9Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China Studies of nuclear clustering rely on charged-particle telescopes to detect breakup fragments and typically re- quire high-resolution scintillators for precise total-energy determination. GAGG(Ce) is a promising scintillator for charged-particle detection at high counting rates because of its high light yield, fast response, and non- hygroscopic nature. However, systematic data on its light-output response to different charged particles remain scarce. In this work, we present a systematic study of the scintillation light-output response of GAGG(Ce) crys- tals to various charged particles and quantify the associated quenching behavior. The relationship between the scintillation light output and the deposited energy is established over a broad range of particle species and ener- gies, providing essential experimental input for response modeling and energy calibration of GAGG(Ce)-based charged-particle detector systems.

Keywords: GAGG(Ce) scintillator, scintillation light-output response, energy calibration, charged-particle telescope

INTRODUCTION

The study of exotic nuclear structures is a central topic in nuclear physics [1]. Owing to the continuous development of the techniques for providing radioactive ions beams (RIB) and the construction of next-generation RIB facilities [2–7], nuclear structure studies have expanded toward regions far from the stability line, where nuclei often behave as weakly bound open quantum systems. The structure of such nuclei can deviate significantly from traditional nuclear structure model expectations, giving rise to exotic structure phenomena such as neutron halos and clustering [8–10]. Nuclear cluster- ing, where nucleons form correlated substructures such as α clusters, is a key emergent feature of nuclear many-body sys- tems [1, 10]. Well-known examples include the Hoyle state of 12C with a 3-α cluster structure [11] and molecular-like clus- ter structures in Be and C isotopes [12, 13]. Studies of nuclear clustering can provide important constraints on nuclear inter- actions and theoretical descriptions of nuclei, as well as the properties of nuclear matter [8, 14, 15].

Experimental studies of clustering are typically carried out using inelastic scattering and knockout reactions, which re- quire precise measurements of energies and emission an- gles of charged-particle reaction products [9]. Consequently, charged-particle telescope arrays with high energy and an- gular resolution have become indispensable tools for such $*$ Corresponding author, zaihong.yang@pku.edu.cn investigations. A variety of charged-particle telescope sys- tems based on combinations of silicon detectors and scintilla- tors have been developed worldwide, including LASSA [16], MUST2 [17], HiRA [18], FARCOS [19, 20], and TO- GAXSI [21].

Motivated by these experimental requirements, we have developed a charged-particle telescope array based on double-sided silicon detectors (DSSD) coupled with Ce- doped Gd3Al2Ga3O12 scintillators, GAGG(Ce). The system is designed to provide particle identification and energy mea- surement over a broad dynamic range, and is optimized for multi-particle coincidence measurements relevant to studies of nuclear cluster structures.

GAGG(Ce) is a new inorganic scintillator material fea- turing high density, high light yield, fast decay time, and excellent chemical and mechanical stability [22]. Unlike conventional NaI(Tl) and CsI(Tl) scintillators, GAGG(Ce) is non-hygroscopic. Previous studies reported dominant decay time constants of approximately 60 - 100 ns [23], making GAGG(Ce) particularly well suited for long-term operation and high count-rate experimental environments.

Despite these favorable properties for nuclear physics ex- periments, systematic studies of the scintillation response of GAGG(Ce) scintillators remain limited, particularly with re- spect to their light-output response to different charged par- ticles. Existing measurements have primarily focused on low-energy α particles and protons [24, 25], while system- atic investigations covering higher energies and heavier ions are scarce. Such information is essential for applications in- volving energetic heavy charged particles, such as quasi-free knockout and inelastic scattering reactions with RIBs.

