CHICO2, a two-dimensional pixelated parallel-plate avalanche counter

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Abstract

CHICO2 (Compact Heavy Ion COunter), is a large solid-angle, charged-particle detector array developed to provide both θ and ϕ angle resolutions matching those of GRETINA (Gamma-Ray Energy Tracking In-beam Nuclear Array). CHICO2 was successfully tested at the Argonne National Laboratory where it was fielded as an auxiliary detector with GRETINA for γ -ray spectroscopic studies of nuclei using a ^{252}Cf spontaneous fission source, stable beams, and radioactive beams from CARIBU. In field tests of the $^{72,76}\text{Ge}$ beams on a 0.5 mg/cm^2 ^{208}Pb target at the sub-barrier energy, CHICO2 provided charged-particle angle resolutions (FWHM) of 1.55° in θ and 2.47° in ϕ . This achieves the design goal for both coordinates assuming a beam-spot size ($> 3 \text{ mm}$) and the target thickness ($> 0.5 \text{ mg/cm}^2$). The combined angular resolution of GRETINA/CHICO2 resulted in a Doppler-shift corrected energy resolution of 0.60% for 1 MeV coincident de-excitation γ -rays. This is nearly a factor of two improvement in resolution and sensitivity compared to Gammasphere/CHICO. Kinematically-coincident detection of scattered ions by CHICO2 still maintains the mass resolution ($\Delta M/M$) of $\sim 5\%$ that enhanced isolation of scattered weak beams of interest from scattered contaminant beams.

Keywords:

Parallel-plate avalanche counter, Charged-particle detection, Pixelation, Radioactive beams

I. Introduction

CHICO is a highly segmented position-sensitive parallel-plate avalanche counter (PPAC) with large solid-angle coverage for the charged-particle detection [1]. CHICO was designed specifically as an auxiliary detector with Gammasphere [2] for γ -ray nuclear spectroscopic studies. CHICO has been successfully fielded since 1996 for experiments exploring nuclear structure physics using a suite of techniques ranging from the quasi-elastic reactions, such as sub-barrier Coulomb excitation, and few-nucleon transfer, to the deep-inelastic reaction and fission. It addressed issues related to the evolution and multifaceted properties of nuclear collectivity, such as shape transition and shape coexistence phenomenon in nuclei [3-14].

CHICO consists of two mirror-image hemispheres where each hemisphere holds 10 PPAC's. The total detection solid-angle coverage is 69% of 4π . The principle of minimum mass was adopted in the design of CHICO to reduce the scattering and attenuation of γ rays. CHICO can be operated steadily at high counting rates (> 500 kHz) over an extended period of time with minimal radiation damage and impact on the performance. The position is measured in spherical coordinates; the polar angle, θ , is determined from the pixelation on the cathode plate using the delay-line readout technique, and the azimuth angle, ϕ , is determined using anode segmentation. For a given experiment, a valid event requires the detection of both scattered and recoiling particles in kinematic coincidence. The measured quasi-two-body kinematics allows precision Doppler-shift corrections for the coincident γ rays observed by Gammasphere. The resulting energy resolution is about 1 % for a 1 MeV γ ray, which is limited by the Ge detector size used by Gammasphere. An example is given in Fig. 1, where the complex band interactions in ^{170}Er were studied using the inelastic reaction between ^{170}Er and ^{238}U at near-barrier energy with Gammasphere/CHICO [3]. The nucleus emitting the γ rays was identified uniquely after the Doppler-shift corrections were applied according to the measured two-body kinematics.

With advent of the modern γ -ray energy tracking arrays such as GRETINA [15], the Doppler-shift correction for the observed γ ray can be improved significantly because tracking the γ ray interactions in the Ge detector provides more precise knowledge of the γ -ray interaction location. For example, the current limit on the γ -ray energy resolution with Gammasphere/CHICO can be improved by a factor of two or more by using GRETINA plus upgrading CHICO to have a position resolution matching that of GRETINA. This upgrade is particularly beneficial for experiments using GRETINA with weak radioactive beams because the improved γ -ray energy resolution increases the sensitivity for γ -ray nuclear spectroscopic studies.

