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Authors: Xu, Mr. Jishao, Cao, Dr. Xiguang, Su, Dr. Ping, Hao, Mr. Yibo, Cheng, Gaoyi, Liao, Mr. Zhengli, Yin, Mr. Weifu, Yonghao Jin, Dr. Xiaobao Wei, Wang, Zengxiang, liu, Dr. yancheng, Zhang, Dr. GuoQiang, Zhuo, Mr. Tianren, Ge, Dr. Ren, Yang, Dr. Yanyun, Junbing Ma, Wang, Dr. Kang, Dr. Shiwei Xu, Bai, Mr. Zhen, Yang, Dr. Guo, Linghao Wang, Wang, Yusen, He, Dr. Wan-Bing, Wang, Jian-Song, Ma, Dr. Chun-Wang, Prof. De-Qing Fang, Dr. Xiguang Cao

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Abstract

In this study, a compact 16-channel integrated charge and current sensitive preamplifier, called CCPA, was developed for the large-scale detector array used in nuclear physics experiments. The CCPA is designed to achieve the pulse shape discrimination method for silicon detectors. The CCPA has a fast response of typically less than 6 ns for the pulse rise time and a low equivalent noise of 1.5 keV at zero input capacitance. Energy dynamic range and pulse decay time can be easily adjusted for different applications by changing the feedback capacitance Cf and resistance Rf. A good energy resolution of 26.87 keV was achieved for 5.486 MeV αparticles from ^{241}Am. The pulse shape discrimination method was applied for the first time in the experiment carried out on the Radioactive Ion Beam Line in Lanzhou (RIBBL1), and the CCPA demonstrated high resolution and stability in beam experiments. The experiment has realized the identification of low energy α particles as low as 5 MeV by pulse shape discrimination method, as well as the hundreds MeV charged particle. It provides a new routine for high precision measurement of low energy charged particles emitted by light nuclear reactions.

Full Text

Preamble

Charge and Current Sensitive Preamplifier and Pulse Shape Discrimination Application

Jishao Xu,[1],[2] Xiguang Cao,[3],[1],[2],† Ping Su,[4] Yibo Hao,[3],[5] Gaoyi Cheng,[4] Zhengli Liao,[6] Weifu Yin,[1],[2] Yonghao Jin,[1],[2] XiaoBao Wei,[5],[7] Zengxiang Wang,[5],[7] Guoqiang Zhang,[1,2] Ge Ren,[3,5] Tianren Zhuo,[5] Yancheng Liu,[1,2] Yanyun Yang,[7] Junbing Ma,[7] Shiwei Xu,[7] Kang Wang,[7] Zhen Bai,[7] Guo Yang,[7] Linghao Wang,[7] Yusen Wang,[8] Wanbing He,[4] Jiansong Wang,[8] Chunwang Ma,[9,5] and Deqing Fang[4]

[1]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China
[4]Key Laboratory of Nuclear Physics and Ion-Beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
[5]College of Physics, Henan Normal University, Xinxiang 453007, China
[6]Center for Instrumental Analysis, Guangxi University, Nanning 530004, China
[7]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[8]Huzhou University, Huzhou 313000, China
[9]Institute of Nuclear Science and Technology, Henan Academy of Science, Zhengzhou 450046, China

In this study, a compact 16-channel integrated charge and current sensitive preamplifier, called CCPA, was developed for large-scale detector arrays used in nuclear physics experiments. The CCPA is designed to implement pulse shape discrimination methods for silicon detectors, featuring a fast response with pulse rise times typically less than 6 ns and low equivalent noise of 1.5 keV at zero input capacitance. The energy dynamic range and pulse decay time can be easily adjusted for different applications by changing the feedback capacitance Cf and resistance Rf. An excellent energy resolution of 26.87 keV was achieved for 5.486 MeV α particles from ^{241}Am. The pulse shape discrimination method was applied for the first time in an experiment carried out on the Radioactive Ion Beam Line in Lanzhou (RIBLL1), where the CCPA demonstrated high resolution and stability under beam conditions. The experiment successfully identified low-energy α particles down to 5 MeV using pulse shape discrimination, as well as charged particles in the hundreds of MeV range. This provides a new approach for high-precision measurement of low-energy charged particles emitted from light nuclear reactions.

