

Design and Construction of Charged Particle Telescope Array for Study of Exotic Nuclear Clustering Structure

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Abstract

The exploration of exotic shapes and properties of atomic nuclei, e.g., α cluster and toroidal shape, is a fascinating field in nuclear physics. To study the decay of these nuclei, a novel detector aimed at detecting multiple alpha-particle events was designed and constructed. The detector comprises two layers of double-sided silicon strip detectors (DSSD) and a cesium iodide scintillator array coupled with silicon photomultipliers array as light sensors, which has the advantages of their small size, fast response, and large dynamic range. DSSDs couple with cesium iodide crystal arrays are used to distinguish multiple alpha hits. The detector array has a compact and integrated design that can be adapted to different experimental conditions. The detector array was simulated using Geant4, and the excitation energy spectra of some alpha-clustering nuclei were reconstructed to demonstrate the performance. The simulation results show that the detector array has excellent angular and energy resolutions, enabling effective reconstruction of the nuclear excited state by multiple alpha-particle events. This detector offers a new and powerful tool for nuclear physics experiments and has the potential to discover interesting physical phenomena related to exotic nuclear structures and their decay mechanisms

Full Text

Preamble

Design and Construction of Charged Particle Telescope Array for Study of Exotic Nuclear Clustering Structure

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The exploration of exotic shapes and properties of atomic nuclei, such as α -cluster and toroidal configurations, represents a fascinating frontier in nuclear physics. To investigate the decay of these nuclei, we have designed and constructed a novel detector specifically aimed at detecting multiple alpha-particle events. The detector comprises two layers of double-sided silicon strip detectors (DSSDs) and a cesium iodide scintillator array coupled with silicon photomultiplier arrays as light sensors, offering advantages of compact size, fast response, and large dynamic range. The DSSDs combined with CsI crystal arrays effectively distinguish multiple alpha hits. The detector array features a compact, integrated design that can be adapted to various experimental conditions. We simulated the detector array using Geant4 and reconstructed excitation energy spectra for several alpha-clustering nuclei to demonstrate its performance. Simulation results show that the detector array achieves excellent angular and energy resolution, enabling effective reconstruction of nuclear excited states through multiple alpha-particle events. This detector provides a new and powerful tool for nuclear physics experiments and holds potential for discovering interesting physical phenomena related to exotic nuclear structures and their decay mechanisms.

Keywords: cluster decay, toroidal structure, telescope array, SiPM, energy resolution

Introduction

The study of exotic nuclear shapes has emerged as an exciting field that opens new avenues of research in nuclear physics. Understanding nuclear shapes is crucial for gaining insight into the underlying physical phenomena governing nuclear structure and behavior. When nuclei are excited to high energies or exhibit high angular momentum, they can adopt a variety of exotic shapes—including linear-chain, toroidal, cylindrical, and bubble configurations—that do not appear under normal conditions. The toroidal nuclear structure was first proposed by Wheeler [1]. Wong systematically studied the conditions for the existence of toroidal nuclei in medium- and heavy-mass regions [2-4] as well as in light-mass regions [5, 6]. Recently, various sophisticated Hartree-Fock (HF) microscopic methods have addressed the issue of light toroidal nuclei [7, 8]. These theoretical studies suggest that such exotic shapes arise from the interplay

between nuclear, centrifugal, and Coulomb forces. Exotic resonance peaks at very high predicted excitation energies in the 7α disassembly of ^{28}Si have been observed, matching well with the excitation energies of toroidal nuclei [9-12], indicating successful population and detection of toroidal high-spin isomers.

The Hoyle state has important implications for nuclear reactions and nucleosynthesis processes occurring in stellar environments. ^8Be and ^{12}C nuclei exhibit distinct cluster structures, such as the well-known Hoyle state of ^{12}C and the $\alpha+2n+2n$ cluster structure of ^8He , which closely resembles the 3α -condensate-like structure of the Hoyle state [13]. The Hoyle state is key to understanding the nature of nuclear forces and structures. Additionally, some studies have demonstrated the emergence of a π -bond linear-chain molecular rotational band in ^{14}C [14]. Recently, new evidence for a predicted Hoyle-like structure in ^{16}O was found [15]. Research on multiple clustering configurations in ^{24}Mg has yielded significant results [16]. Furthermore, typical clustering structures in ^{12}Be and linear-chain clustering structures in neutron-rich ^{16}C have been observed [17, 18], indicating that clustering is a general phenomenon in light nuclei [19-22]. Therefore, it is plausible to assume that heavier conjugate nuclei possess similar cluster states.