Contaminant beams are a common problem for experiments using radioactive beams; sometimes they can be orders of magnitude more intense than the primary beam. Therefore, it is important for any auxiliary detector to have the ability to tolerate, and discriminate, the contaminants. The two-body kinematics measured by CHICO offers the opportunity, not only to make the precision Doppler-shift correction, but also to distinguish contaminant beams other than isobars. The same capability remains for the

upgraded CHICO2 detector. Details of this upgrade together with the report on the performance are given in the following sections.

II. Design of a two-dimensional pixelated parallel-plate avalanche counter

CHICO has a resolution better than 1° in the θ coordinate, which is adequate for the mass resolution of the scattered ejectiles, and for Doppler-shift correction of the coincident de-excitation γ -rays. However, the angular span of $\sim 9^\circ$ provided by CHICO for the ϕ coordinate, which is obtained by the location of segmented anode in the PPAC, must be improved to a resolution of $\sim 1^\circ$ to meet the required ϕ precision for GRETINA. In principle, this can be accomplished by adding pixelation in the ϕ coordinate in conjunction with the existing pixelation in the θ coordinate of the position-sensing cathode board of CHICO. The same delay-line read-out technique for the θ measurement can be applied for the ϕ measurement. Delay-line readout is a simple and attractive technique for this application since the number of read-out parameters is significantly reduced compared to the direct read-out of the pixels. However, the ability to combine θ and ϕ pixelation required field tests of its applicability before implementation. Note that a fine position resolution matching to that of GRETINA also can be achieved using the wire instead of pixel for the position measurement [16].

The proof-of-principle work on the delay-line read-out technique for the pixelated two-dimensional position-sensing cathode board was carried out at the Lawrence Livermore National Laboratory (LLNL) using a test cathode board constructed with the checkerboard pattern shown schematically in Fig. 2. The board has 31×31 pixels connected to two sets of three 10-ns delay chips (1 ns/tap). Each pixel has a dimension of 1.6×1.6 mm with 0.4 mm between them. The pixel location is determined from the time difference between the read-out of two ends of the delay line for each coordinate. Excellent uniformity and linearity in the position determination were achieved and documented in Ref. [17]. The advantage of using delay-line readout is obvious since a total of only four read-out parameters are needed to determine the location of 961 pixels.

CHICO uses spherical coordinates and thus the ϕ pixel width varies as a function of θ . Therefore, design of the two-dimensional pixelated cathode board for CHICO2 required knowledge of the image charge distribution for a given avalanche in the PPAC. This image-charge distribution was measured, as a function of position, using a specialized pixelated board with a string of 21 electrically insulated pixels. Each pixel has a dimension of 0.8×0.8 mm with a gap of 0.2 mm between them. The measurement was carried out using a collimated ^{252}Cf source on a single pixel and the pulse height of this pixel together with adjacent pixels at a distance of 2, 4, 5, and 6 mm away were recorded. The FWHM (Full Width at Half Maximum) of this distribution was measured to be ~ 5 mm for a gap of 3 mm between anode and cathode, and is consistent with a model calculation. The details of this measurement and discussion are presented in Ref. [17].

A valid signal for CHICO2 requires that both the θ and ϕ pixels be read out for each location. Simulation calculations showed that the best compromise of angle resolution and detection-efficiency uniformity for CHICO2 was achieved using the Rochester

“sandwich-board” geometry employed on the pixelated cathode board illustrated in Fig. 3. The θ strip is 0.5° wide corresponding to a physical size varying from 1 to 2 mm to preserve the highest angle resolution. The ϕ pixel is 1.4° wide with the physical size varying from 2 to 4 mm.

The reduction in cavity size of GRETINA, relative to Gammasphere, required removal of the clamping flanges around the perimeter of CHICO. The vacuum seal between the two hemispheres of CHICO2 now is achieved by applying compression along the beam axis.

