A two-dimensional readout PAD-type annular Parallel Plate Avalanche Counter for heavy ion γ-ray coincidence measurements

Authors: Lin, Zhuang-Yu, Wang, Shouyu, Ma, Mr. Peng, Zhang, Dr. Yue-zhao, Dr. HAN, Xing-Chi, Wang, Shouyu

Date: 2025-10-11T22:42:43+00:00

Abstract

In order to perform γ-particle coincidence measurements in Coulomb excitation experiments, a two-dimensional readout pad-type annular Parallel Plate Avalanche Counter (PPAC) has been developed. The cathode consists of multilayer PCB, enabling position readout in both the and ϕ directions via a delay-line module, which significantly reduces the complexity of the readout electronics. The sensitive area in the direction spans from a radius of 18 mm to 60 mm, with a step size of 1 mm, while the ϕ direction covers two sector regions from 6° 174° and 186° 354°. The detector was tested using a 241Am α-source and exhibited an anode signal rise time of about 5 ns. The angular resolution in both the and ϕ directions is better than 2°, demonstrating that the PPAC meets the experimental requirements for both position and time resolution. Upon the completion of HIAF, this detector will be of great significance for the development of gas detectors used in high intensity nuclear spectroscopy experiments.

Full Text

Preamble

A Two-Dimensional Readout PAD-Type Annular Parallel Plate Avalanche Counter for Heavy Ion γ-Ray Coincidence Measurements

Zhuang-Yu Lin[1], Peng Ma[1],[2], Yue-Zhao Zhang[1],[3], Xing-Chi Han[1], and Shou-Yu Wang[1],[3],†

[1]Provincial Key Laboratory of Nuclear Science, Nuclear Energy Technology and Comprehensive Utilization, School of Nuclear Science, Energy and Power Engineering, Shandong University, Jinan, Shandong 250061, P. R. China

[2]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, Gansu 730000, P. R. China
[3]WeiHai Research Institute of Industrial Technology of Shandong University, Weihai, Shandong 264209, P. R. China

We have developed a two-dimensional readout pad-type annular Parallel Plate Avalanche Counter (PPAC) for γ-particle coincidence measurements in Coulomb excitation experiments. The cathode consists of a multilayer PCB that enables position readout in both the and directions via a delay-line module, which significantly reduces the complexity of the readout electronics. The sensitive area spans radial distances from 18 mm to 60 mm in the direction with 1 mm step size, while the direction covers two sector regions from 6°–174° and 186°–354°. Testing with a ^{241}Am α-source demonstrated an anode signal rise time of approximately 5 ns. The angular resolution in both and directions is better than 2°, confirming that the PPAC meets experimental requirements for both position and time resolution. Upon completion of HIAF, this detector will be of great significance for developing gas detectors used in high-intensity nuclear spectroscopy experiments.

Keywords: Parallel plate avalanche counter, Two-dimensional position readout, Position resolution, Particle-γ coincidence measurement, Coulomb excitation experiments

Introduction

The atomic nucleus is a quantum many-body system composed of protons and neutrons bound by the strong interaction, with contributions from weak and electromagnetic interactions. It exhibits rich physical phenomena, and studying nuclear structure helps us understand the world around us and the origins of the universe. Nuclear shape is one of its fundamental properties, reflecting the distribution of nucleons within the nucleus. Different nuclear shapes are associated with the spontaneous breaking of different symmetries [1, 2]. For example, the rotation of triaxial deformed nuclei can lead to spontaneous breaking of chiral symmetry, which helps us understand chiral phenomena in chemistry and biology [2, 3]. Pear-shaped nuclei correspond to spontaneous breaking of spatial reflection symmetry, which is connected to fundamental CP symmetry violation and aids in studying new physics beyond the Standard Model [4]. Therefore, accurately measuring nuclear shapes is not only key to investigating exotic nuclear structures but also plays a critical role in addressing major fundamental scientific questions.

