The identification methods of light charged particles with a CsI(Tl) detector based on the pulse shape analysis technique

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Abstract

Four types of pulse shape analysis (PSA) algorithms were examined with the objective of identifying the light charged particles utilizing a CsI(Tl) detector. These included the fall time comparison method, the charge comparison method, the Reconstructive Particle IDentification (RPID) method, and the Quick Particle IDentification (QPID) method. The beam test with the CsI(Tl) detector demonstrates that the charge comparison method, the RPID method, and the QPID method exhibit satisfactory capacities in identifying the incident particles of hydrogen and helium isotopes. Conversely, the fall time comparison method exhibits suboptimal performance in particle identification. A crystal array and a silicon detector array, which can compose a telescope system, are under construction at the experimental terminals of the HIAF-HIRIBL facility. The present study demonstrates that the CsI(Tl) detector alone can achieve a better result in identifying the incident particles with a charge number Z less than 3. This capability enables the restriction of silicon detectors utilization to the forward polar angle region, with the larger polar angle region covered by CsI(Tl) detectors during some specific experimental studies. CsI(Tl) detectors have been demonstrated to exhibit sufficient performance in identifying light charged particles.

Full Text

Preamble

The identification methods of light charged particles with a CsI(Tl) detector based on the pulse shape analysis technique∗ Guo-Li Zhang,1, 2 Duo Yan,1, † Yu-Hong Yu,1, 2, 3 Zhi-Yu Sun,1, 2, 3 Shu-Wen Tang,1, 2 Xue-Heng Zhang,1, 2,

3 Shi-Tao Wang,1, 2 Fang Fang,1, 3 Yong-Jie Zhang,1, 2 Ya-Zhou Sun,1, 2 and Shu-Ya Jin1 1State Key Laboratory of Heavy Ion Science and Technology, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China 2School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China 3Advanced Energy Science and Technology Guangdong Laboratory, Huizhou 516000, China Four types of pulse shape analysis (PSA) algorithms were examined with the objective of identifying the light charged particles utilizing a CsI(Tl) detector. These included the fall time comparison method, the charge com- parison method, the Reconstructive Particle IDentification (RPID) method, and the Quick Particle IDentification (QPID) method. The beam test with the CsI(Tl) detector demonstrates that the charge comparison method, the RPID method, and the QPID method exhibit satisfactory capacities in identifying the incident particles of hy- drogen and helium isotopes. Conversely, the fall time comparison method exhibits suboptimal performance in particle identification. A crystal array and a silicon detector array, which can compose a telescope system, are under construction at the experimental terminals of the HIAF-HIRIBL facility. The present study demonstrates that the CsI(Tl) detector alone can achieve a better result in identifying the incident particles with a charge number Z less than 3. This capability enables the restriction of silicon detectors utilization to the forward polar angle region, with the larger polar angle region covered by CsI(Tl) detectors during some specific experimental studies. CsI(Tl) detectors have been demonstrated to exhibit sufficient performance in identifying light charged particles.

Keywords: Particle identification, CsI(Tl) detector, Pulse shape analysis

INTRODUCTION

The exotic nuclei, particularly those situated near drip- lines, represent a subject of profound fascination within the realm of nuclear physics [1]. Its significant applications in- clude the examination of various nuclear models [2, 3], the deduction of the stellar evolution [4, 5], and even the guaran- tee of human health, such as with radio-pharmaceuticals [6, 7]. The experimental study of exotic nuclei is predominantly conducted through the analysis of nuclear reactions. Due to the typical unavailability of the radioactive target, the experi- ments are conducted in inverse-kinematic mode. The identifi- cation of beam-like fragments is paramount for experimental studies.