III. Electronics and data acquisition system

In addition to the design and fabrication of the new pixelated two-dimensional cathode board, the upgrade activity for CHICO2 also includes the development of a new generation fast amplifier and a new VME-based data acquisition (DAQ) system. The amplifier was redesigned and fabricated, by Swan Research LLC [18], to accommodate four channels for the cathode and one for the anode with the highest reliability possible. The amplifier gain is set to 200 for the anode channel and to 800 for the cathode ones. All channels have a bandwidth of 500 MHz.

CHICO2 has a DAQ system that is independent of that used for GRETINA. Two kinds of valid events are defined for any given experiment using GRETINA/CHICO2. The first type event is a particle single event, which requires at least two particles detected by CHICO2, or one particle for backward scattering. This decision is made by a CAEN V1495 programmable trigger/logic module. The input to this trigger/logic unit is a group of 20 anode signals from CHICO2 (10 each from the forward and backward PPAC’s), which are processed by a CAEN V812, constant-fraction discriminator, and each have a signal width of 50 ns. Therefore, the time window for the particle-particle coincidence is > 90 ns. This particle single event passes through a scale-down unit before being defined as valid. The second type event is a particle- γ coincident event, which preserves the timing of the particle detected by CHICO2 with the γ signal of 600 ns in width from GRETINA. To make this particle- γ coincidence, it is necessary to delay the signal from CHICO2 by ~ 700 ns. All the above trigger/logic requirements are handled by custom-designed firmware stored in the CAEN V1495 module. The synchronization of the timestamp and trigger information between the two DAQ systems is provided by an interface module, MyRAID [19], developed at Argonne National Laboratory (ANL).

The timing of the anodes and cathodes are determined by a CAEN V1190A, a multi-hit real-time TDC (time-to-digital converter), which allows setting the offset of the matching window with respect to the trigger by up to $2 \mu\text{s}$. This is a very economical option since there is no physical delay needed of the time signals derived directly from CHICO2. As mention earlier, there are four channels for the cathodes and one for the anode of each PPAC. Therefore, a total of 100 read-out channels from two TDC modules is required to account for the 20 PPAC’s in CHICO2 with an instrument time resolution of 100 ps. An additional 20 channels was included for anode pulse height determination using a CAEN V792 charge-to-digital converter with current integration. This allowed for a time walk correction of the anode signal according to the pulse height. However, this was not

materialized due to the signal degradation after $\sim 1 \mu\text{s}$ delay required by the coincident condition imposed by the slowness of GRETINA.

IV. Operation and performance

Extensive mechanical, vacuum, and electronic modifications plus initial testing of CHICO2 was performed at Rochester, after which CHICO2 was shipped to ANL for tests using Gammasphere, and then with GRETINA. The performance of CHICO2, and the hand-shaking with GRETINA, were fully tested with a ^{252}Cf source of $\sim 8 \mu\text{Ci}$. This spontaneous fission source, sandwiched between two aluminum foils of $2.5 \mu\text{m}$ thickness, is ideal for the test since CHICO2 can be triggered by a pair of fission fragments and GRETINA can be triggered in coincidence with the detection of prompt fission γ rays, which has an average multiplicity of 8.75 [20]. A reconstructed mass spectrum from the measured kinematics of fission fragments shows that a mass resolution ($\Delta M/M$) of $\sim 5\%$ was obtained, which is nearly the same as achieved by CHICO. This indicates that a similar anode time and cathode θ angular resolution was obtained by both CHICO2 and CHICO. The operation of CHICO2 is no different from that of CHICO, and the same gas handling system is used to stabilize the gas pressure at ~ 4.0 Torr of isobutane by regulating the gas flow through a feedback system [1]. The typical pulse height is ~ 600 mV for the anode, as well as ~ 400 mV and ~ 200 mV for the θ and ϕ of cathode, respectively, when using a detector bias voltage of 460 V.