Keywords: Exotic nuclear structures · Charge and current sensitive preamplifier · Pulse shape discrimination · Low energy charged particle · Silicon detector

Introduction

Clustering is prevalent in the ground states of light nuclei far from the beta stability line, as well as in the excited states of nuclei along the stability line [1–5]. Cluster structure is of profound significance for understanding and validating various nuclear structure models and plays a crucial role in studying 3α reaction rates and the formation of P-nuclei in high-temperature nuclear astrophysics environments. When atomic nuclei are excited to high-energy and high-angular-momentum states, they can exhibit various exotic shapes such as rings, cylinders, and bubble structures [6].

Wheeler proposed that under certain conditions, atomic nuclei can adopt toroidal shapes. Following this suggestion, C.Y. Wong explored possible toroidal and bubble nuclei [7-11]. Theoretical studies suggest that these ring-like shapes arise from the interplay among nuclear, centrifugal, and Coulomb forces. In recent observations of the 7α decay of ^{28}Si, resonant excited states at very high energies were discovered [12–14], which are in good agreement with theoretical calculations for excited toroidal ^{28}Si [15, 16]. Similarly, Hoyle states have important implications for nuclear reactions and nucleosynthesis processes occurring in stellar environments. The Hoyle state of ^{12}C has been a notable example with a well-developed α cluster [17], and recent evidence has been found for predicted Hoyle-like structures in ^{16}O [18]. Other cluster structures have also been identified in ^{8}He, ^{12}Be, ^{16}C, and ^{24}Mg [19–22]. These excited states of cluster nuclei and toroidal nuclei may possess exotic shapes and have the potential to decay into multiple α clusters. Experimental studies of nuclei with multiple α cluster states require precise measurement and track coincidence of α particle emission. To study these exotic nuclear clustering structures, we have developed a sophisticated telescope array [23].

The telescopes consist of two layers of DSSDs and a CsI array to study exotic nuclear clustering structures; detailed configurations can be found in reference [23]. We use pulse shape discrimination (PSD) to identify charged particles and improve the performance of the detector array. The theoretical basis of PSD has been established [24–26]. Large-scale charged particle arrays such as FAZIA [27–30] and GRIT [31] have explored PSD techniques for light and low-energy particles, though these have yet to be applied on a large scale to more general situations. Other large-scale arrays under construction, including GODDESS [32], GASPARD [33], TRACE [34], HYDE [35], and CSHINE [36–38], also plan to employ this new method. The PSD method shows great potential and promise for significantly enhancing charged particle measurement capabilities.

Charged particle emission exhibits rich physics near the cluster emission threshold. Recently, photonuclear reactions performed at the HIγS facility have demonstrated that photonuclear reactions can serve as a new approach for studying exotic nuclear clustering structures [40]. The intermediate-energy gamma source in China, Shanghai Laser Electron Gamma Source (SLEGS), has been commissioned [41], and various experimental spectrometers have been developed at SLEGS for photonuclear reactions [42–44]. Spectrometers for photofission reactions are also being planned. The schematic layout of the SLEGS beamline is shown in reference [41]. A new high-performance laser gamma source, VEGA, is under construction at the ELI-NP nuclear facility [45]. The PSD method can serve as a powerful technique for measuring and identifying low-energy charged particles emitted from photonuclear reactions [46–48]. Measurements of the ^{7}Li(γ, t)^{4}He ground state cross section between Eγ = 4.4-10 MeV have been performed at the HIγS facility of TUNL, where charged particle analysis was conducted using kinematic identification techniques [49]. Events matching α-t were severely affected by electron background induced by the γ beam. Given that the electron mass is 1/1836 that of a proton, the pulse shape method is feasible for eliminating electronic background, after which kinematic discrimination can be used to extract the desired target events [50].