Direct nuclear reactions have emerged as a highly effective experimental probe, providing crucial insights into the struc- ture of exotic nuclei within the intermediate and high energy range. In the context of sophisticated experiments involving specific reaction channels, such as the knockout reaction [8], it is common to observe the presence of one or more light fragments alongside the beam-like heavy residue among the nuclear reaction products. The experimental measurements of the heavy residue, in conjunction with the emitted γ-rays, were frequently utilized to ascertain the total cross-section, $*$ We would like to express our gratitude to the CEE Collaboration for their authorization to

position our detectors adjacent to theirs and utilize their beam time to study our research topic. This work was supported by the project of top-notch leading talents in Gansu Province, the National Nat- ural Science Foundations of China (No. 12375186), and the Research Program of Heavy Ion Science and Technology Key Laboratory, Institute of Modern Physics, Chinese Academy of Sciences (HIST2025KS01). † Corresponding author, yanduo@impcas.ac.cn irrespective of the distinct reaction channels [9, 10]. The ad- ditional measurement of the light fragments on an event-by- event basis can facilitate the distinction between elastic and inelastic reaction channels and provide an assessment of the influence of each reaction mechanism on the result [8]. In the context of the quasi-free proton scattering reaction in inverse- kinematics mode, the measurement of nucleon pairs consti- tutes the element approach to impose constraints on the ob- servable energy and momentum space of the single-particle state [11, 12]. The objective of this study is to examine the identification methods for light charged particles, with a particular focus on the isotopes of Hydrogen: proton (p), deuteron (d), and triton (t).

The High-Intensity heavy-ion Accelerator Facility (HIAF) in Huizhou, China, is scheduled to commence operations in 2026 [13, 14]. The HIgh-rigidity Radioactive Ion Beam Line (HIRIBL), formerly designated as the High-energy FRagment Separator (HFRS), is an in-flight beam separator operated in relativistic energies region at the HIAF [15, 16]. Two experi- mental terminals, designated as MF4 and MF6, are currently under construction at HIAF-HIRIBL. The purpose of these terminals is to explore the nuclear landscape, with a particu- lar focus on exotic nuclei at the limits of nuclear stability [17].

At these terminals, a crystal array will be constructed around the reaction target to measure the emitted γ-rays as well as the light charged particles [18–20]. Additionally, the con- struction of an array of double-sided silicon strip detectors is planned between the reaction target and the crystal array to obtain the tracks of the light charged particles. Figure 1 [Figure 1: see original paper] is the schematic view of the detectors layout. The identifica- tion of light charged particles is achieved through the integra- tion of these two arrays, employing the conventional ΔE-E method [21, 22]. Given that the high-beam energies result in the kinematic forward focusing of the produced light-charged particles, the silicon strip detector array will be positioned to cover only the forward polar-angle region. Furthermore, it is economically advantageous to utilize a reduced number of sil- icon strip detectors, given the sensitivity of their performance to radiation damage. This sensitivity often necessitates the replacement of the detectors for each experimental iteration.

Consequently, within the specified region of the larger polar angle, the employment of CsI(Tl) detectors is exclusively des- ignated for the measurement of light charged particles. The Pulse Shape Analysis (PSA) method will be employed to per- form Particle IDentification (PID) with these CsI(Tl) detec- tors.

Fig. 1. Schematic view of the detectors layout at the experimental terminals of HIRIBL.

The PSA method for CsI(Tl) scintillator is predicated on the phenomenon that the proportion of fluorescence with dif- ferent decay time varies with the ionization density of the incident particle [23]. This phenomenon facilitates the attainment of PID through the analysis of the output digitized waveform of the CsI(Tl) crystal, which is obtained by means of waveform digitization technique. Presently, PSA is widely employed in the identification of particles exhibiting differ- ent interaction mechanisms with scintillation materials, in- cluding the discrimination of charged particles, neutrons, and γ-rays [24, 25]. In the context of identifying charged parti- cles, the PSA method has been utilized on a limited number of occasions [26–28]. The FAZIA array serves as a perti- nent illustration [28–30]. The module of the FAZIA array is composed of two silicon detectors and a CsI(Tl) crystal, which collectively form three-stage telescopes based on the ΔE-E method. The use of PSA method has been demon- strated in both the first silicon detector and the CsI(Tl) crys- tal, with the objective of enhancing the performance of PID.

A number of studies have been conducted on the performance of the CsI(Tl) crystal using the PSA method [26, 27, 31–34].

The findings of the aforementioned studies indicate that the CsI(Tl) crystal can achieve isotope discrimination through the PSA method for Z 3, and facilitate adequate charge separa- tion for Z up to 19. This provides the necessary confidence for the efficacy of our proposed scheme. However, the per- formance of the detector must be verified, and this constitutes the primary focus of the present study.