The excited states of clustering and toroidal nuclei tend to form exotic shapes that can decay into multiple alpha clusters. Experimental investigation of nuclei with alpha-cluster states requires precise measurement of multiple alpha particles emitted during the decay process [23, 24]. To study these phenomena, advanced experimental techniques have been developed to meet the requirements of high-resolution measurement of multiple alpha-particle events. The coincident detection of these particles reveals crucial insights into nuclear fragmentation processes, helping to understand the underlying physics of nuclear structure and decay mechanisms. Several detectors have been specifically developed for measuring multiple alpha particles and have been used at various research facilities worldwide. One approach to studying nuclear reactions involving multiple alpha particles employs detectors capable of measuring the energy and direction of each alpha particle. The Cylindrical Array for Tracking and Spectroscopy (CATS) at the Grand Accélérateur National d' Ions Lourds (GANIL) consists of two low-pressure multiwire proportional chambers that can detect and identify alpha particles at high counting rates [25]. A state-of-the-art 4π charged-particle detector array called ChAKRA operates at the Variable Energy Cyclotron Center, facilitating high-resolution charged-particle reaction and spectroscopy studies [26]. FAZIA can detect charged particles in the Fermi energy domain based on three telescope stages [27]. CSHINE, a detector for studying asymmetric nuclear matter, offers opportunities for experimental studies on collision dynamics and nuclear equations of state in heavy-ion reactions at Fermi energies [28]. Peking University teams performed calibration tests on two annular detector arrays and achieved outstanding results in discriminating light-charged particles [29].

The measurement of multiple α particles is a hot topic in nuclear physics because

it can provide new insights into exotic nuclear structure and dynamics. Multiple α particles from clustering nuclei decay are challenging to measure due to limitations in solid-angle coverage and low reaction cross-sections. High-resolution and high-sensitivity detectors are required to reconstruct the breakup process of nuclei that emit multiple α particles. However, such detectors are rare and expensive, and they must handle large amounts of background information that can obscure rare events of interest. Therefore, new methods are required to reduce background interference and enhance the signal-to-noise ratio [30-32]. The development of specialized detectors and innovative data analysis techniques is essential for advancing this field. Recently, machine learning methods have been used to study and analyze Hoyle states [33, 34] and clustering structures [35], which can be applied to classify and predict experimental data. The future of this field lies in designing compact, dedicated detectors that can address specific experimental difficulties and challenges, particularly in sophisticated experiments exploring interesting clustering phenomena in nuclei [36-39]. The following sections introduce the specific structure and detection performance of the detector in terms of design, construction, simulation, and measurement.

II. Design and Construction

The detector consists of two layers of double-sided silicon strip detectors (DSSDs) and CsI detectors with a frame arranged to maximize the sensitive area for particle collection and detection. Frame design is crucial, as shown in Fig. 1 [Figure 1: see original paper]. Telescope arrays are built with aluminum frames because aluminum is low-cost, lightweight, and has low reaction and activation cross sections, thereby minimizing impact on detection. Therefore, the front frame of the cesium iodide is made of high-purity aluminum.

The overall detector structure can be broadly divided into four parts. As shown in Fig. 1, the gap between the two BB7-type DSSDs is 10 mm. To prevent the DSSDs from being damaged by the tension of the Kapton cables, four aluminum pads are attached to secure the Kapton cables. A custom-made frame fits the trapezoidal CsI tightly and protects it from damage. The frame also contains a slot for the DSSD signal wires. The cesium iodide crystal is sandwiched between a reflective layer and an aluminized film on the front surface to collect light.

The optoelectronic conversion readout module consists of 25 silicon photomultipliers (SiPMs) and their power supply and control circuits. Each SiPM is attached to a CsI crystal. The frames ensure that the SiPM and CsI are well aligned so that scintillation light from the CsI can be collected and converted into charge signals by the SiPM as efficiently as possible. The frames also provide mechanical support and stability to the module and prevent the CsI from sliding out of position. The SiPM signal readout module incorporates a temperature feedback circuit that can correct signal amplitude variations due to temperature shifts.

The signals from the four 34-channel cables from the DSSDs and 25-channel lines

from the SiPMs are collected using a circuit board connected to the electronics analysis module. The 25-channel signal lines are split into common 16-channel cables that can match various data acquisition modules.

A. Detectors

A Si-CsI combination detector for multiple α -particle coincidence measurements can detect the energy and position of multiple α particles with high precision [40-42], helping to explore the fundamental laws governing these particle interactions. This design utilizes 25 CsI crystals, each shaped as a sloping ridge with the hypotenuse pointing toward the collision center, causing α particles to deposit energy in only one crystal. The front and rear faces of each crystal measure $12.96 \times 12.96 \text{ mm}^2$ and $15.16 \times 15.16 \text{ mm}^2$, respectively, with a height of 50 mm. The 5×5 CsI crystals were sandwiched between TeO_2 for good reflection and combined into the frustum of a square pyramid with dimensions of $66 \times 66 \text{ mm}^2$ on the front side and $77 \times 77 \text{ mm}^2$ on the rear side. An array of 25 CsI crystals was machined from a single large crystal piece to ensure similar physical properties, and TiO_2 was sandwiched between the crystals to act as a reflection layer and adhesive. This design renders the telescope array robust and compact.