In this work, we present a systematic study of the light- output response of GAGG(Ce) scintillators to various charged particles, including 4 He, 10Be, 10C, 11C, 16C, and 18O with energies above 100 MeV. The scintillation efficiency, ex- pressed as dL/dE, is analyzed as a function of the linear energy transfer (LET), dE/dx. These results provide essen- tial experimental input for understanding quenching effects in GAGG(Ce) scintillators and support for their application in charged-particle detector system for nuclear structure stud- II. EXPERIMENTAL SETUP AND DETECTOR SYSTEM The experiment was carried out at the RIBLL1 beam line [26] of the Institute of Modern Physics, Chinese Academy of Sciences. Secondary beams of 4He, 10Be, 10C, and 11C were produced via fragmentation of a 12C primary beam with an energy of approximately 80 MeV/nucleon, while the 16C secondary beam was produced using an 18O primary beam with an energy of approximately 60 MeV/nu- cleon. All secondary beams were purified and transported to the experimental terminal by the RIBLL1 beam line. An energy-degraded 18O primary beam was also delivered di- rectly to the GAGG(Ce) crystals for dedicated response measurements. The beam intensity was limited to approximately 1.5 × 105 pps in order to reduce the dead time of the data acquisition system.

A schematic view of the experimental setup is shown in Fig. 1

Figure 1

Figure 1: Figure 1

. An ΔE − E telescope was constructed using a DSSD as the ΔE detector, followed by an array of GAGG(Ce) scin- tillators serving as the E detector. The ΔE detector was a 500-µm-thick DSSD with an active area of 64 mm × 64 mm.

The E detector consisted of an array of 36 GAGG(Ce) scin- tillator crystals, labeled from 0 to 35 as indicated in Fig. 1.

All scintillators were manufactured by Scionix (Netherlands), with individual crystal dimensions of 20 mm × 20 mm × 25 mm.

Fig. 1. Schematic view of the experimental setup at RIBLL1 beam- Beams of different particle species and energies were di- rectly injected into the telescope. After passing through the DSSD, the residual energies of the incident particles were fully deposited in the GAGG(Ce) scintillators. The parti- cle species used in the measurement and the corresponding deposited energies in the GAGG(Ce) scintillators, calculated using LISE++ [27] while accounting for energy losses in the secondary target and the DSSD, are listed in Table 1 .

To enhance light collection efficiency, the lateral surfaces of each GAGG(Ce) crystal were wrapped with enhanced specular reflector (ESR) film. The beam-incident surface was covered with a 2-µm-thick aluminized Mylar foil, which pro- vided effective light shielding while minimizing energy loss of the incident particles. The rear surface of each scintillator was coupled to a Hamamatsu S3590-08 photodiodes (PD), with an active area of 10 mm × 10 mm, using optical silicone grease.A photograph of a fully assembled scintillator unit is shown in Fig. 2 FIGURE:2, and a photograph of the photodiode is shown in Fig. 2(b).

Fig. 2. Photograph of (a) a fully assembled scintillator unit (b) and the photodiode The output signals from the photodiodes were amplified us- ing charge-sensitive preamplifiers (SPA-02) [28] before digi- tization. The preamplifiers feature a compact design and high channel density, which allows convenient installation inside the chamber, and significantly simplifies cabling and experimental setup. The decay time constant of the preamplifiers is set to 20 µs, optimized for the requirements of the present measurements.

Signal digitization and data acquisition were performed us- ing 16-channel Pixie-16 digital pulse processors manufac- tured by XIA LLC. The Pixie-16 modules were installed in a Compact PCI/PXI-based chassis and are capable of transferring data from the module memory to the host computer at rates up to 109 MB s−1 [29]. Digital trapezoidal filtering, implemented in the Pixie-16 module, was applied to process the exponentially decaying signals from the charge-sensitive preamplifiers, enabling accurate pulse-height (energy) extraction and timing measurements.

A schematic diagram of the signal chain is shown in Fig. 3 [FIGURE:3].

Scintillation light produced in each GAGG(Ce) crystal is de- tected by a PD, and converted into a charge signal, which is subsequently feed into a charge-sensitive preamplifier (SPA- 02) for amplification and shaping. The preamplifier outputs are then delivered to the Pixie-16 modules for digitization.