This paper is organized as follows: Section II contains the experimental details of the present study. Section III presents the results and discussions of the performance of the PID for hydrogen and helium isotopes with the CsI(Tl) detector. The present study' s conclusion is outlined in Section IV.

II. EXPERIMENTAL DETAILS The experiment was conducted at the External Target Facil- ity (ETF) [35] of the Heavy Ion Research Facility in Lanzhou (HIRFL). A 56Fe beam with an energy of 350 MeV/u was transmitted to the ETF and bombarded a Fe target. The de- tectors, composed of a silicon detector and a CsI(Tl) detector, were configured into a ΔE-E telescope. This telescope was situated at a distance of approximate 6 m downstream from the target and at a polar angle of approximately 30 $\circ$ with re- spect to the beam direction. The silicon detector exhibited an active area of 50$\times$$50 mm2 and a thickness of 500 µm. The CsI(Tl) crystal was one of the modules designed for the crys- tal array at a backward polar angle for the purpose of develop- ing a benchmark test [19]. It exhibited a frustum shape, and its geometric dimensions are delineated in Figure 2 [Figure 2: see original paper]. A Hama- matsu R7724 Photo-Multiplier Tube (PMT) [36] was coupled to the larger trapezoidal end surface of the crystal. This con- figuration was advantageous for the collection of scintilla- tion light due to the " focusing effect" of the tapered crystal shape [37, 38]. The EJ550 silicone grease, a product of Eljen Tech-

nology Company, was utilized for the purpose of opti- cally coupling the CsI(Tl) crystal and the PMT [39]. The re- maining surfaces of the CsI(Tl) crystal were initially wrapped with ESR film from 3M Company [40], followed by a layer of Teflon, and subsequently covered with black tape for light screen. A heat-shrink tube was utilized to secure the PMT with the CsI(Tl) crystal. It is important to acknowledge that the silicon detector had previously been utilized in a formal experiment, resulting in a significant deterioration in perfor- mance. The energy resolution for α particles emitted from 244Cm was measured to be 7.2 % (FWHM) when the measurement was performed in an air circumstance (energy de- position in the silicon detector was approximately 3 MeV).

Nevertheless, the ΔE-E method was still sufficiently precise to identify the charged particles with charge number $Z < 3$.

In consideration of the CsI(Tl) detector, the energy resolution was determined to be 9.6 % (FWHM) for the photo peak of the γ-rays emitted from the 137Cs radioactive source.

In consideration of the objective of the present paper, the scintillation signal of the CsI(Tl) crystal extracted from the PMT was transmitted directly to the CAEN DT5740, a 32- channel, 12-bit, 62.5 MS/s desktop waveform digitizer [41], without undergoing additional processing. The silicon de- tector signal was introduced into an ORTEC Model 142PC preamplifier [42], and subsequently transmitted to an ORTEC Model 572A amplifier [43]. The shaping time was set to 3 μs, and the coarse gain was set to 50. The unipolar output sig- rived from the output of a spectroscopy amplifier, the ampli- tudes of the waveform were directly extracted by searching the maximum values of the normal waveform. These values were designated as the energy deposition values for the sili- con detector. In the context of the CsI(Tl) detector, a digital charge integration (dQDC) technique was utilized to extract the energy deposition information [45].

Fig. 2. Schematic view of the dimensions of the CsI(Tl) crystal that was used in the present study. The units in the picture are cm. nal from Model 572A amplifier was finally transmitted to the CAEN DT5740 digitizer. The trigger of the electronic sys- tem was the inner channel trigger of DT5742 digitizer, which was generated by the silicon detector. Figure 3 [Figure 3: see original paper] presents a schematic representation of the electronic system.

Fig. 4 [Figure 4: see original paper]. Flow diagrams of the data analysis methods for the silicon and the CsI(Tl) detectors. The following list explains the meanings of the acronyms used in the diagrams: MAF stands for Moving Average Filter. BL-R stands for Baseline Restoration. Amp-Ext stands for Amplitude Extraction. dQDC stands for digital charge integra- tion.