The preamplifier plays a pivotal role as an electronic module, serving to match impedance between the detector and spectroscopy amplifier. The Mesytec MPR-16 module is too large for easy integration into large-scale detector arrays. ORTEC charge-sensitive preamplifier modules 142A, 142B, and 142C [51] are designed with low noise and fast rise time, specifically tailored for optimal matching with single charged particle detectors. The China Institute of Atomic Energy has successfully developed an integrated charge-sensitive preamplifier with good performance and stability in experiments [52, 53]. However, the preamplifiers mentioned above are not designed for PSD and do not provide a separate current signal, which would enable deeper investigation of PSD beyond the existing rise time signal analysis method using charge-sensitive preamplifiers [29, 31, 54].

To facilitate more comprehensive investigation into pulse shape discrimination, H. Hamritas conceptualized a specialized charge and current sensitive preamplifier for PSD techniques utilizing silicon detectors [54]. This innovation was successfully employed in projects such as FAZIA. GRIT designed the iPACI chip specifically for PSD, capable of simultaneously outputting current and charge signals while reducing amplifier size [31]. We have designed a 16-channel integrated Charge and Current sensitive Preamplifier (CCPA). The CCPA circuit features a simple structure and low cost, enabling widespread deployment in large-scale detector arrays. This advancement can drive the popularization of PSD with silicon detectors. The CCPA, owing to its compact size, can be effectively cooled by a small water-cooled plate and easily placed in the vacuum target chamber for close connection with the silicon detector, thereby significantly reducing noise levels.

II. Circuit Design of CCPA

The CCPA circuit is divided into two key parts, along with its attached high-voltage circuit for the detector and test circuit. The two core components consist of an integrator circuit composed of C1, R1, and PA1, and a differentiator circuit composed of C2, C3, R3, and PA3 (Fig. 2 [Figure 2: see original paper]). The integrator circuit includes a capacitor (C1), a resistor (R1), and operational amplifier PA1. The operational amplifier PA1 is a low-noise 1.05 GHz FastFET operational amplifier developed using Analog Devices' proprietary eXtra fast complementary bipolar (XFCB) process, which enables the amplifier to achieve ultra-low noise (4 nV/$\sqrt{}$Hz) as well as very high input impedance. The resistance-capacitance feedback network, denoted as Rf and Cf, constitutes a charge integration and discharge circuit. The energy sensitivity and pulse decay time are determined by Rf, Cf, and PA1. PA3, in conjunction with components C2, C3, and R3, forms the differential amplification circuit to provide the current signal from the silicon detector (Fig. 2). PA3 is a unity-gain stable, high-speed, voltage-feedback amplifier with low distortion, low noise, and high slew rate, featuring a bandwidth of 850 MHz, a slew rate of 2800 V/µs, and a $±$5 V supply voltage. It is an ideal candidate for systems requiring high dynamic range, precision, and speed. The high-voltage circuit comprises two resistors, R4, and a filtering capacitor, C4, designed to eliminate minor high-frequency noise from the high-voltage power supply.

The CCPA PCB has six layers, including the signal layer, ground layer, positive power layer, ground layer, negative power layer, and ground layer, as shown in Fig. 3 [Figure 3: see original paper]. By utilizing these layers, interference between the power supply and signals can be effectively reduced. A high-impedance node is susceptible to picking up stray signals in the system, so keeping it as short as possible reduces this effect. The layout of an input node with high impedance is of great importance; other signals should be located away from this signal path, and there should be no internal power planes underneath it. Where space is limited, we slot around high-impedance input nodes to provide additional isolation and reduce contamination effects. The signal layer and ground layer establish approximately 50-ohm impedance. The output signal employs an MCX interface to connect coaxial cables for data acquisition, reducing signal interference while preserving a compact form factor. All signal interfaces are installed on the rear side to facilitate direct contact between the front chip and water cooler for heat dissipation. The system is cooled by a liquid cooling radiator, which can cool the CCPA to room temperature while operating at full power in vacuum.