The Coulomb excitation reaction excludes complex short-range nuclear interactions and involves only electromagnetic interactions that can be described by well-established theories. It is therefore the most direct and reliable method for measuring the electric multipole moments and reduced transition probabilities of nuclear excited states, providing direct experimental evidence of nuclear deformation [5]. Owing to the advantages of the Coulomb excitation method and the recent rise of radioactive nuclear beam facilities, there has been renewed international interest in studying exotic nuclear deformations. For instance, at TRIUMF National Laboratory in Canada, the spectroscopic quadrupole moment of ^{12}C was directly measured, confirming its oblate deformation [6]; at Argonne National Laboratory in the United States and at CERN in Europe, the electric octupole transition probabilities in ^{144,146}Ba and ^{222,224}Ra were directly measured, providing experimental evidence for stable octupole deformation in these nuclei [7-10].

In Coulomb excitation experiments, the outgoing projectile nucleus, target nucleus, and de-excitation γ-rays are measured by particle detectors and γ-ray detectors, respectively. During data processing, particle-γ coincidence measurements are used to select γ-rays corresponding to the target nucleus, providing cross-section information from which nuclear deformation is extracted. This requires the γ-ray detector to have good energy resolution, while the particle detector must distinguish between projectile and target nuclei and provide position information for both, which is used for Doppler correction of the γ-rays. HPGe detectors are commonly used for γ-ray measurements in these experiments due to their superior energy resolution. For particle detection, silicon semiconductor detectors, scintillation detectors [11], and gas detectors are options, each offering good position resolution. Silicon detectors distinguish particles based on energy differences between projectile and target nuclei [12, 13], while gas detectors differentiate based on time-of-flight differences [14]. Compared to silicon detectors, gas detectors offer better radiation resistance and can operate in high-intensity beam environments, allowing them to accumulate higher statistics during the same beam time and yield more accurate experimental results.

Currently, PPACs used in nuclear spectroscopy experiments in China typically employ wire-type structures, predominantly in square configurations [15, 16]. No two-dimensional readout PAD-type annular PPAC has been developed previously. With the completion of the High Intensity heavy ion Accelerator Facility (HIAF) [17], experiments in high-current environments will become widespread, creating an urgent need to develop particle detectors suitable for high-intensity conditions. As a gas detector, PPAC exhibits exceptional resistance to radiation damage and can be widely applied in various nuclear physics experiments.

This work presents the design of a two-dimensional readout PAD-type annular parallel plate avalanche counter. Compared to traditional PPACs, this design offers two distinct advantages. From the detector geometry perspective, unlike square PPACs, the annular PPAC enables direct readout of scattered particle scattering angle information in spherical coordinates without coordinate transformation. Moreover, the angular resolution remains consistent regardless of the scattered particle' s impact location on the detector. Compared to sector PPACs, the annular PPAC significantly simplifies the readout electronics configuration. While sector PPACs such as CHICO require hundreds of readout channels to cover the 4π solid angle, the annular PPAC designed herein requires only 28 channels. This also simplifies the detector' s gas circuitry and structure, facilitating assembly and adjustment during experiments. From the perspective of two-dimensional detector readout, traditional PPACs typically read out one-dimensional position information from both the anode and cathode planes. In contrast, the annular PPAC described herein integrates the readout of and angles onto a single multilayer PCB, thereby enhancing the PPAC' s two-dimensional position resolution. In CHICO, the angle information is read out by segmented anodes with a resolution of 9° [14]. Another annular PPAC (APPAC) also reads out angle information through segmented anodes, but its resolution is only 22.5° [18]. In contrast, the annular PPAC described in this paper achieves positional resolution within 2° for both and angles.

The following sections present our work: Section II presents PPAC simulation results, demonstrating that both time resolution and position resolution meet experimental requirements. Section III describes the principles of PPAC two-dimensional readout, along with the detector' s structure and assembly. Section IV shows test results for the square PPAC test prototype and the annular PPAC, and Section V concludes this work.