Figure 5 [Figure 5: see original paper] represents the ΔE-E spectrum extracted through the preceding procedures. Despite the suboptimal energy res- olution of the silicon detector, a discernible distinction is ex- hibited among the isotopes

of hydrogen, p,d and t. The 3He and 4He bands are also present in the top-right region of the spectrum. However, the counts are minimal and thus could not be adequately represented in the subsequent PSA spectra.

Fig. 3. Schematic view of the electronic system in the present study.

There is one more thing to mention here: Given that the majority of the light charged particles produced were suffi- ciently energetic to penetrate the CsI(Tl) crystal, a 10 mm thick iron degrader was employed upstream the silicon detector to enhance the count of the full energy deposition event.

III. RESULTS AND DISCUSSIONS A. ΔE-E spectrum Fig. 5. ΔE-E spectrum obtained with the Si-CsI(Tl) telescope.

The ΔE-E spectrum was initially extracted as the refer- ence for the PSA spectra. As illustrated in Figure 4, the data analysis methods for the silicon detector and the CsI(Tl) de- tector are represented by the respective flow diagrams. The recorded waveform for both silicon and CsI(Tl) detectors was initially processed with a moving average filter [44]. Sub- sequently, it was processed with a baseline restoration algo- rithm on an event-by-event basis. The baselines were ob- tained by averaging the amplitudes of the initial 200 sam- ple points of the acquisition time windows for the digitizer.

At this juncture, the normal waveform with positive polarity and an approximate zero baseline had been obtained. Given that the recorded waveform of the silicon detector was de- B. Pulse Shape Analysis CsI(Tl) crystal has been found to exhibit varied responses depending on the type of incident particles [23, 46]. This serves as the foundation for particle identification using the PSA technique with CsI(Tl) crystal. The signal of the CsI(Tl) detector is, In principle, expressible as the sum of a series of exponential components. Recent studies have demonstrated the presence of three distinct components [46, 47]. Given that the time window of DT5740 is 16 µs, the intensity of the tail component is sufficiently small for neglect. Consequently, we hypothesize that the CsI(Tl) crystal is composed of two components: a fast and a slow one. The signal of CsI(Tl) crystal is then given by:

L(t) = where Nf and Ns represent the integrated luminescence for the fast and slow components, respectively. τf and τs rep- resent the corresponding decay time constants with typical values of 0.7 and 3 µs, respectively, for the 662 keV γ-rays irradiation at room temperature [46, 47].

Fig. 6 [Figure 6: see original paper]. Illustration of waveform for different types of incident par- ticles. The amplitudes were normalized to a value of 500, and the reach times were made the same. To illustrate the minor differences between the waveform, the graph was presented on a logarithmic scale with the y-axis.

The normal waveform of the CsI(Tl) detector obtained in Section III A is the input of the present work. Figure 6 presents the normalized waveform for different types of in- cident particles, as illustrated in Figure 5. A clear separa- tion

between particles with different charge number Z is ev- ident. With respect to isotopes, the differences are minor.

However, a more precipitous decline in the trailing edge of the waveform is still observable for the isotope with a heav- ier mass. The underlying cause of these discrepancies lies in that the ratios between Nf and Ns in Equation 1 are var- ied with different kinds of incident particles, which results in different shapes of waveform generated by the CsI(Tl) de- tector. The primary objective of the PSA technique is to uti- lize an algorithm to demonstrate these discrepancies in order to identify the particles. A multitude of corresponding algo- rithms have been developed. In this paper, we will examine four of these methods: the rise-time (fall-time) comparison method [48, 49], the digital charge comparison method [49–51], Reconstructive Particle IDentification (RPID) [52], and Quick Particle IDentification (QPID) [53–55]. The last two algorithms were developed for CALIFA [56], whose con- struction is similar to our crystal array.

1. Fall time comparison method at trailing edges

As demonstrated in Figure 6, the leading edges of the waveform for different particles demonstrate minimal dis- crepancy, while the trailing edges exhibit notable variation.