Fig. 1 [Figure 1: see original paper]. Schematic layout of the SLEGS beamline from literature [41]
Fig. 2. CCPA circuit schematic
Fig. 4 [Figure 4: see original paper]. Linearity plot.

III. Performance Test Results

We conducted comprehensive testing of the CCPA using a pulse generator and an α source to gain a clearer understanding of the preamplifier' s performance. The CCPA demonstrates excellent performance in linearity, speed, and resolution tests.

A. Linearity Test

Linearity is crucial for spectrum measurement. We performed linearity testing on the CCPA using the DG5352 function generator produced by RIGOL. We generated ramps with the DG5352, injected the signal into the amplifier, and observed that the current waveform yielded a pulse width of 25 ns. We employed a Tektronix oscilloscope to observe the waveforms of the current and charge signals, which were then routed to a DT5730 digitizer for digital processing. Charge and current amplitude values are shown (Fig. 4) as a function of input energy, expressed in MeV and µA. Linear fitting was applied to the data points, revealing excellent linearity for both the charge signal (R^2 = 0.99996) and the current signal ($R^2 = 0.99997$). This demonstrates that the CCPA has outstanding linearity.

B. Speed Test

We utilized the DG5352 function generator for speed measurements on the CCPA, generating fast-rising signals with a rise time (10%-90%) of 2.9 ns and inputting them to the CCPA via a 30 cm coaxial cable. By adjusting this signal, the CCPA can output at full scale. The measured rise time for the charge signal was 8.7 ns, and for the current signal, it was 5 ns. After removing the rise time contribution from the function generator itself, we obtained a response time of less than 6 ns (0 pF) for the CCPA.

C. α Source Test and Energy Resolution

We connected a CCPA (C1 = 1 pF) to a 300 µm W1-type Double-Sided Silicon Strip Detector (DSSD) manufactured by Micron Semiconductor Ltd. A ^{241}Am α source was used to evaluate the energy resolution. The signal generated by the CCPA, shown in Fig. 5a [Figure 5: see original paper], clearly displays both the charge and current signals. The noise of the charge signal and current signal is less than 2 mV and 1 mV, respectively. The generated signal was then input into the CAEN DT5730 digitizer, and we employed a trapezoidal filter to process and shape the charge signal. The resulting α source energy spectrum is shown in Fig. 5b [Figure 5: see original paper], achieving an energy resolution of 0.49%. The equivalent charge noise is 26.87 keV. When generating a signal with the same amplitude using a function generator, the resolution is 0.1%. The equivalent charge noise (0 pF) of the CCPA is 5.4 keV.

Prior to beam experiments, we also tested the PSD capability of the CCPA (C1 = 5 pF) with a 300 µm DSSD using three α sources. The PSD particle identification spectrum shown in Fig. 5c clearly reveals α particles with three distinct energies. The PSD method employed in Fig. 5c was the "Energy vs Current maximum" approach. The CCPA achieves very high resolution due to its low noise, with α particles of different energies forming distinct bands in the diagram.

IV. In-Beam Experiment with CCPA

The CCPA modules were applied to a beam experiment at the Radioactive Ion Beam Line in Lanzhou (RIBLL1), using a 35 MeV/u ^{28}Si beam incident on a 1 mg/cm^2 ^{27}Al target. To study the 7α disassembly of ^{28}Si, we utilized six sets of telescopes to detect emitted charged particles. Fig. 6 [Figure 6: see original paper] shows the layout of the detector array used in the experiment. Telescopes 1#, 2#, and 3# are composed of a 300 µm and a 1000 µm BB7-type DSSD, along with a 3$\times 3 CsI-PMT array. Telescope 4# comprises a 300 m and a 500 m BB7-type DSSD, along with a 3\times 3 CsI-PMT array. Telescopes 1#–4# are positioned symmetrically around the beama... type DSSD, along with a 5\times$5 CsI-SiPM array.