The pulse-height and timing information are extracted on an event-by-event basis using digital signal processing, and the processed data are transferred to the host computer for storage Table 1. Particle species and deposited energies in GAGG calculated using LISE++ Particle deposited energy in GAGG(Ce) (MeV) Fig. 3. Schematic of the electronics and data-acquisition chain. and offline analysis.

III. PULSE SHAPE Prior to the beam-test experiment, cosmic-ray events were used to examine the signal characteristics and readout perfor- mance of the GAGG(Ce) scintillators. A representative wave- form recorded with an oscilloscope is shown in Fig. 4 FIGURE:4. To obtain a typical pulse shape, a large number of waveforms were time-aligned at their peak positions and averaged point by point, as shown in Fig. 4(a). The observed signal pulse width is approximately 20 µs, and the baseline fluctuation is within $±$5 mV, indicating stable signal output and acceptable electronic noise levels.

To accommodate the high count-rate conditions anticipated in RIB experiments, the decay time constant of the charge- sensitive preamplifier was optimized by adjusting the input resistance. As shown in Fig. 4(b), the resulting pulse width of about 20 µs is sufficiently short to handle event rates of 100 kHz, thereby satisfying the experimental requirements.

IV. RELATIVE LIGHT OUTPUT FOR DIFFERENT PARTICLES The output signals from the charge-sensitive preamplifiers were digitized and processed by the XIA acquisition system.

Each waveform is shaped by a digital trapezoidal filter, and the trapezoid height is extracted as the pulse amplitude, here- after denoted as the ADC value.

Using crystal No. 15 as a representative example, the mea- sured ADC values for all beam settings are shown in Fig. 5 [FIGURE:5] together with the corresponding deposited energies in the GAGG(Ce) crystal. A clear quenching behavior is observed: for a given deposited energy, the measured light output de- creases as the incident ion becomes heavier, due to the in- crease of the LET (dE/dx).

For a fixed electronic configuration and shaping parame- ter setting, the ADC value is proportional to the scintilla- tion light collected by the PD. Therefore, the ADC values can be regarded as a measure of the relative light output of the GAGG(Ce) scintillator. To quantify the quenching effect, we investigated the dependence of the relative light output on particle species and deposited energy, and modeled the scin- tillation efficiency dL/dE as a function of LET.

Figure 7

Figure 2: Figure 7

A. Birks Model As a commonly used empirical description of scintillation quenching, the Birks formula relates the light output per unit path length dL/dx to the stopping power of the charged par- ticle [30] S (dE/dx) 1 + kB (dE/dx) where the parameter S is a scintillation normalization con- stant and kB is the Birks factor describing the reduction of scintillation efficiency with increasing dE/dx. The Birks for- mula has been successfully used to describe the behavior of various scintillator materials, such as CsI [31, 32]. Dividing Eq. 1 by dE/dx yields 1 + a1 (dE/dx) where a0 and a1 are fit parameters. The total light output for a particle depositing an energy E0 in the crystal is obtained by integrating dL/dE over the deposited energy Fig. 4. (a) Representative GAGG(Ce) scintillator waveform recorded during the cosmic-ray signal inspection. (b) Average waveform obtained by peak-aligned averaging of multiple signals.

Fig. 5. Measured light output (in ADC channels) versus the de- posited energy for different beams (GAGG(Ce) crystal No. 15). The uncertainties of the data are much smaller than the marker size and are therefore not shown.

Fig. 6 [FIGURE:6]. Relative light output as a function of deposited energy for different ions measured with GAGG(Ce) crystal No. 15. Points de- note the experimental data, and solid lines show the fit results using the Birks formula [30]. (cid:90) E0 1 + a1 (dE/dx) dE′ + C Accordingly, the total light output is given by where C accounts for the overall offset in the relative light- output scale.