IV.1 Results from the accelerated stable beams

The first field test of GRETINA/CHICO2 using accelerated beams, was a study of the shape coexistence in Ge isotopes and was carried out using $^{72,76}\text{Ge}$ beams at 301 and 318 MeV, respectively, bombarding a ^{208}Pb target of $\sim 0.5 \text{ mg/cm}^2$ thickness [21]. The identification of either Ge-like or Pb-like particle, detected by any given PPAC, was established by the measured two-body kinematics; namely, the angle-angle correlation and the time-of-flight difference between two detected particles by paired PPAC's in coincidence. A typical spectrum of the time-of-flight difference vs. the scattering angle of θ for a given forward PPAC is shown in Fig. 4 for the case of ^{72}Ge on ^{208}Pb . Note that the accelerated beam was collimated to $\sim 3 \text{ mm}$ on the target. Events with either the scattered ^{72}Ge , or the recoiling ^{208}Pb , detected for any given PPAC, are uniquely identified. Shown in Fig. 5 is the projected time-of-flight difference spectrum for a given PPAC with a gating width of 0.5° in θ and 3.0° in ϕ of the partner PPAC. With the same gating condition, the projected θ spectra at three different angles are given in Fig. 6. Assuming the position and time resolution is the same for the paired PPAC's, then the time resolution (FWHM) of 1.20 ns, and position resolution (FWHM) of 1.55° in θ were achieved. The current limitation on time and position resolution is mainly due to the target thickness and the intrinsic resolutions are similar to those obtained by CHICO, which is demonstrated in our mass measurement using the ^{252}Cf fission source.

Obviously events with either Ge-like or Pb-like particle detected in a given PPAC can be identified uniquely from not only the time-of-flight difference (shown in Figs. 4 and 5) but also the θ - θ correlation (shown in Fig. 6) between two detected particles by

corresponding paired PPAC's. The coplanarity of this reaction is demonstrated in Fig. 7, where the difference between two measured ϕ angles is centered at 180° . A ϕ angle resolution (FWHM) of 2.47° was measured assuming the paired PPAC's have the same resolution. This ϕ angular measurement, unique to CHICO2, is the major factor to achieve a significant improvement in the γ -ray energy resolution, which fully utilizes the γ -ray energy tracking capability of GRETINA.

IV.2 Results with the accelerated radioactive beams

Experiments with reaccelerated radioactive beams extracted from CARIBU [22] were fielded using GRETINA/CHICO2 for $^{144,146}\text{Ba}$, $^{98\text{m}}\text{Y}$, $^{98,100}\text{Zr}$, ^{106}Mo , and ^{110}Ru . In general, these experiments are no different from those with stable beams. However, the inherent obstacle for radioactive beams is the beam purity since isobars or contaminants of the same M/Q can cohabit with similar or greater intensity. Thus, it is critically important for the charged-particle detector system to have the ability to distinguish between the primary radioactive beam, and contaminants, as well as being tolerant of possible high counting rates due to the contaminant beams. For any given reaction, the two-body kinematics measured by CHICO2 can be used to discriminate scattering of contaminant beams if they are not isobaric. This gives CHICO2 a great advantage for experiments with radioactive beams. An example is given in Fig. 8, where the time-of-flight difference vs. the scattering angle of θ is plotted for the reaction of a ^{144}Ba ($T_{1/2} = 11.5$ s) beam on a ^{208}Pb of 1 mg/cm^2 thickness target using a bombarding energy of 650 MeV [23]. Events with this primary beam constitute only a small fraction of the total events, which is dominated by contaminants of ^{36}Ar , $^{108,113}\text{Cd}$, ^{134}Xe , and ^{180}Hf . Nevertheless, they can be isolated from the measured two-body kinematics except for isobars and ^{134}Xe . Note that to minimize the beam tuning effort, the ^{144}Ba beam was collimated to ~ 5 mm diameter on the target instead of the more optimum ~ 3 mm used for stable beams. The larger diameter aperture worsens the mass resolution and lengthens the tail of the mass distribution. However, this disadvantage didn't diminish the ability to differentiate the primary beam from contaminants.