II. Detector Simulation

In Coulomb-excitation experiments, a PPAC must provide particle identification using time-of-flight (TOF) differences to separate projectile-like and target-like scattered particles (recoils). This imposes a timing requirement of < 1 ns for the gas detector. We performed Geant4 simulations for a case of a 301 MeV ^{72}Ge beam bombarding a 0.5 mg/cm^2 thickness ^{208}Pb target. The simulation results are shown in Fig. 1 [Figure 1: see original paper]. The Y-axis shows the particles' TOF difference and the X-axis is the detector ring number (segmentation in the polar angle,). The simulated trends are consistent with published experimental observations [19]. Simulations with alternative beam-target combinations likewise indicate that, within a given ring, the minimum particle TOF differences are approximately 8-10 ns. Fig. 1 shows the simulation results of a ^{58}Ni beam bombarding a ^{150}Sm target. Typically, the timing resolution of a PPAC ranges from a few hundred picoseconds up to 1 ns [16, 20-22], and the signal rise time (defined as the time for the pulse to increase from 10% to 90% of its amplitude) is 5-10 ns [18]. These values indicate that PPACs provide sufficient timing performance to resolve particle time-of-flight differences in Coulomb-excitation experiments.

The PPAC position resolution directly impacts the accuracy of Doppler correction applied to detected γ rays in such experiments. This position resolution is closely linked to avalanche multiplication in the working gas and the ensuing formation and transport of the electron cloud. Using the Garfield++ software, we studied the avalanche and diffusion processes of electrons by simulating their drift trajectories under strong electric fields and calculating the transverse and longitudinal diffusion coefficients, as shown in Fig. 2 [Figure 2: see original paper]. The simulation results indicate that, in isobutane gas at pressures of 5-15 mbar, when the PAD size exceeds 1.5 mm $\times$ 1.5 mm, the electron cloud is likely to impinge on only a single PAD. Therefore, the PAD size must be strictly controlled in the design of the cathode board.

III. Design and Construction

A. Two-Dimensional Delay Line Readout

The PPAC is a gas detector operating in the proportional region. It typically consists of an anode (thin foil or wire structure) that provides the operating voltage and a cathode (printed circuit board or wire structure) that collects the electron cloud signal [23]. The space between the cathode and anode is filled with a working gas, typically low-pressure isobutane or argon (5-15 mbar) [24].

The two-dimensional position signals of traditional PPACs are usually not received on the same plane [25, 26]. For example, in the CHICO setup, the anode membrane is responsible for receiving signals in the direction, while the cathode readout board is responsible for receiving signals in the direction. Due to the geometric dimensions of the anode membrane, the resolution in the angle is relatively low in this design. Another structure places two metal wires for position readout in different dimensions on either side of the anode high-voltage membrane. Although this design improves position resolution in both directions, it increases the detector' s thickness and geometric dimensions, occupying more space in the target chamber. With the advancement of multilayer PCB circuit board manufacturing technology, we can integrate the two-dimensional signal readout layers onto a single cathode circuit board. This not only reduces the geometric size of the detector but also improves position resolution in the angle.

The two-dimensional readout principle of PPAC is shown in Fig. 3 [Figure 3: see original paper]. Electrons that undergo avalanche amplification in the gas gap are collected by the copper pads on the top layer of the PCB, and the electrical signals are routed through vias to signal output layers in different directions. Finally, all signals are collected on the bottom layer and transmitted to the delay-line module via FPC flexible cables for direct readout. Each pad can only output a signal in one direction [19]; otherwise, it is impossible to determine the exact location of the signal if a pad receives a signal and outputs it in two directions simultaneously.

Signals in the same direction are connected through the LC delay-line module, with two signals output from both ends. By calculating the time difference between the arrival of the delayed signals at both ends and performing position scaling using formula (1), one-dimensional position information can be obtained [27, 28].

$$\text{Position} = \frac{T_1 - T_2}{T_1 + T_2} \times L$$

In the formula, T_1 and T_2 represent the channel numbers recorded in the TDC after the signals are output from both ends of the delay line, and L is the geometric length of the detector’ s sensitive area in that direction.