For each ion species, dE/dx was obtained from the corre- sponding stopping-power calculation using LISE++, assum- ing a GAGG(Ce) density of 6.63 g cm−3 and Eq. 3 was used to fit the measured relative light output. Fig. 6 summarizes the resulting light-output trends for crystal No. 15, and Ta- ble 2 lists the obtained parameters. With the Birks model, the deposited energies reconstructed from the measured light output show a 1-15% deviation from the LISE++ calculated values over the full data set.

B. Modified Birks Model To improve the description of scintillation response at low LET, Koba et al. introduced an additional term in the denom- inator, leading to the modified Birks parameterization [33]: 1 + a1 (dE/dx) + a−1 (dE/dx)−1 (cid:90) E0 1 + a1 (dE/dx) + a−1 (dE/dx)−1 dE′ + C The fit result obtained using the modified Birks model for crystal No. 15 is shown in Fig. 7

, and the fitted parameters are summarized in Table 2 . Compared with the standard Birks model, the modified Birks parameterization provides a visi- bly improved description of the data. The deviation between reconstructed and expected deposited energies is reduced to within 3 % over the investigated energy and particle range.

Similar improvements are also observed for other crystals in the array, indicating that the modified Birks model provides an adequate empirical description of the scintillation response —particularly the quenching behavior —of GAGG(Ce) scintillators for energetic charged particles.

C. Crystal-to-crystal comparison To evaluate the reproducibility of the scintillation response, seven GAGG(Ce) crystals located near the center of the array were selected and analyzed using the same procedure. Within Fig. 7. Relative light output as a function of deposited energy for different ions measured with GAGG(Ce) crystal No. 15. Points de- note the experimental data, and solid lines show the fit results using the modified Birks parameterization [33].

Fig. 8 [FIGURE:8]. a1 values from the modified Birks fits for seven GAGG(Ce) crystals near the center of the array. The error bars indicate the fit uncertainties. The red dashed line indicates the average a1 value for the selected 7 crystals.

Table 2. Fit parameters for crystal No. 15. parameters Model Birks Modified Birks Parameter Value 94.03(2) 1.354(7) 84.6(10) 0.99(4) -0.0091(6) the modified Birks framework, the parameter a1 provides a convenient quantitative characterization of the quenching strength.

As shown in Fig. 8, the extracted a1 values are all close to 1, indicating that the quenching behavior is highly consistent among these crystals from the same production batch. The red dashed line in Fig. 8 indicates the average a1 value for the selected 7 crystals. This consistency suggests that the fit- ted parameters derived in this work are representative of the response of the GAGG(Ce) crystals, rather than reflecting an isolated case of a single detector. Consequently, the obtained parameterization can be applied to similar GAGG(Ce) scin- tillators for response estimation and quenching correction in future charged-particle detection experiments under compa- rable conditions.

D. Discussion Previous studies of GAGG(Ce) have largely focused on light ions, mainly protons and α particles, at relatively low energies, providing limited reference data for the higher de- posited energies and heavier nuclei relevant to quasi-free knockout-reaction measurements with radioactive ion beams.

Furuno et al. reported measurements for protons with en- ergies of 5 MeV to 68 MeV and α particles with energies of 8 MeV to 54 MeV in GAGG(Ce) [25]. Fig. 9 [FIGURE:9] shows a comparison between their results and the present work. To remove the overall scale difference, both results were nor- malized to the light output of 4He at a deposited energy of Edep 116.5 MeV. In addition, the relative light output of 16C as a function of deposited energy is included as a repre- sentative example of a heavier nucleus at higher energy.

Fig. 9. Comparison of the relative light output of GAGG:Ce ob- tained using the parameterization from the present work (solid lines) with that reported by Furuno et al. 25 for 4He and 16C. Solid circles represent the experimental data from the present work.

After normalization, the two results are quite close for 4He, both showing good agreement with the data.