Consequently, the fall time comparison method was em- ployed to extract this variation. The fall time was defined as the time required for the signal to diminish from 90 % to 10 % of its peak value. To extract the relatively accurate time for the point at which the trailing edge of the wave- form crosses the threshold, a linear interpolation algorithm was employed [57]. Figure 7 [Figure 7: see original paper] represents the plot of the ex- tracted fall time against the light output of the CsI(Tl) detec- tor. The performance for the isotopes identification is subop- timal. In accordance with the Reference [57], we also exam- ined the PID performance of the fall time comparison method in conjunction with the parabolic and cubic polynomial inter- polation methods, which are based on the Lagrange interpo- lation algorithm. The results indicated that there were no im- provements in the PID performance. This phenomenon can be attributed to the long decay time of the CsI(Tl) crystal, which results in a prolonged trailing edge of the waveform generated by the CsI(Tl) detector. As demonstrated in Fig- ure 3 of Reference [57], the time resolutions of the signals tend to be consistency between the results extracted by lin- ear and cubic interpolation algorithms when the rise time of the waveform increases. Furthermore, a substantial number of ” NaN” and ” Inf” events were obtained through the appli- cation of parabolic and cubic interpolation algorithms, a con- sequence of the division operation inherent in these interpo- lation algorithms.

Fig. 7. PID spectrum under the fall time comparison method. The fall time was derived through the implementation of a linear inter- polation algorithm.

2. Charge comparison method

The charge comparison method, alternatively referred to as the double-gate integration method, involves the integra- tion of the waveform within two distinct time windows. This process is employed to extract the cumulative discrepancies in the waveform of various incident particles. The sample point exhibiting the maximum amplitude of the waveform was designated as the reference point for the time windows.

As demonstrated in Figure 6, the observed discrepancies for the various incident particles were primarily attributable to the different fast decay components of the waveform, which manifested as the distinct shapes at the trailing end of the waveform. Therefore, two short time windows, as illus- trated in Figure 6, were employed at these two locations for the purpose of comparison. The other time window, desig- nated as the long time window, incorporated nearly the entire waveform. The integration values were designated Qshort 1, Qshort 2 and Qlong, respectively. The lengths of two short time windows were optimized through the implementation of repeated trials.

Figures 8(a) and (c) illustrate the PID spectra for Qshort against Qlong. The separation of the different incident parti- cles is evident. However, due to the differing scales on the y- axis, direct comparison of these two plots is not immediately apparent. Accordingly, the PID function was implemented, defined as follow: f pid = Qshort i Qshort i + Qlong , i = 1, 2.

In accordance with the data presented in Figures 8(a) and (c), the corresponding plots for fpid versus the light output of the CsI(Tl) detector are shown in Figures 8(b) and (d), present- ing a more clear illustration for PID performance. It can be demonstrated that the two settings of the short time windows shown in Figure 6 can achieve a similar performance level in terms of PID.

3. RPID method

As previously outlined, the foundation of PSA technique is that the ratio between Nf and Ns in Equation 1 depends on the different categories of incident particles, thereby yielding output waveform of different shapes. The RPID method was designed to extract the values of Nf and Ns from the recorded waveform directly [52]. The underlying principle is rooted in the Moving Window Deconvolution (MWD) algorithm, a sophisticated mathematical technique that has the capability to eliminate an exponential component with the specified de- cay time from the raw waveform [58, 59].

In the original version of the RPID method, two MWD procedures are processed successively to eliminate the exponential components of the Charge-Sensitive Amplifier (CSA) and the scintillation decay of the CsI(Tl) crystal [52]. In the context of the present case, the CSA was not utilized, and only the latter MWD pro- cedure was required.

It is important to note that the τf and τs are the input pa- rameters in the

RPID method and are assumed to be constants for different incident particles. To obtain the values of τf and τs of the CsI(Tl) crystal that we used, the PID spectrum in Figure 8 Figure 8: see original paper was employed to separate the incident particles, and a double-exponential function fitting was performed for each waveform on an event-by-event basis. As illustrated in Figure 9 [Figure 9: see original paper], the histograms represent the extracted τf and τs val- ues for different categories of incident particles. It has been observed that the values of extracted τf and τs depend on the types of incident particles, which contradicts the hypothesis.

It is not possible to ascertain the types of incident particles prior to the data analysis procedure. For the trade-off, we would utilized the mean values of τf = 48.6 (777.6 ns) and τs = 248.6 (3977.6 ns) of the isotope p, obtained by Gaussian fitting of the corresponding histograms, to perform the RPID method in our case.