B. Detector Construction

Two PPACs were developed in this work: a square PPAC prototype for testing detector operating conditions, and an annular PPAC for reading out azimuthal-angle information (in spherical coordinates) in Coulomb-excitation experiments. The structures of the two PPACs are described below.

The structure of the square PPAC is shown in Fig. 4 [Figure 4: see original paper]. The detector is primarily composed of a cathode circuit board and an anode foil fabricated from 2-µm-thick Mylar; spacing between them is set by nylon standoffs. 1520-series LC delay units from Data Delay Devices are soldered to both sides of the cathode PCB. The whole detector is housed in a sealed aluminum box filled with the working gas. The cathode board measures 98.5 mm × 98.5 mm; the sensitive region is a 60 mm × 60 mm area made up of square copper pads, each pad measuring 0.9 mm × 0.9 mm with a pitch of 0.1 mm.

The structure of the annular PPAC is shown in Fig. 5 [Figure 5: see original paper]. The detector comprises a cathode PCB, an anode foil, an external window foil, a detector frame, LC delay-line readout boards, and several supporting rings. The detector’ s outer diameter is 160 mm, and the inner hole diameter is 17.5 mm. The cathode sensitive area consists of two fan-shaped segments (upper and lower), covering azimuthal angle ( ) ranges of 6°–174° and 186°–354° with a resolution of 2°. In the polar ( ) direction, the sensitive area covers radial distances from 18 mm to 60 mm with a step of 1 mm; when the target is 36 mm from the detector, the coverage is 26.5°–59° with a resolution between 0.5° and 1.5°.

From tests on the square PPAC, we set the spacing between the cathode and anode foils, as well as between the anode foil and the outer window foil, to 7 mm. Details of the tests are presented in the next section. Both the outer window foil and the anode foil are made of 2-µm-thick Mylar and are bonded to a PCB annular frame with epoxy resin. Because the experiment requires simultaneous detection of both projectile and target nuclei positions, the signals from the projectile and target arriving at the anode must serve as the start times for their respective delay-line readouts. Reaction kinematics indicate that when the projectile strikes the upper half of the detector, the recoiling target nucleus will strike the lower half; therefore, the anode foil must be partitioned so that firing of one half does not affect the other. We implemented a 1-mm-wide groove in the anode PCB frame. After bonding the Mylar to the frame, the foil was cut along the groove with a blade and then insulated and fixed with epoxy resin, electrically isolating the upper and lower halves of the anode foil. Additionally, the detector frame is made of acrylic, and internal supports and gaskets are made of PTFE to insulate the anode high voltage. Photographs of the fully assembled PPAC unit are shown in Fig. 6 [Figure 6: see original paper], and photographs of detector components are shown in Fig. 7 [Figure 7: see original paper].

IV. Test and Performance

A. Test Results of Square PPAC

Extensive experiments have shown that, within the gas gap of a gas detector, the drift velocities of electrons and ions in the electric field exhibit a functional relationship with the reduced electric field strength E/P, where E is the operating electric field intensity and P is the operating gas pressure. In addition, the distance between the cathode and anode (hereinafter referred to as the plate spacing) and the type of working gas also affect the diffusion range of electrons and ions. Since each pad on the detector' s cathode plate can only collect one-dimensional position information, it is necessary to control the ion diffusion range to about two to three pads in order to obtain two-dimensional position information.

To this end, a 60 mm × 60 mm square PPAC test prototype was designed to study the effect of different operating pressures, voltages, and plate spacings on ion diffusion and position resolution. To achieve better position resolution during testing, a diaphragm with an array of small holes—each 1 mm in diameter and spaced 2.54 mm apart—was placed facing the radiation source in front of the detector.