Shown in Fig. 9 is the Doppler-shift corrected γ -ray spectrum with a gate surrounding the ^{144}Ba -like events in Fig. 8. States with spin up to 10^+ for the positive-parity band and up to 9^- of the negative-parity band in ^{144}Ba were populated. The γ transitions from those excited states can be uniquely identified and their intensity can be determined despite the high background and low count rate of transitions from weakly populated negative-parity states. This background is mainly due to the Compton scattering events for γ transitions in ^{134}Xe , even after exploiting energy tracking in GRETINA.

The Doppler-corrected γ -ray energy resolution (FWHM) is 0.65% for the 847 keV transition in ^{134}Xe , which is close to a factor of 2 better than that of Gammasphere/CHICO, in spite of using a larger beam spot diameter of ~ 5 mm on target. In comparison, the Doppler-corrected γ -ray energy resolution was 0.6% for the ~ 1 MeV transition in ^{72}Ge using a beam spot of ~ 3 mm on target. A specific experiment to demonstrate the quantitative improvement of the γ -ray energy resolution was fielded with a ^{136}Xe beam on a 0.58 mg/cm^2 ^{194}Pt target at the bombarding energy of 623 MeV using

both Gammasphere/CHICO2 and GRETINA/CHICO2. The energy resolution for the $2^+ \rightarrow 0^+$ transition (1313 keV) in ^{136}Xe was improved to 9.7 keV for GRETINA/CHICO2 from 16.4 keV for Gammasphere/CHICO2, which mainly can be attributed to the introduction of ϕ measurement in CHICO2.

V. Summary

The CHICO heavy-ion detector array has been upgraded extensively to develop the CHICO2 detector array that provides both θ and ϕ angle resolutions required to match those of GRETINA (Gamma-Ray Energy Tracking In-beam Nuclear Array). CHICO2 includes position-sensing cathode boards pixelated in the spherical coordinates for both θ and ϕ . CHICO2 and GRETINA have been tested extensively using both a ^{252}Cf fission source, and heavy-ion beams. A field test of a ^{72}Ge beam scattered by a thin ^{208}Pb target, gave a position resolution of 1.55° in θ and 2.47° in ϕ which was achieved using a beam spot of ~ 3 mm in diameter and a target thickness of 0.5 mg/cm^2 . This position resolution is comparable to that of GRETINA and is the design goal for CHICO2. CHICO2 was operated as an auxiliary detector for GRETINA to study the γ -ray nuclear spectroscopy using stable beams as well as radioactive beams from CARIBU at the Argonne National Laboratory. Several experiments using sub-barrier Coulomb excitation, or deep-inelastic reaction methods have been fielded successfully for nuclear structure studies. The Doppler-corrected γ -ray energy resolution for coincident de-excitation γ rays, observed using CHICO2 in conjunction with GRETINA, is 0.60% for ~ 1 MeV γ rays. This is nearly a factor of two improvement compared to using Gammasphere/CHICO for such studies, which mainly can be attributed to the introduction of ϕ measurement. This improvement in Doppler-corrected γ -ray energy resolution is a significant improvement for nuclear spectroscopic studies using weak radioactive beams. Moreover, kinematically-coincident detection of scattered ions by CHICO2 provided mass resolution that enhanced isolation of scattered weak beams of interest from scattered contaminant beams.

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[1] M.W. Simon, D. Cline, C.Y. Wu, R.W. Grey, R. Teng, and C. Long, Nucl. Instrum. Methods Phys. Res. A 452 (2000) 205.

[2] I.Y. Lee, Proceedings of the Workshop on Gammasphere Physics, Berkeley, CA, Edited by M.A. Deleplanque, I.Y. Lee, and A.O. Macchiavelli (World Scientific, Singapore, 1996), p. 50.