Figure 10 [Figure 10: see original paper] is the final digitized pulse shapes modified by the RPID algorithm. The primary steps can be found in Reference [52]. Given that the decay time of the waveform for p was designated as the input parameters in the algorithm, the resulting waveform for p, d, t, and punch-through events was deemed to be in satisfactory form. Conversely, the waveform for the isotopes of helium demonstrated a certain degree of distortion. The observed distortions can be attributed to the relatively large differences in the values of the decay time, τf and τs, from the designated input parameters in the algo- rithm. When extracting the values of Nf and Ns, we carefully avoided the distortion parts, resulting in the PID spectrum shown in Figure 11 Figure 11: see original paper. In accordance with the Equation 2, we have also defined the pid function: f pid = Ns + Nf Figure 11(b) shows the PID spectrum of fpid as a function of the light output of the CsI(Tl) detector. Both the spec- tra depicted in Figures 11(a) and (b) manifest distinct sepa- rations between the isotopes of hydrogen and punch-through events. With respect to the isotopes of helium, the perfor- mance in PID remains satisfactory, suggesting that the RPID method can still demonstrate adequate performance in PID when the input parameters contain several deviations. How- ever, it should be noted that the available data set does not include charge number z greater than 2. The capability of the RPID method to identify lithium isotopes with the input parameters setting of hydrogen remains uncertain.

4. QPID method

The QPID method is basically the charge comparison method. The QPID method is analogous to the RPID method in that both aim to extract Nf and Ns values to identify the incident particles. The distinguishing aspect of the QPID method is its utilization of integrated charge values within two prede- fined time windows to extract these values. The integra- tion time windows have been meticulously selected to ensure that the two integrated charge values, Qf and Qs, are predom- inantly determined by each component of the CsI(Tl)

crystal with different decay time, τf and τs, respectively. The pri- mary version of the QPID algorithm is initiated from the mod- ified waveform generated by the MWD algorithm [53, 54], which aims to eliminate the influence of CSA. In the absence of a CSA, it is necessary to employ the QPID algorithm with the modified input waveform of the CsI(Tl) crystal, as delin- eated by Equation 1. The zero time was set to the sample point with the maximum amplitude of the waveform.

The accumulative charges Q(t) of the CsI detector at the time t can be expressed as:

Fig. 8. PID spectra under the charge comparison method. (a) and (c) are the spectra of two different defined Qshort as the functions of Qlong, while (b) and (d) are the correspond spectra of fpid against light output of the CsI(Tl) detector.

Q(t) = (cid:90) t (cid:90) t I(t′) dt′ (cid:90) t L(t′) dt′ e− t′ τs) dt′ = Nf (1 − e τf) + Ns(1 − e− t τs), where I(t) and L(t) are the output current and luminous light of the CsI(Tl) detector respectively. Following the procedures in the references [53, 54], the transfer matrix can be obtained as follow: (cid:19) (cid:18)A B (cid:32) τf − e τf − e τf e− t1 τf e− t3 τs − e− t2 τs − e− t4 (cid:33) where A, B, C, and D are the elements of the transfer matrix, and (t1, t2) and (t3, t4) are the two integration time intervals.

Then, the Nf and Ns can be obtained with Equation 6: (cid:19) (cid:18)Nf AD − BC (cid:19) (cid:18) D −B (cid:18)Qf (cid:19) It can be seen that the algorithm depends on the values of τf and τs. We would still use the values for isotope p in the following procedures.

References [53, 54] suggest A,D $→$1 and B,C $→$0 for the purpose that Qf and Qs are mainly depended on Nf and Ns, respectively. This results in t1 = 0 and t4 →∞. Consider- ing the time window in the data analysis process, t4 was set to be 400 (6.4 µs). The functions B/A and C/D need to take the minimum value. However, this results in t2 →t1 and t3 →t4, which is of no practical use. The graph in Figure 12 [Figure 12: see original paper] shows the values for each element of the transfer matrix with the parameters t1 = 0 and t4 = 400. We found that the func- tions A-B and D-C could take the maximum values when the parameters t2 and t3 took the value: t2 = t3 = τf τs τf − τs which was around 100 (1.6 µs). At this point, A is close to 1 and B is less than half of A. Also, C is close to 0 and D is more than twice the value of C, as shown in Figure 12. This configuration could be served as the optimal condition for the aforementioned suggestion. Subsequently, the value would be incorporated into the algorithm, with the integration time intervals set at (0, 100) and (100, 400), respectively.