The telescope unit consists of two layers of DSSD coupled to CCPA modules and a CsI-SiPM array. The CCPA is situated within a vacuum chamber in close proximity to the DSSD. In this experiment, for the 300 μm silicon detector, we employed a 5 pF feedback capacitance for the CCPA, capable of handling an energy range exceeding 400 MeV. For the 1000 μm silicon detector, a CCPA preamplifier with a feedback capacitance of 12 pF was used, suitable for an energy range greater than 900 MeV.

We employed the MDPP-32 digitizer manufactured by Mesytec to acquire the preamplifier signals. The digitizer is placed outside the vacuum chamber and connected to the CCPA using coaxial cables through a flange. By adjusting the gain of the digitizer, we optimized the energy dynamic range to achieve the best discrimination of emitted particles.

A. Fragment Identification with ΔE(Si1)−E(Si2) Method

The ΔE−E technique is based on the Bethe-Bloch energy loss formula, measuring the energy deposited by particles in two detectors after passing through the first layer. In the ΔE−E correlation, a particle stopped in Si2 helps establish one of the quasi-hyperbolic correlations frequently used for particle identification: as the incident particle energy E_0 increases, the energy deposited in Si1 decreases while that in Si2 increases. As E_0 continues to increase, Si2 can no longer stop the particles, and the energy deposited in both Si1 and Si2 decreases [50, 56, 58].

The detector array equipped with CCPA preamplifiers demonstrated excellent performance in the beam experiment. The energy resolution of the detector system consistently remained better than 1% throughout the experiment. Fig. 7 [Figure 7: see original paper] illustrates a typical ΔE(Si1)−E(Si2) particle identification plot for telescope 5#. All detected elements are clearly identifiable across the entire dynamic range, with distinct and well-separated isotope bands.

A Figure of Merit (FoM) is defined as $\mathrm{FoM} = |\mathrm{PID}_2 - \mathrm{PID}_1|/(\mathrm{FWHM}_1 + \mathrm{FWHM}_2)$ for adjacent atomic numbers as a function of energy, where FWHM_1 and FWHM_2 are the full widths at half maximum of the Gaussian distributions of two adjacent isotopes with atomic numbers A and A+1, and PID_1 and PID_2 are the centroids of the peaks. We straightened and projected the isotope bands using CERN ROOT, as shown in Fig. 8 [Figure 8: see original paper]. If FoM is greater than 0.7, the isotope bands are considered "well separated" [30, 54]. For the helium-3 and helium-4 isotope bands in Fig. 8, FoM equals 2.35, indicating excellent identification. This effect is also observed for other elements. We optimized the energy dynamic range to achieve the best discrimination of emitted particles. All telescope arrays in the experiment exhibit similar performance characteristics, demonstrating that the CCPA can work effectively with detectors to achieve good energy resolution and particle identification.

B. Particle Identification with ΔE(Si1+Si2)−E(CsI(Tl)) Method

Most energetic particles pass through both silicon detectors and reach the subsequent CsI(Tl) scintillators [50]. In this method, the x-axis represents the light output of the CsI(Tl) scintillators collected by SiPM, and the y-axis represents the total energy measured by the two silicon detectors (Fig. 9 [Figure 9: see original paper]). The PSD method has been widely used in scintillator detectors, and its application to silicon detectors has become a focus of research in recent years. This method enables particle identification using only the energy and signal rise time information from a single silicon detector, which not only greatly reduces the threshold for particle identification but also simplifies the detector complexity. PSD requires energy combined with a current-related value to identify particles. In this study, the shape-dependent parameter we used is the maximum value of the current signal versus energy.