316 [3] C.Y. Wu, D. Cline, M.W. Simon, R. Teng, K. Vetter, M.P. Carpenter, R.V.F.
 317 Janssens, and I. Wiedenhover, Phys. Rev. C 61 (2000) 021305(R).
 318 [4] C.Y. Wu, D. Cline, M.W. Simon, G.A. Davis, R. Teng, A.O. Macchiavelli, and K.
 319 Vetter, Phys. Rev. C 64 (2001) 064317.
 320 [5] A.B. Hayes, D. Cline, C.Y. Wu, M.W. Simon, R. Teng, J. Gerl, Ch. Schlegel, H.J.
 321 Wollersheim, A.O. Macchiavelli, K. Vetter, P. Napiorkowski, and J. Srebrny, Phys. Rev.
 322 Lett. 89 (2002) 242501.
 323 [6] H. Hua, C.Y. Wu, D. Cline, A.B. Hayes, R. Teng, R.M. Clark, P. Fallon, A. Goergen,
 324 A.O. Macchiavelli, and K. Vetter, Phys. Lett. B 562 (2003) 201.
 325 [7] H. Hua, C.Y. Wu, D. Cline, A.B. Hayes, R. Teng, R.M. Clark, P. Fallon, A. Goergen,
 326 A.O. Macchiavelli, and K. Vetter, Phys. Rev. C 69 (2004) 014317.
 327 [8] J.J. Valiente-Dobon, P.H. Regan, C. Wheldon, C.Y. Wu, N. Yoshinaga, J.F. Smith, D.
 328 Cline, R.S. Chakravarthy, R. Chapman, M. Cromaz, P. Fallon, S.J. Freeman, A. Gorgen,
 329 W. Gelletly, A. Hayes, H. Hua, D. Langdown, I.Y. Lee, X. Liang, A.O. Macchiavelli,
 330 C.J. Pearson, Zs. Podolyak, G. Sletten, R. Teng, D. Ward, D.D. Warner, and, A.D.
 331 Yamamoto, Phys. Rev. C 69 (2004) 024316.
 332 [9] C.Y. Wu, H. Hua, D. Cline, A.B. Hayes, R. Teng, R.M. Clark, P. Fallon, A. Goergen,
 333 A.O. Macchiavelli, and K. Vetter, Phys. Rev. C 70 (2004) 064312.
 334 [10] A.B. Hayes, D. Cline, C.Y. Wu, J. Ai, H. Amro, C. Beausang, R.F. Casten, J. Gerl,
 335 A.A. Hecht, A. Heinz, R. Hughes, R.V.F. Janssens, C.J. Lister, A.O. Macchiavelli, D.A.
 336 Meyer, E.F. Moore, P. Napiorkowski, R.C. Pardo, Ch. Schlegel, D. Seweryniak, M.W.
 337 Simon, J. Srebrny, R. Teng, K. Vetter, and H.J. Wollersheim, Phys. Rev. Lett. 96 (2006)
 338 042505.
 339 [11] C.Y. Wu, H. Hua, D. Cline, A.B. Hayes, R. Teng, D. Riley, R.M. Clark, P. Fallon,
 340 A. Goergen, A.O. Macchiavelli, and K. Vetter, Phys. Rev. C 73 (2006) 034312.
 341 [12] A.M. Hurst, C.Y. Wu, M.A. Stoyer, D. Cline, A.B. Hayes, S. Zhu, M.P. Carpenter,
 342 K. Abu Saleem, I. Ahmad, J.A. Becker, C.J. Chiara, J.P. Greene, R.V.F. Janssens, T.L.
 343 Khoo, F.G. Kondev, T. Lauritsen, C.J. Lister, G. Mukherjee, S.V. Rigby, D. Seweryniak,
 344 and I. Stefanescu, Phys. Rev. C 81 (2010) 014312.
 345 [13] A.B. Hayes, D. Cline, K. Moody, I. Ragnarsson, C.Y. Wu, J.A. Becker, M.P.
 346 Carpenter, J.J. Carroll, D. Gohlke, J.P. Greene, A.A. Hecht, R.V.F. Janssens, S.A.
 347 Karamian, T. Lauritsen, C.J. Lister, R.A. Macri, R. Propri, D. Seweryniak, X. Wang, R.
 348 Wheeler, and S. Zhu, Phys. Rev. C 82 (2010) 044319.
 349 [14] D. Ward, A.O. Macchiavelli, R.M. Clark, D. Cline, M. Cromaz, M.A. Deleplanque,
 350 R.M. Diamond, P. Fallon, A. Gorgen, A.B. Hayes, G.J. Lane, I.Y. Lee, T. nakatsukasa,
 351 G. Schmidt, F.S. Stephens, C.E. Svensson, R. Teng, K. Vetter, and C.Y. Wu, Phys. Rev.
 352 C 86 (2012) 064319.
 353 [15] S. Paschalis, I.Y. Lee, A.O. Macchiavelli, C.M. Campbell, M. Cromaz, S. Gros, J.
 354 Pavan, J. Qian, R.M. Clark, H.L. Crawford, D. Doering, P. Fallon, C. Lionberger, T.
 355 Loew, M. Petri, T. Stezelberger, S. Zimmermann, D.C. Radford, K. Lagergren, D.
 356 Weisshaar, R. Winkler, T. Glasmacher, J.T. Anderson, and C.W. Beausang, Nucl.
 357 Instrum. Methods Phys. Res. A 709 (2013) 44.
 358 [16] A. Breskin, Nucl. Instrum. and Methods 196 (1982) 11.
 359 [17] C.Y. Wu, D. Cline, E. Kwan, A. Chyzh, A. Hayes, I.Y. Lee, and D. Swan, Lawrence
 360 Livermore National Laboratory, LLNL-TR-484110 (2011).
 361 [18] Swan Research LLC, 4675 Tyrell Rd., Owosso, MI 48867.