Taking the X direction as an example, according to the principle of delay line readout, the one-dimensional position along the X axis can be obtained by subtracting the TDC channel count recorded at the X2 end from that at the X1 end, and then applying channel calibration. Fig. 8 [Figure 8: see original paper] shows the one-dimensional position spectra in the X and Y directions. The peaks in the spectra correspond to particles passing through the 1 mm diameter holes in the diaphragm and hitting the cathode plate. By comparing the Gaussian fit σ values of these peaks with the hole diameter, the detector' s position resolution in the X and Y directions can be determined.

Plotting the one-dimensional position spectra of both X and Y directions together yields the two-dimensional position spectrum of the PPAC test prototype, as shown in Fig. 9 [Figure 9: see original paper], where the shapes of the holes on the diaphragm are clearly visible.

By varying multiple sets of operating gas pressures, voltages, and plate spacings, the detector' s position resolution was observed. At a plate spacing of 7 mm, several operating voltages were adjusted to study the effect of voltage on detector performance. The test results are summarized in Table 1 , where the units of σx, σy, and the peak positions of X1 + X2 are all given in TDC channel counts.

It can be seen that when the plate spacing is 3 mm, both the detector' s two-dimensional resolution and detection efficiency are poor. When the plate spacing is greater than or equal to 5 mm, the electron cloud diffusion meets the requirements for two-dimensional readout, and the detection efficiency is generally above 75%. Moreover, as the plate spacing increases, the peak position of X1 + X2 shifts higher, indicating increased electron cloud diffusion. Consequently, a higher operating voltage is required to achieve the same amplitude of the PPAC cathode signal. However, when the operating voltage is too high, sparking occurs at the PPAC anode, which not only reduces detection efficiency but can also damage the anode foil. Considering position resolution, detection efficiency, and other factors, we conclude that the PPAC performs optimally at a plate spacing of 7 mm and an operating gas pressure of 8 mbar, with a high voltage adjusted such that the anode signal amplitude reaches about -300 mV. These conditions are adopted as the default parameters for subsequent detector design and testing.

B. Test Results of Annular PPAC

In the vacuum target chamber of the laboratory, we tested the annular PPAC using a ^{241}Am-α radiation source, with isobutane gas at a pressure of 8 mbar filling the detector. To ensure the detector operated continuously without sparking, the voltage on the anode foil was set to -800 V, and a first-stage preamplifier was added to compensate for the reduced signal amplitude from the cathode plate due to the lower operating voltage. The PPAC then underwent several 24-hour continuous radioactive source tests with a count rate of approximately 10^7 per hour. No sparking was observed throughout the tests, demonstrating that the PPAC is capable of stable operation under high-intensity experimental conditions.

Fig. 10 [Figure 10: see original paper] shows the anode and cathode signals observed on an oscilloscope. It can be seen that after two stages of amplification, when the anode signal amplitude reaches 100 mV, the cathode signal amplitude can reach around 1 V, with a rise time of about 5 ns. This indicates that by setting a higher CFD threshold, we can filter out valid signals from noise without affecting the detector' s time resolution. Furthermore, we tested the partitioning effect between the upper and lower anode foils, as shown in Fig. 11 [Figure 11: see original paper]. When the anode in the upper half generates a signal, the anode in the lower half does not produce a signal with sufficient amplitude to trigger, and vice versa.

Fig. 12 [Figure 12: see original paper] shows the one-dimensional (1D) position spectra of the annular PPAC in the and directions. The upper panel corresponds to the -direction 1D position spectrum, while the lower panel corresponds to the -direction 1D position spectrum, where the range is from 186° to 268°. It can be seen that the -direction spectrum of the detector is relatively uniform. However, in the direction, due to the unequal lengths of the inner and outer rings, its uniformity is not easily discernible in the 1D spectrum. Therefore, a two-dimensional (2D) position spectrum needs to be plotted to further examine the signal uniformity of the detector.