The ΔE−E method employs two detectors to separately measure the particle' s ΔE deposited in the first detector and the residual E in the following detector. Particle identification is achieved based on the different deposited energies characteristic of different particle types in the ΔE and E silicon detectors. The particle identification threshold of the ΔE−E method depends on the thickness of the ΔE detector [25]. Using a thinner ΔE detector can further reduce the PID threshold. For instance, passing through a 60 µm DSSD requires at least 9.2 MeV of particle energy, meaning the minimum energy for identifying α particles exceeds 9.2 MeV using the ΔE−E method. In realistic measurements, a smaller threshold value is often required. However, due to manufacturing process limitations, thinner silicon detectors have poorer thickness uniformity. The aforementioned 60 µm silicon detector has a thickness non-uniformity larger than 4%, resulting in poor energy measurement accuracy that does not meet experimental requirements [57].

Research indicates that compared to front-side incidence, rear-side incidence—where particles enter from the side with lower electric field strength—is more favorable for extracting particle species information from the pulse shape [50, 55]. This is attributed to the fact that under rear-side incidence conditions, the plasma effect broadens the variation range of the signal rise time in silicon detectors. To better study PSD, the DSSDs of telescopes 5# and 6# are positioned to face the beam with their rear sides, so that reaction products are injected into the DSSDs from the rear side. Simultaneously, we employed the PADC mode of the MDPP-32 digitizer to acquire the peak values of the current pulses, maximizing the rise-time differences of the charge signals produced by different stopped products with the same energy.

We constructed a two-dimensional spectrum of the maximum value of the current signal pulse versus the energy signal. The α band is clearly distinguishable in Fig. 10 [Figure 10: see original paper]. Particles of different charges are clearly separated, forming parabola-like bands. Particles with larger charge require higher energy to penetrate the same thickness of silicon, and simultaneously, particles with larger charge of the same energy form plasma columns in silicon detectors that dissociate slowly, resulting in a small current signal and high discrimination threshold. The information presented in Fig. 10 is consistent with this physical principle. The PSD method compensates for the drawback of the ΔE(Si1)−E(Si2) method, which cannot distinguish low-energy particles stopped in the first silicon layer. This enables us to identify 5 MeV α particles. Using the ΔE(Si1)−E(Si2) method would require silicon detectors thinner than 60 µm to achieve discrimination of charged particles at such low energies. However, due to the junction capacitance of silicon detectors and manufacturing limitations, the energy resolution of thin silicon strips (< 60 µm) is significantly inferior to that of 300 µm silicon detectors.

It should be noted that many factors influence the effectiveness of PSD. The sampling frequency of the digitizer plays a critical role in accurately capturing current signal information. It has been shown that sampling rates below 200 MSa/s significantly degrade discrimination quality [60]. In this experiment, the PADC of the MDPP-32 (80 MHz) lacks adequate filtering functionality for fast pulses less than 100 ns. The application of appropriate filtering algorithms can reduce reliance on high sampling rates and enhance discrimination capability [28, 60]. For discrimination of light particles from low-energy nuclear reactions, selecting a high-gain version of the preamplifier can improve discrimination quality. Similarly, the use of high-quality silicon detectors is essential [30, 62]. Currently, the pulse shape method using silicon detectors allows identification of light particles (Z=1) with energies as low as 2 MeV [50, 61, 63].

V. Summary

We have developed a new type of preamplifier, the CCPA—a 16-channel, fast-responding, high-resolution charge and current output preamplifier—and applied it on a large scale in beam experiments. The excellent performance of the CCPA was further confirmed through α source testing. Silicon-silicon-CsI(Tl) detectors were used in an experimental setup with a 35 MeV/u ^{28}Si beam incident on ^{27}Al targets to investigate exotic α-cluster nuclear configurations. The detector array used in this experiment has demonstrated high energy resolution, high granularity, and strong identification capability. The results of the digital PSD technique for identifying stopped reaction products are highly satisfactory, with products of different Z clearly separated. If a CCPA with higher gain is employed and the filtering capability of the digitizer is enhanced, the PSD method will yield even better results. This study provides a new approach for achieving high energy resolution and strong particle identification of products in low-energy nuclear physics experiments such as photonuclear reactions.

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