- [19] J.T. Anderson, Argonne National Laboratory, Report # ANL-15/07 (2015).
- [20] A. Chyzh, C.Y. Wu, E. Kwan, R. A. Henderson, T. A. Bredeweg, R. C. Haight, A. C. Hayes-Sterbenz, H. Y. Lee, J. M. O'Donnell, and J. L. Ullmann, Phys. Rev. C 90 (2014) 014602.
- [21] A.D. Ayangeakaa, R.V.F. Janssens, C.Y. Wu, J.M. Allmond, J.L. Wood, S. Zhu, M. Albers, S. Almaraz-Calderon, B. Bucher, M.P. Carpenter, C.J. Chiara, D. Cline, H. Crawford, H.M. David, J. Harker, A. Hayes, C.R. Hoffman, B.P. Kay, K. Kolos, A. Korichi, T. Lauritsen, A.O. Macchiavelli, A. Richard, D. Seweryniak, and A. Wiens, Submitted to Phys. Lett. B (2015).
- [22] R.C. Pardo, G. Savard, S. Baker, C. Davids, E.F. Moore, R. Vondrasek, and G. Zinkann, Nucl. Instrum. Methods Phys. Res. B 261 (2007) 965.
- [23] B. Bucher, S. Zhu, C. Y. Wu, R. V. F. Janssens, D. Cline, A. B. Hayes, M. Albers, A. D. Ayangeakaa, P. A. Butler, C. M. Campbell, M. P. Carpenter, C. J. Chiara, J. A. Clark, H. L. Crawford, M. Cromaz, H. M. David, C. Dickerson, E. T. Gregor, F. G. Kondev, J. Harker, C. R. Hoffman, B. P. Kay, A. Korichi, T. Lauritsen, A. O. Macchiavelli, R. C. Pardo, A. Richard, M. A. Riley, G. Savard, M. Scheck, D.Seweryniak, M. K. Smith, R. Vondrasek, and A. Wiens, Submitted to Phys. Rev. Lett. (2015).