Different from the square PPAC, in addition to calibrating the delay-line channel values to the detector' s geometrical dimensions, plotting the 2D position spectrum of the annular PPAC also requires transforming the polar coordinate system into a Cartesian coordinate system. The 2D position spectrum of the PPAC after channel calibration and coordinate transformation is shown in Fig. 13 [Figure 13: see original paper]. The figure displays a sector region with ranging from 186° to 268°, in which the detector shows good uniformity in its 2D position readout.

Furthermore, we placed an aperture in front of the detector, as shown in the right panel of Fig. 14 [Figure 14: see original paper]. The small holes on the aperture have a diameter of 1 mm and a spacing of 2.54 mm. The left panel of Fig. 14 shows the 2D position spectrum obtained with the aperture in place. The image clearly shows the patterns of the small holes. The upper left two columns exhibit missing hole patterns, which are attributed to partial holes being obscured by insulating tape. Additionally, the two-dimensional image exhibits a shift due to the radiation source not being precisely positioned at the center. A two-dimensional Gaussian fit was applied to circular spots within the two-dimensional position spectrum, yielding σx and σy values both approximately 0.4 mm. Fig. 15 [Figure 15: see original paper] displays enlarged images of the two-dimensional Gaussian fits for two of these circular spots. This result indicates that the detector' s position resolution is better than 1 mm. Based on the detector placement in the experiment, the corresponding angular resolutions in and are both less than 2°, which meets the experimental requirements.

V. Summary

In the present paper, we report for the first time the development of a two-dimensional delay-line readout PAD-type annular PPAC for Coulomb excitation experiments. Unlike conventional PPAC detectors, the annular PPAC in this paper integrates the two-dimensional position readout of the azimuthal and polar angles onto a single cathode circuit board. This design not only improves the angular resolution in both and directions, but also simplifies the scale of the readout electronics and the detector structure by employing a delay-line readout scheme and an annular cathode design.

Prior to the development of the annular PPAC, a square PPAC prototype was constructed and tested to determine the optimal working gas pressure, voltage, and plate spacing for detector operation. The annular PPAC was then tested using a ^{241}Am α radiation source. The measured anode signal had a rise time of approximately 5 ns, and the cathode signal amplitude, after two stages of amplification, reached about 1 V, satisfying the experimental requirements for time resolution. Under 24-hour testing with a high-count-rate radiation source (10^7/h), the PPAC detector exhibited no sparking phenomena, demonstrating its stable operation in high-intensity experimental environments. The detector exhibited good uniformity in the two-dimensional position spectrum. When a collimator was placed in front of the detector, the resulting two-dimensional position spectrum clearly revealed the pattern of holes on the collimator, with a diameter of 1 mm and a spacing of 2.54 mm. This indicates that the detector has a position resolution better than 1 mm, which corresponds to angular resolutions in and better than 2°, meeting the experimental requirements for position resolution. This provides robust support for subsequent nuclear spectroscopy experiments conducted under high-intensity conditions.

Acknowledgements: The authors are grateful for the support of the nuclear detector group at the Institute of Modern Physics, Chinese Academy of Sciences. Special appreciation goes to Prof. Li-Min Duan and Prof. He-Run Yang for valuable suggestions on the design and testing of the PPAC. We thank Dr. En-Hong Wang for helpful discussions and language revision of the manuscript.

Author Contributions: All authors contributed to the study conception and design. The physical background, overall direction, funding support, and administration of this work were led primarily by the corresponding author Shou-Yu Wang. The determination of the PPAC parameters and the simulation of the PPAC were jointly completed by Zhuang-Yu Lin, Peng Ma, Yue-Zhao Zhang, and Xing-Chi Han. The fabrication, assembly, and testing of the PPAC were jointly completed by Zhuang-Yu Lin and Peng Ma. The first draft of the manuscript was written by Zhuang-Yu Lin and all authors commented on previous versions of the manuscript.

Data Availability: The related data are available from the corresponding author upon reasonable request.

Declarations of Conflict of Interest: The authors declare no competing interest.