In contrast, larger deviations appear for heavier ions and at higher de- In particular, the parameterization of Fu- posited energies. runo et al. fails to adequately describe the response for 16C, whereas the present parameterization provides a consistent and reliable description. This comparison indicates that the results reported here are more suitable for applications involv- ing higher deposited energies and heavier nuclei than those covered in previous studies.

V. ENERGY RESOLUTION The light-output response functions obtained in the previ- ous sections provide an energy calibration for the GAGG(Ce) scintillators. Based on this calibration, the energy resolution of the GAGG(Ce) crystals was evaluated using the 4He beam.

By restricting the energy spread of the secondary 4He beam, the particles entering the telescope were prepared with an approximately monoenergetic energy distribution, en- abling a reliable determination of the energy resolution of the GAGG(Ce) scintillators. Events corresponding to particles incident nearly normal to the scintillator surface were selected using the position information provided by the DSSD, thereby minimizing variations in the incident angle and positions and thus the associated uncertainties in energy deposition.

Under these conditions, the energy resolution of the GAGG(Ce) crystals in the array was determined for the 212.9 −MeV 4He beam. As a representative example, the en- ergy spectrum measured with the GAGG(Ce) crystal located at the center of the array (crystal No. 15) is shown in Fig. 10 [FIGURE:10], together with the corresponding Gaussian fit. An energy res- olution of 0.76(2)% (FWHM) was obtained for this crystal, demonstrating that the GAGG(Ce) scintillators provide suf- ficient energy resolution for the requirements of the present and future charged-particle detection experiments.

Fig. 10. Energy spectrum measured with a GAGG(Ce) scintillator for a 212.9 MeV 4He beam. The red line represents the Gaussian fit, giving an energy resolution of 0.76(2)%.

VI. SUMMARY In this work, a systematic study of the the scintillation light-output response of GAGG(Ce) scintillators to various [1] Y. Ye, X. Yang, H. Sakurai, and B. Hu, Nature Reviews Physics 7, 21 (2025). [2] J. C. Yang, J. W. Xia, G. Q. Xiao, H. S. Xu, H. W. Zhao, X. H. Zhou, X. W. Ma, Y. He, L. Z. Ma, D. Q. Gao, J. Meng, Z. Xu, R. S. Mao, W. Zhang, Y. Y. Wang, L. T. Sun, Y. J. Yuan, P. Yuan, W. L. Zhan, J. Shi, W. P. Chai, D. Y. Yin, P. Li, J. Li, L. J. Mao, J. Q. Zhang, and L. N. Sheng, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 317, 263 (2013). [3] J. W. Xia, W. L. Zhan, B. W. Wei, Y. J. Yuan, M. T. Song, W. Z. Zhang, X. D. Yang, P. Yuan, D. Q. Gao, H. W. Zhao, X. T. Yang, G. Q. Xiao, K. T. Man, J. R. Dang, X. H. Cai, Y. F. charged particles has been carried out. The light-output response of GAGG(Ce) scintillators was investigated using beams of different species and energies. The experimental data were analyzed using both the standard Birks model and a modified Birks parameterization. While the standard Birks model provides a qualitative description of the response, the modified Birks model yields a significantly improved agree- ment with the experimental data. The resulting fit parame- ters of the modified Birks model were found to be consistent across multiple GAGG(Ce) crystals from the same production batch, indicating good reproducibility and enabling a trans- ferable description of the scintillation response, particularly the quenching behavior. Based on the established calibration, the energy resolution of the GAGG(Ce) crystals was evaluated using a 4He beam with a deposited energy of 212.9 MeV.

Taking the central crystal (No. 15) as a representative exam- ple, an energy resolution of 0.76(2)% (FWHM) was achieved, demonstrating that the detector performance satisfies the re- quirements of charged-particle detection measurements in nu- clear physics experiments. These results provide a practical basis for estimating light yield and signal amplitude in future experiments.

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