Figure Captions

Fig. 1 Doppler-shift corrected spectra for the projectile-like nuclei (bottom panel) and the target-like nuclei (middle panel). Labeled peaks are $I \rightarrow (I - 2)$ transitions for the inelastic channel. The top panel is the raw coincident spectrum observed by Gammasphere and the sharp peak at 932 keV is an isomeric transition in ^{170}Er .

Fig. 2 Panel view of the pixelated two-dimensional position-sensing cathode board. The arrow points the direction of interconnected pixels of the same color and the location of delay lines. The delay-line read-out technique is used to determine the horizontal position of x in red and the vertical position of y in blue.

Fig. 3 Schematic view of the pixelated cathode board and the accompanying transmission line for CHICO2. The board has a total of 1478 pixels covering the angular range from 12° to 85° in θ and 28° out of 2π in ϕ . Seven and half 10-ns delay chips are used for the read-out of the θ coordinate and two 10-ns delay chips are used for the read-out of the ϕ coordinate. The signal is read-out from both ends of the delay line for both θ and ϕ coordinates. Each transmission line carries a total of five signals, four for cathode and one for anode, from the individual PPACs to the amplifier located outside the detector chamber.

Fig. 4 Spectrum of the time-of-flight difference between two detected particles by paired PPAC's in coincidence vs. the scattering angle for a given forward PPAC for the case of ^{72}Ge on a ^{208}Pb target of 0.5 mg/cm^2 thickness with the bombarding energy at 301 MeV. The backward scattered events also are included since the recoiling ^{208}Pb is going forward. Two types of events are shown; the lower curve represents events with the scattered ^{72}Ge detected and the upper one represents events with the recoiling ^{208}Pb detected.

Fig. 5 Spectrum of projected time-of-flight difference for the partner PPAC to the one shown in Fig. 4 by gating the scattering angle of θ between 45° and 45.5° and a span of 3.0° for ϕ . The time resolution (FWHM) of 1.7 ns was obtained for the paired PPAC's and the individual one should have a time resolution of 1.20 ns assuming both have the same time resolution.

Fig. 6 Projected θ spectra for a given PPAC with the same gating condition described in Fig. 5 except for θ at 65° , 70° , and 75° on the partner PPAC. The θ angular resolution (FWHM) of 2.2° was obtained for the paired PPAC's and the individual one should have a θ angular resolution of 1.56° assuming both have the same θ angular resolution.

Fig. 7 The coplanarity for the quasi-elastic reaction between ^{72}Ge and ^{208}Pb at the bombarding energy of 301 MeV is illustrated, where the ϕ - ϕ correlation between them is plotted. The spectrum centers at $\sim 180^\circ$. The ϕ angular resolution (FWHM) of 3.5° was obtained for the paired PPAC's and the individual one should have a ϕ angular resolution of 2.47° assuming both have the same ϕ angular resolution.

Fig. 8 Spectrum of the time-of-flight difference vs. the scattering angle for the reaction between ^{144}Ba and ^{208}Pb with the bombarding energy at 650 MeV, obtained by requiring at least one γ ray detected by GRETINA in coincidence. Events involving the primary beam of ^{144}Ba can be isolated from those of contaminant beams except for isobars and ^{134}Xe . The major contaminates are ^{36}Ar , $^{108,113}\text{Cd}$, ^{134}Xe , and ^{180}Hf .

Fig. 9 Doppler-shift corrected γ -ray spectrum with a gate on ^{144}Ba -like events in Fig. 8. The deterioration in the quality of γ transitions for weakly populated negative-parity states in ^{144}Ba is evident and mainly due to the Compton events of γ transitions in ^{134}Xe .

Figure 1

Figure 2

440
441
442

Some gnd traces not shown.

Figure 3

443
444

Figure 4

Figure 5

453

Figure 6

Figure 7

Figure 8

Figure 9