References

[1] S. Frauendorf, Spontaneous symmetry breaking in rotating nuclei. *Rev. Mod. Phys.* **73**, 463-514 (2001). doi: 10.1103/RevModPhys.73.463.

[2] P. A. Butler and W. Nazarewicz, Intrinsic reflection asymmetry in atomic nuclei. *Rev. Mod. Phys.* **68**, 349-421 (1996). doi: 10.1103/RevModPhys.68.349

[3] K. Starosta, T. Koike, C. J. Chiara et al., Chiral Doublet Structures in Odd-Odd N = 75 Isotones: Chiral Vibrations. *Phys. Rev. Lett.* **86**, 971-974 (2001). doi: 10.1103/PhysRevLett.86.971

[4] D. Voss, Nuclei Crash Through The Looking-Glass. *Science* **291**, 962 (2001). doi: 10.1126/science.291.5506.962a

[5] D. Cline, Nuclear shapes studied by Coulomb excitation. In: *Nuclear Structure 1985* (eds R. Broglia, G. Hagemann, B. Herskind), Elsevier, Amsterdam, pp. 313-326 (1985). doi: https://doi.org/10.1016/B978-0-444-86979-1.50026-0

[6] M. Kumar Raju, J. N. Orce, P. Navrátil et al., Reorientation-effect measurement of the first 2+ state in ^{12}C: Confirmation of oblate deformation. *Phys. Lett. B* **777**, 250-254 (2018). doi: https://doi.org/10.1016/j.physletb.2017.12.009

[7] L. P. Gaffney, P. A. Butler, M. Scheck et al., Studies of pear-shaped nuclei using accelerated radioactive beams. *Nature* **497**, 199-204 (2013). doi: https://doi.org/10.1038/nature12073

[8] P. A. Butler, L. Gaffney, P. Spagnoletti et al., Evolution of Octupole Deformation in Radium Nuclei from Coulomb Excitation of Radioactive ^{222}Ra and ^{228}Ra Beams. *Phys. Rev. Lett.* **124**, 042503 (2020). doi: 10.1103/PhysRevLett.124.042503

[9] B. Bucher, S. Zhu, C. Y. Wu et al., Direct evidence of octupole deformation in neutron-rich ^{144}Ba. *Phys. Rev. Lett.* **116**, 112503 (2016). doi: 10.1103/PhysRevLett.116.112503

[10] B. Bucher, S. Zhu, C. Y. Wu et al., Direct Evidence for Octupole Deformation in ^{146}Ba and the Origin of Large E1 Moment Variations in Reflection-Asymmetric Nuclei. *Phys. Rev. Lett.* **118**, 152504 (2017). doi: 10.1103/PhysRevLett.118.152504

[11] X.-C. Han, S. Wang, H.-Y. Wu et al., CsI-bowl: an ancillary detector for exit channel selection in γ-ray spectroscopy experiments. *Nucl. Sci. Tech.* **34**, 133 (2023). doi: 10.1007/s41365-023-01289-x

[12] E. Lunderberg, J. Belarge, P. C. Bender et al., JANUS –A setup for low-energy Coulomb excitation at ReA3. *Nucl. Instrum. Methods Phys. Res., Sect. A* **885**, 30-37 (2018). doi: https://doi.org/10.1016/j.nima.2017.12.057

[13] M. Rocchini, K. Hadyńska-Klęk, A. Nannini et al., SPIDER: A Silicon PIe DEtectoR for low-energy Coulomb-excitation measurements. *Nucl. Instrum. Methods Phys. Res., Sect. A* **971**, 164030 (2020). doi: https://doi.org/10.1016/j.nima.2020.164030

[14] M. W. Simon, D. Cline, C. Y. Wu et al., CHICO, a heavy ion detector for Gammasphere. *Nucl. Instrum. Methods Phys. Res., Sect. A* **452**, 205-222 (2000). doi: https://doi.org/10.1016/S0168-9002(00)00429-0