The detector consists of three layers: two DSSDs and a CsI scintillator. The BB7-type DSSD from Micron Semiconductor Ltd. measures the position and energy loss of incident particles. The BB7-type DSSD, which has a larger sensitive area and narrower strips than the W1 type, features an active area of $63.96 \times 63.96 \text{ mm}$ consisting of 32 strips approximately 2 mm wide on each side. DSSDs with thicknesses of 300 μm , 500 μm , and 1000 μm were purchased depending on experimental requirements. This detector type is suitable for high-resolution measurement of charged particles. Heavy ions deposit their full energy in the DSSDs, whereas lighter particles such as alpha particles punch through the DSSDs and deposit their residual energy in the CsI. This configuration allows the detector to identify and locate multiple alpha particles simultaneously, making it suitable for various applications requiring high angular resolution for charged-particle detection.

The semiconductor material of the Si detector forms a p-n junction, making it highly sensitive to charged particles. The detector can also locate particle interactions within the detector with high spatial resolution, which is essential for accurately distinguishing multiple-hit events. Moreover, the detector has a low threshold level that enables detection of very low-energy particles.

By combining signals from both DSSD layers and applying kinematic judgments, particle momentum can be accurately determined. The hit position can also be used in conjunction with the final CsI scintillator array to reduce uncertainty in particle momentum direction. This significantly improves the accuracy of particle momentum determination by reducing effects from multiple hits and detector resolution.

A two-layer DSSD allows us to obtain multiple values of energy or energy loss for each particle combined with the CsI array, enabling particle identification using the ΔE -E method.

The Si-CsI detector is a versatile device for multi-alpha-particle detection, combining the advantages of Si detectors—which determine particle position and energy with high precision—and CsI scintillators. The SiPM is a key component, offering high sensitivity and fast response time for accurate detection and measurement of low-energy particles [43–45]. SiPMs coupled with scintillator crystals such as lutetium-yttrium oxyorthosilicate and $\text{LaBr}_3(\text{Ce})$ have been highly sought after in various fields [46, 47]. The SiPM-CsI combination exhibits favorable detection performance characteristics. The high sensitivity and small size of SiPMs enable detectors to achieve high spatial resolution and precise energy measurements. Additionally, SiPMs have good single-photon resolution, providing high-precision photon counting and particle identification capabilities.

One challenge in using DSSDs is the possibility of multiple alpha particles simultaneously hitting the detector. The combination of X-position from the front side and Y-position from the back side leads to ambiguous position measurements if more than one particle hits the DSSD, making accurate particle momentum calculation difficult. To overcome this issue, an additional DSSD layer can obtain multi-channel signals and hit positions. Using a two-layer DSSD provides an additional set of positional information (alternative X and Y positions). The real hit position should lie on the same line as the reaction center (the target). Based on this principle, we can determine the real positions of double-hit events.

SiPMs are ideal for compact detectors due to their high integration and small size. Previous studies have indicated that the spectral response of SiPMs is compatible with CsI emission spectra. Because SiPM+CsI can detect γ rays, it can serve as a portable dosimeter for environmental dose equivalent measurements [45]. The combination used for proton detection achieves well-separated protons and deuterons at energies below 12 MeV [48]. Using Pulse Shape Discrimination (PSD), α particles can be easily separated from β - γ events [51, 52]. Additionally, CsI crystals coupled to SiPMs have been used to detect α particles and low-energy protons, tested using the Tandem Van-de-Graaff at INFN-Laboratori Nazionali del Sud (LNS) [49]. Thus, the CsI-SiPM combination can also be applied in heavy-ion collision experiments. SiPMs are high-performance detectors that detect and amplify single-photon signals. The advantages of SiPMs over conventional photomultiplier tubes (PMTs) are manifold: high photon detection efficiency, single-photon sensitivity, fast response time, low operating voltage, low power consumption, and small size. They also exhibit good radiation and magnetic resistance, making them adaptable to various environments and conditions. Therefore, using SiPMs as back-end photoelectric signal conversion devices for CsI enhances detection capabilities by enabling efficient light signal readout and processing.

III. Simulation

Geant4 provides a toolkit for simulating the detection process, offering various models for physical processes such as elastic scattering, inelastic scattering, ionization, and trajectory refinement. These models are essential for studying particle interactions with different materials in detector designs. Geant4 also allows detailed definition of complex detector geometries, enabling accurate modeling and performance evaluation.

Experimental results showed that the kinetic energy of α particles from ^{28}Si breakup was lower than 300 MeV [10]. Alpha particles with energies below 520 MeV can be fully stopped in a 50 mm CsI crystal. Therefore, α -particle energy can be measured using CsI crystals. Furthermore, alpha-conjugate nuclei with higher masses, such as ^{12}C , ^{16}O , ^{20}Ne , and ^{24}Mg , are mostly stopped in the DSSDs. Consequently, the experiment can simultaneously detect both light and heavy particles of interest.