Figure 13 [Figure 13: see original paper] is the PID spectra with the modified QPID method. The spectra of Qs versus Qf and Ns versus Nf are illustrated in Figures 13(a) and (c), respectively. The PID functions are defined in accordance with Equations 2 and 3.

Fig. 9. The histograms of the extracted values of decay time of the CsI(Tl) crystal for different incident particles. (a) is the histogram of τf , while (b) is the histogram of τs.

Fig. 11. PID spectra under the RPID method. (a) is the spectrum of Ns against Nf , while (b) is the spectrum of fpid as a function the light output of the CsI(Tl) detector.

Fig. 10. Plot of the final modified waveform for the RPID algo- rithm. The lines with different color are the schematic view of the waveform shapes for the different incident particles.

Fig. 12. The graph for the element values of the transfer matrix versus the time (t2 for A and B, and t3 for C and D) in the unit of sample points (16 ns). The parameters t1 and t4 are set to be 0 and 400, respectively. The decay time of CsI(Tl) crystal is adjusted to be the values of proton, which can be found in the text.

The corresponding PID spectra are illustrated in Figures 13(b) and (d). It is evident that clear separations between the dif- ferent incident particles can be discerned in either of the PID spectra. Since the isotopes of helium can be clearly identi- fied, the QPID algorithm, which is equivalent to the RPID algorithm, demonstrates tolerance with the input parameters of decay time of the CsI(Tl) detector.

IV. CONCLUSION We examined the four PSA methods for identifying the incident particles with a CsI(Tl) detector. These PSA methods include the fall time comparison method at trailing edges, the Fig. 13. PID spectra under the modified QPID method. charge comparison method, the RPID, and the QPID. With the exception of the first method, the subsequent three meth- ods demonstrate notable efficacy in identifying particles with a charge number Z less than 3. Both RPID and QPID methods exhibit a high degree of tolerance with the input parameters of the decay time of the CsI(Tl) detector, thereby substantiat- ing the robust of these PSA methods in the identification of hydrogen and helium isotopes.

The good PID performance obtained by means of the charge comparison method, RPID method and QPID method with the CsI(Tl) detector serves to demonstrate the feasibil- ity of our scheme. That is to say, the utilization of CsI(Tl) detectors alone for identification of light incident particles within the large polar angle region. In our previous research, we planned to implement the PSA algorithms within the on- [1] Yanlin Ye, Xiaofei Yang, Hiroyoshi Sakurai et al., Physics of exotic nuclei. Nat. Rev. Phys. 7, 21 (2025). doi: 10.1038/s42254-024-00782-5 [2] Kang Wei, Yan-Lin Ye, and Zai-Hong Yang, Clustering in nuclei: progress and perspectives. Nucl. Sci. Tech. 35, 216 (2024). doi: 10.1007/s41365-024-01588-x [3] Liu-Yuan Shen, Qi Yuan, Hong-Hui Li et al., Study of shell board FPGA chips at a forward polar angle region. This approach was intended to reduce the pressure of data transmis- sion in the DAQ system and to enable the real-time PID func- tion [18]. The algorithms that are

written to the FPGA must not be overly complex. With regard to these three PSA meth- ods, the most concise algorithm is the charge comparison method, followed by the QPID method, and finally the RPID method. It is evident that both QPID and RPID algorithms necessitate a substantial amount of multiplication and divi- sion operations, which are not FPGA friendly. However, with respect to the CsI(Tl) detectors at the large polar angle re- gion, a significant decrease in event count is observed in each detector. This could facilitate the acquisition of raw wave- form information within the DAQ system. Consequently, the utilization of any one of these three PSA methods is deemed appropriate in the context of offline data analysis. evolution in neutron-rich boron, carbon, and nitrogen isotopes with in-medium similarity renormalization group calculations.

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Note: Figure translations are in progress. See original paper for figures.