[15] X. Wei, F. Guan, H. Yang et al., Development of Parallel Plate Avalanche Counter for heavy ion collision in radioactive ion beam. *Nucl. Eng. Technol.* **52**, 575-580 (2020). doi:10.1016/j.net.2019.08.020

[16] P. Ma, C.-G. Lu, J.-S. Wang et al., Capability of PPAC in investigation of resonant properties in ^{18}Ne via ^{17}F+p. *At. Energy Sci. Technol.* **45**, 356-359 (2011). url: https://www.osti.gov/etdeweb/biblio/22023109

[17] J.C. Yang, J.W. Xia, G.Q. Xiao et al., High Intensity heavy ion Accelerator Facility (HIAF) in China. *Nucl. Instrum. Methods Phys. Res. Sect. B* **317**, 263-265 (2013). doi:10.1016/j.nimb.2013.08.046

[18] A. Jhingan, H. J. Wollersheim, R. Kumar et al., An annular parallel plate avalanche counter for heavy-ion γ-ray coincidence measurements. *Nucl. Instrum. Methods Phys. Res., Sect. A* **922**, 209-216 (2019). doi: https://doi.org/10.1016/j.nima.2018.12.075

[19] C. Y. Wu, D. Cline, A. Hayes et al., CHICO2, a two-dimensional pixelated parallel-plate avalanche counter. *Nucl. Instrum. Methods Phys. Res., Sect. A* **814**, 6–11 (2016). doi: https://doi.org/10.1016/j.nima.2016.01.034

[20] H. Kumagai, A. Ozawa, N. Fukuda et al., Delay-line PPAC for high-energy light ions. *Nucl. Instrum. Methods Phys. Res., Sect. A* **470**, 562–570 (2001). doi: https://doi.org/10.1016/S0168-9002(01)00804-X

[21] Diao, XY., Guan, FH., Wang, YJ. et al., Reconstruction of fission events in heavy ion reactions with the compact spectrometer for heavy ion experiment. *NUCL SCI TECH* **33**, 40 (2022). doi: 10.1007/s41365-022-01024-y

[22] Kang, MX., Zhang, JZ., Wu, HY. et al., Commissioning of the fast neutron detector array at China Institute of Atomic Energy. *NUCL SCI TECH* **36**, 86 (2025). doi: 10.1007/s41365-025-

[23] Zhang, GL., Yao, YJ., Zhang, GX. et al., A detector setup for the measurement of angular distribution of heavy-ion elastic scattering with low energy on RIBLL. *NUCL SCI TECH* **28**, 104 (2017). doi: 10.1007/s41365-017-0249-0

[24] M. Cortesi, J. Yurkon, A. Stolz, Measurements of secondary scintillation in low-pressure CF_4 with a SiPM, from a parallel-plate avalanche geometry. *JINST* **11**, P04017 (2016). doi: 10.1088/1748-0221/11/04/P04017

[25] S. Hanai, S. Ota, R. Kojima et al., Development of Strip-Readout PPAC for high-intensity heavy ions. *Nucl. Instrum. Methods Phys. Res., Sect. B* **541**, 194–196 (2023). doi: https://doi.org/10.1016/j.nimb.2023.05.016

[26] Z. Li, X. Wei, Y. Yang et al., The development of segmented electrode thin-film parallel plate avalanche counter (PPAC). *JINST* **19**, P02005 (2024). doi: 10.1088/1748-0221/19/02/P02005

[27] H. Kumagai, T. Ohnishi, N. Fukuda et al., Development of Parallel Plate Avalanche Counter (PPAC) for BigRIPS fragment separator. *Nucl. Instrum. Methods Phys. Res., Sect. B* **317**, 717–727 (2013). doi: https://doi.org/10.1016/j.nimb.2013.08.050

[28] M. Cortesi, Y. Ayyad, J. Yurkon, Development of a parallel-plate avalanche counter with optical readout (O-PPAC). *JINST* **13**, P10006 (2018). doi: 10.1088/1748-0221/13/10/P10006

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