A. Angular Resolution

The DSSDs provide position information for particles hitting the detector, allowing calculation of the θ and ϕ emission angles. Assuming the Z-axis aligns with the incident particle beam direction, θ and ϕ can be obtained as follows:

$$\theta = \arctan\left(\frac{\sqrt{x^2 + y^2}}{z}\right)$$

$$\phi = \arctan\left(\frac{y}{x}\right)$$

where x , y , z represent position information obtained from the DSSDs.

Angular resolution is crucial for system performance. To evaluate the desired angular resolution, we selected several discrete values of θ and ϕ . The distance between the target and detectors was set at 150 mm to cover forward angles up to $\pm 25^\circ$. The θ distribution without ϕ restriction is shown in Fig. 2 Figure 2: see original paper. The detectors can cover ϕ angles from 0° to 360° , except for gaps between telescope arrays. The ϕ distribution is shown in Fig. 2(b).

Fig. 2 shows that the FWHM of angular resolution for θ ranges from 0.2° to 0.4° , whereas the FWHM for ϕ is approximately 2.2° . The measurements of θ and ϕ reveal noticeable differences in angular resolution capability between single DSSD and double-layer DSSD configurations, with the double-layer DSSD performing better. These angular resolution capabilities affect reconstruction of fragmented nuclei during multiple alpha events. Hence, two DSSD layers enable more precise event reconstruction. The next section illustrates differences in particle excited-state reconstruction between single- and double-layer DSSDs.

B. Event Reconstruction

By collecting and analyzing data from particles emitted in nuclear collision processes, we can infer the dynamics and nuclear state of collision events. Event reconstruction is a crucial technique for extracting physical information from data, and its performance and accuracy are essential parameters affecting charged-particle telescope array performance.

Low-energy particle collision outcomes can be characterized by several parameters, such as the excitation energy of fragments before decay and the angular distribution of fragments. These parameters provide valuable information about collision dynamics and mechanisms, as well as properties and structures of particles and fragments involved. Therefore, measuring and analyzing experimental parameters of low-energy particle collisions is essential.

Important physical parameters include E_x , denoting the excitation energy of projectile nuclei, and E_{tot} , denoting the total kinetic energy of all fragments in the laboratory frame:

$$E_{tot} = \sum K_{lab} + K_{recoil}$$

$$E_x = \sum K_{c.m.} - Q$$

where $K_{c.m.}$ denotes the kinetic energy in the center-of-mass frame of the summed particles, Q is the Q -value of the nuclear reaction representing the mass difference between initial reactants and final products, K_{lab} denotes kinetic energy in the laboratory frame, and K_{recoil} represents recoil nuclear energy calculated from energy and momentum conservation.

This information is crucial for comprehensive understanding of experimental physical processes. By combining cascade decay processes, we can gain insights into fundamental particle properties and the energy distribution and dynamics of the overall system. Additionally, according to charge multiplicity distribution, the temperature of heavy-ion collisions can be determined, which can be applied to analyze reaction dynamics [50].

The spectrum from ^{28}Si fragmenting into 7α particles [10] was used as input for Geant4 simulation to model the detection process, with alpha particles hitting the detectors event-by-event. Such simulations are more realistic and allow better evaluation and analysis of detector performance under experimental conditions. However, based on these data, approximately 20% of 7α events may be lost due to detection geometry efficiency.

Fig. 3 [Figure 3: see original paper] shows the excitation energy distribution of ^{28}Si reconstructed from 7α particles. Panel (a) shows the overall distribution, while panel (b) shows the distribution with input values restricted between 83 MeV and 85 MeV.

Fig. 3 demonstrates that calculated results with double DSSDs match simulated input well, whereas single DSSD shows poor performance for 7α events. Some events respond simultaneously on multiple silicon strips, interfering with position resolution of a single DSSD, whereas double DSSDs can eliminate such effects through momentum analysis.

This charged-particle detector array was specially designed and optimized for alpha-particle detection. It can detect 7α -particle events occurring in experiments, as well as fragmentation of alpha-conjugate nuclei into N alpha events. By analyzing data from these events, we can reconstruct nuclear excitation energies.

One possible explanation for 7α -particle production might be cascade decay of ^{28}Si , meaning decay products may contain other alpha-conjugate nuclei such as ^8Be and ^{12}C . To investigate this hypothesis, data from alpha-conjugate nuclei should be analyzed. Reconstructing the cascade decay process of ^{28}Si to understand how it produces 7α particles represents a novel approach for studying nuclear structure and dynamics of ^{28}Si and its decay products.

Fig. 4 [Figure 4: see original paper] shows excitation energy distributions for ^8Be breaking up into 2α particles and ^{12}C breaking up into 3α particles.

The excitation energy of ^8Be is low, and the 2α particles from decay have very small emission angles in collisions, requiring high angular resolution to detect 2α events. ^8Be nuclei are produced in large numbers in reactions, indicating a high rate of double-alpha hit events in experiments. Therefore, simulating detector response to ^8Be fragmentation events is important. Fig. 4(a) depicts excitation energy spectra of ^8Be reconstructed using 2α particles. When 2α particles hit the detector simultaneously, two sets of X-Y values are obtained, corresponding to two spatial positions. Single-layer DSSD cannot distinguish the real α -hit position, causing results to deviate from input values. Double-layer DSSDs provide another set of spatial positions from which hit positions can be determined through momentum analysis. In addition to ^8Be , ^{12}C can also be produced during reactions. The production of ^{12}C in stars via the triple-alpha process depends on a specific resonance of ^{12}C called the Hoyle state. This resonance has important implications for nuclear structure theory and nuclear astrophysics applications. It is essential to evaluate detector capability to reconstruct ^{12}C fragmentation events occurring in the Hoyle state. Simulation results are presented in Fig. 4(b). In simulations reconstructing ^{12}C , double-layer DSSDs outperformed single-layer DSSD. As shown in Fig. 4, the charged-particle telescope array reconstructs excitation energies of ^8Be and ^{12}C with reasonable accuracy. Alpha particles derived from double-layer DSSD provided more accurate excitation energies than those from single-layer DSSD. Therefore, a double-layer DSSD design is required for this purpose.

Moreover, results demonstrate that the telescope array is versatile and suitable for various experiments beyond those involving disintegration of ^{28}Si into 7α particles. It can also achieve good performance in experiments generating mul-

multiple alpha particles or multiple fragments of different masses, owing to its high angular resolution.

The telescope array exhibited remarkable performance and accuracy in excitation energy spectra of reconstructed nuclei, making it a vital tool for studies involving these processes.

IV. Measurement

Simulation results indicate that the detector meets experimental performance requirements; however, further validation is necessary to assess actual performance. Currently, evaluation of the detector's charged-particle detection capability is limited to using a ^{241}Am source. The decay of ^{241}Am primarily produces alpha particles with energy of 5.486 MeV. These particles have low penetration depth and can be stopped by a single DSSD layer. Therefore, energy resolution can be determined separately for DSSD and CsI components. The energy resolution of the cesium iodide scintillation detector was measured.

Fig. 5 [Figure 5: see original paper] shows test results for 25 CsI+SiPM detectors with the ^{241}Am α source. Data points are fitted with a Gaussian function.

The energy spectrum of the telescope array consists of 25 CsI crystals coupled to 25 SiPMs at 30 V voltage and gain of 20 on the operational amplifier circuit, as shown in Fig. 5. Small performance differences are observed among CsI crystals, possibly due to variation in alpha spectra from heterogeneity of CsI crystals, although they originated from one large block. Additionally, radioactive source position during measurement may influence results.

Fig. 6 [Figure 6: see original paper] shows that energy resolution is approximately 9%. Compared with traditional designs, sandwiched TiO_2 can achieve comparable energy resolution [51, 52].

According to Fig. 7 [Figure 7: see original paper], energy resolution of the CsI+SiPM composite detector depends on voltage applied to SiPM. Higher voltage results in higher gain, smaller dynamic range, and better energy resolution. However, when detecting high-energy particles, increased noise and saturation effects caused by high voltage can affect detector resolution. To detect high-energy alpha particles up to 300 MeV, voltage applied to SiPM should be set as low as possible. However, overall performance of the telescope array for high-energy particles—including energy resolution, crosstalk, and charged-particle identification capability—must be assessed through online beam tests.

V. Summary

A novel detector array consisting of two DSSDs and a 5×5 cesium iodide scintillator array coupled with a SiPM array for particle identification and trajectory tracking was designed and tested, aiming at detection of multiple α -particle events with high position resolution. The high sensitivity and excellent timing

performance of SiPM make it a good light signal readout module. CsI+SiPM detectors can be used in experiments to detect low-energy protons or deuterons. However, this is the first attempt to use the CsI+SiPM array to detect high-energy particles in heavy-ion collisions. The compact and robust telescope array is suitable for various experimental scenarios owing to the small size of SiPM and sandwiching technology applied for the CsI array.

Using the Geant4 toolkit, detector responses to α particles with different energies and angles have been simulated. Simulation results indicate that the detector array has high angular and energy resolution, enabling accurate distinction of multiple α -particle events. Additionally, reconstruction of ^{28}Si excitation energy using 7α is satisfactory. This telescope array coupled with SiPM represents a novel design for nuclear physics experiments, which can be used not only in experiments investigating exotic toroidal structures but also in future studies of excitation states involving nuclear clusters, contributing to exploration of decay and dynamics of exotic nuclear shapes.

References

- [1] J. A. Wheeler, *Nucleonics Notebook*, 1950 (unpublished), see also p. 297 in G. Gamow, *Biography of Physics*, Harper & Brothers Publishers, N. Y. 1961; Princeton University Graduate Course Physics 576 Take-Home Examination Problem 2, May 22, 1963 (unpublished).
- [2] A. Kosior, A. Staszczak, C. Y. Wong, *Toroidal Nuclear Matter Distributions of Superheavy Nuclei Constrained Skyrme-HFB Calculations*. Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States), <https://doi.org/10.5506/APhysPolBSupp.10.249>
- [3] C. Y. Wong, *Toroidal nuclei*. Phys. Lett. B **41**, 446-450 (1972). [https://doi.org/10.1016/0370-2693\(72\)90671-5](https://doi.org/10.1016/0370-2693(72)90671-5).
- [4] C. Y. Wong, *Toroidal and spherical bubble nuclei*. Ann. Phys. **77**, 279-353 (1973). [https://doi.org/10.1016/0003-4916\(73\)90420-X](https://doi.org/10.1016/0003-4916(73)90420-X)
- [5] C. Y. Wong, *Rotating toroidal nuclei*. Phys. Rev. C **17**, 331 (1978). [10.1103/PhysRevC.17.331](https://doi.org/10.1103/PhysRevC.17.331)
- [6] C. Y. Wong, *Hot toroidal and bubble nuclei*. Phys. Rev. Lett **55**, 1973 (1985). <https://doi.org/10.1103/PhysRevLett.55.1973>
- [7] A. Staszczak, *High-spin isomers. toroidal Phys. Lett.* C. Y. Wong, (2014). <https://doi.org/10.1016/j.physletb.2014.10.013>.
- [8] T. Ichikawa, J. A. Maruhn, N. Itagaki, et al., *Existence of an Exotic Torus Configuration in High-Spin Excited States of Ca 40*. Phys. Rev. Lett. **109**, 232503 (2012). DOI: <https://doi.org/10.1103/PhysRevLett.109.232503>
- [9] X. G. Cao, E. J. Kim, K. Schmidt, et al., *Examination of evidence for resonances at high excitation energy in the 7α disassembly of ^{28}Si* . Phys.

- Rev. C **99**, 014606 (2019). DOI: <https://doi.org/10.1103/PhysRevC.99.014606>
- [10] X. G. Cao, E. J. Kim, K. Schmidt, et al., *α and α Conjugate Fragment Decay from the Disassembly of ^{28}Si at Very High Excitation Energy*. JPS. Conf. Proc. **32**, 010038 (2020). DOI: <https://doi.org/10.7566/JPSCP.32.010038>
- [11] X. G. Cao, E. J. Kim, K. Schmidt, et al., *Evidence for resonances in the 7α disassembly of ^{28}Si* . AIP. Conf. Proc. **2038**, 020021 (2018). DOI: <https://doi.org/10.1063/1.5078840>
- [12] Z. X. Ren, P. W. Zhao, S. Q. Zhang, et al., *Toroidal states in ^{28}Si with covariant density functional theory in 3D lattice space*. Nucl. Phys. A **996**, 121696 (2020). DOI: <https://doi.org/10.1016/j.nuclphysa.2020.121696>
- [13] Z. H. Yang, Y. L. Ye, B. Zhou, et al., *Observation of the Exotic 02^+ Cluster State in ^8He* . Phys. Rev. Lett. **131**, 242501 (2023). DOI: <https://doi.org/10.1103/PhysRevLett.131.242501>
- [14] J. Han, Y. Ye, J. Lou, et al., *Nuclear linear-chain structure arises carbon-14*. Commun. Phys. (2023). DOI: <https://doi.org/10.1038/s42005-023-01342-6>
- [15] J. H. Chen, Y. L. Ye, K. Ma, et al., *New evidence of the Hoyle-like structure in ^{16}O* . Sci. Bull. **68**, 1119-1126 (2023). <https://doi.org/10.1016/j.scib.2023.04.031>
- [16] D. X. Wang, Y. L. Ye, C. J. Lin, et al., *α -cluster decay from ^{24}Mg resonances produced in the $^{12}\text{C} (^{16}\text{O}, ^{24}\text{Mg}) \alpha$ reaction*. Chin. Phys. C **47**, 014001 (2023). DOI 10.1088/1674-1137/ac9e9a
- [17] Z. H. Yang, Y. L. Ye, Z. H. Li, et al., *Observation of Enhanced Monopole Strength and Clustering in ^{12}Be* . Phys. Rev. Lett. **112**, 162501 (2014). <https://doi.org/10.1103/PhysRevLett.112.162501>
- [18] Y. Liu, Y. L. Ye, J. L. Lou, et al., *Positive-Parity Linear-Chain Molecular Band in ^{16}C* . Phys. Rev. Lett. **124**, 192501 (2020). <https://doi.org/10.1103/PhysRevLett.124.192501>
- [19] Y. Liu, Y. L. Ye, *Nuclear clustering in light neutron-rich nuclei*. Nucl. Sci. Tech. **29**, 184 (2018). DOI: 10.1007/s41365-018-0522-x
- [20] R. Bijker, F. Iachello, *Cluster structure of light nuclei*. Prog. Part. Nucl. Phys. **110**, 103735 (2020). DOI: 10.1016/j.pnpnp.2019.103735
- [21] M. Freer, H. Horiuchi, Y. Kanada-En'yo, et al. *Microscopic clustering in light nuclei*. Rev. Mod. Phys. **90**, 035004 (2018). DOI: 10.1103/RevModPhys.90.035004
- [22] T. Ichikawa, J. A. Maruhn, N. Itagaki et al., *Linear Chain Structure of Four- α Clusters in ^{16}O* . Phys. Rev. Lett. **107**, 112501 (2011). <https://doi.org/10.1103/PhysRevLett.107.112501>
- [23] M. Barbui, K. Hagel, V. Z. Goldberg, et al., *Exploring the alpha cluster structure of nuclei using the thick target inverse kinematics technique for multiple alpha decays*. EPJ. Web. Conf. **66**, 03005 (2014). DOI: <https://doi.org/10.1051/epjconf/20146603005>

- [24] J. Bishop, T. Kokalova, M. Freer, et al., *Experimental investigation of α condensation in light nuclei*. Phys. Rev. C **100**, 034320 (2019). DOI: <https://doi.org/10.1103/PhysRevC.100.034320>
- [25] D. Ferenc, *Imaging hybrid photon detectors with minimized dead area and protection against positive ion feedback*. Nucl. Instrum. Methods. Phys. Res. A **431**, 460-475 (1999). [https://doi.org/10.1016/S0168-9002\(99\)00209-0](https://doi.org/10.1016/S0168-9002(99)00209-0)
- [26] S. Kundu, T. K. Rana, C. Bhattacharya, et al., *ChAKRA: The high resolution charged particle detector array at VECC*. Nucl. Instrum. Methods. Phys. Res. A **943** 162411 (2019). <https://doi.org/10.1016/j.nima.2019.162411>
- [27] G. Poggi, *FAZIA: Prototyping a next-generation 4π array for nuclear reaction-dynamics studies*. Eur. Phys. J. Spec. Top. **150**, 369-372 (2007). <https://doi.org/10.1140/epjst/e2007-00350-1>
- [28] J. Wang, F. H. Guan, X. Y. Diao, et al., *CSHINE for studies of HBT correlation in heavy ion reactions*. Nucl. Sci. Tech. **32**, 4 (2021). <https://doi.org/10.1007/s41365-020-00842-2>
- [29] H. Y. Zhu, J. L. Lou, Y. L. Ye, et al., *Two annular CsI (Tl) detector arrays for the charged particle telescopes*. Nucl. Sci. Tech. **34**, 159 (2023). DOI: <https://doi.org/10.1007/s41365-023-01319-8>
- [30] H. K. Wu, C. Li. *A ROOT-based detector test system*. Nucl. Sci. Tech. **32**, 115 (2021). <https://doi.org/10.1007/s41365-021-00952-5>
- [31] K. X. Huang, Z. J. Li, Z. Qian, et al., *Method for detector description transformation to Unity and application in BESIII*. Nucl. Sci. Tech. **33**, 142 (2022). <https://doi.org/10.1007/s41365-022-01133-8>
- [32] D. Guo, Y. H. Qin, S. Xiao, et al., *An FPGA-based trigger system for CSHINE*. Nucl. Sci. Tech. **33**, 162 (2022). <https://doi.org/10.1007/s41365-022-01149-0>
- [33] W. B. He, Y. G. Ma, L. G. Pang, et al., *High-energy nuclear physics meets machine learning*. Nucl. Sci. Tech. **34**, 88 (2023). <https://doi.org/10.1007/s41365-023-01233-z>
- [34] H. Wu, Y. Wang, Y. Wang, et al., *Machine learning method for $12C$ event classification and reconstruction in the active target time-projection chamber*. ArXiv. **2304**, 13233 (2023). <https://doi.org/10.1016/j.nima.2023.168528>
- [35] J. He, W. B. He, Y. G. Ma, S. Zhang et al., *Machine-learning-based identification for initial clustering structure in relativistic heavy-ion collisions*. Phys. Rev. C **104**, 044902 (2021). <https://doi.org/10.1103/PhysRevC.104.044902>
- [36] W. B. He, Y. G. Ma, X. G. Cao, et al., *Dipole oscillation modes in light α -clustering nuclei*. Phys. Rev. C **94**, 014301 (2016). <https://doi.org/10.1103/PhysRevC.94.014301>
- [37] X. G. Cao, Y. G. Ma, *Progress of theoretical and experimental studies on α cluster structures in light nuclei*. Chin. Sci. Bull. **60**, 1557-1564 (2015).

<https://doi.org/10.1360/N972014-01335>

- [38] W. B. He, X. G. Cao, Y. G. Ma, *Application of EQMD model to researches of nuclear exotic structures*. Nucl. Tech. **37**, 100511 (2014). 10.11889/j.0253-3219.2014.hjs.37.100511
- [39] W. B. He, Y. G. Ma, X. G. Cao, et al., *Giant Dipole Resonance as a Fingerprint of α Clustering Configurations in ^{12}C and ^{16}O* . Phys. Rev. Lett. **113**, 032506 (2014). <https://doi.org/10.1103/PhysRevLett.113.032506>
- [40] F. Guan, Y. Wang, X. Diao, et al., *Track recognition for the ΔE - E telescopes with silicon strip detectors*. Nucl. Instrum. Methods. Phys. Res. A **1029**, 166461 (2022). <https://doi.org/10.1016/j.nima.2022.166461>
- [41] W. Khan, C. H. He, Q. M. Zhang, et al., *Design of CsI(Tl) detector system to search for lost radioactive source*. Nucl. Sci. Tech. **30**, 132 (2019). <https://doi.org/10.1007/s41365-019-0658-3>
- [42] Y. B. Xu, X. Q. Li, X. L. Sun, et al., *The design and performance of charged particle detector onboard the GECAM mission*. Radiat. Detect. Technol. Methods. **6**, 53-62 (2022). <https://doi.org/10.1007/s41605-021-00298-x>
- [43] D. Yan, Z. Y. Sun, K. Yue, et al., *Design and construction of a multi-layer CsI (Tl) telescope for high-energy reaction studies*. Nucl. Instrum. Methods. Phys. Res. **843**, 5-10 (2017). <https://doi.org/10.1016/j.nima.2016.10.053>
- [44] W. Lu, L. Wang, Y. Yuan, et al., *Monte Carlo simulation for performance evaluation of detector model with a monolithic LaBr₃ (Ce) crystal and SiPM array for γ radiation imaging*. Nucl. Sci. Tech. **33**, 107 (2022). <https://doi.org/10.1007/s41365-022-01081-3>
- [45] T. Teranishi, Y. Ueno, M. Osada, et al., *Pulse shape analysis of signals from SiPM-based CsI (Tl) detectors for low-energy protons: Saturation correction and particle identification*. Nucl. Instrum. Methods. Phys. Res. A **989**, 164967 (2021). <https://doi.org/10.1016/j.nima.2020.164967>
- [46] Y. Y. Li, C. Y. Li, K. Hu, *Design and development of multi-channel front end electronics based on dual-polarity charge-to-digital converter for SiPM detector applications*. Nucl. Sci. Tech. **34**, 18 (2023). <https://doi.org/10.1007/s41365-023-01168-5>
- [47] W. Lu, L. Wang, Y. Yuan, et al., *Monte Carlo simulation for performance evaluation of detector model with a monolithic LaBr₃ (Ce) crystal and SiPM array for γ radiation imaging*. Nucl. Sci. Tech. **33**, 107 (2022). <https://doi.org/10.1007/s41365-022-01081-3>
- [48] P. Buzhan, A. Karakash, Y. Teverovskiy, *Silicon Photomultiplier and CsI (Tl) scintillator in application to portable H(10) dosimeter**. Nucl. Instrum. Methods. Phys. Res. A **912**, 245-247 (2018). <https://doi.org/10.1016/j.nima.2017.11.067>
- [49] M. Bondí, M. Battaglieri, M. Carpinelli, et al., *Large-size CsI (Tl) crystal read-out by SiPM for low-energy charged-particles detec-*

tion. Nucl. Instrum. Methods. Phys. Res. A **867**, 148-153 (2017). <https://doi.org/10.1016/j.nima.2017.06.024>

[50] Y. D. Song, R. Wang, Y. G. Ma, et al., *Determining the temperature in heavy-ion collisions with multiplicity distribution*. Phys. Lett. B **814**, 136084 (2021). <https://doi.org/10.1016/j.physletb.2021.136084>

[51] N. V. H. Viet, K. Takahisa, M. Nomachi, et al., *Pulse Shape Discrimination of CsI (Tl) with Photomultiplier Tube and MPPCs*. 2019 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC). 1-3 (2019). [10.1109/NSS/MIC42101.2019.9059996](https://doi.org/10.1109/NSS/MIC42101.2019.9059996)

[52] Viet N. V. H., Nomachi M., Takahisa K., et al. *Pulse shape discrimination of CsI (Tl) with a photomultiplier tube and multipixel photon counters*. IEEE. Trans. Nucl. Sci. **68**, 203-210 (2020). [10.1109/TNS.2020.3047615](https://doi.org/10.1109/TNS.2020.3047615)

[53] G. Stellin, S. Elhatisari, U. G. Meißner, *Breaking and restoration of rotational symmetry in the low energy spectrum of light α -conjugate nuclei on the lattice I: 8Be and 12C* . Eur. Phys. J. A **54**, 232 (2018). <https://doi.org/10.1140/epja/i2018-12671-6>

[54] N. Zoghi-Foumani, M. R. Shojaei, A. A. Rajabi, *A new non-microscopic study of cluster structures in light alpha-conjugate nuclei*. Chin. Phys. C **41**, 014104 (2017). <https://doi.org/10.1088/1674-1137/41/1/014104>

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