HALIMA: A Hybrid Array for LIfetime MeAsurement of Neutron-Rich Nuclei at IMP

Authors: Jia, Dr. Zihao, Fang, Dr. Yongde, Dr. Sicheng Wang, Wei, Dr. Hua, Dr. Hongyi Wu, Dr. Guangxin Zhang, Yuan (Nuclear physics), Dr. Cenxi, Wang, Zhixuan, Dr. Junhong Xu, Li, Dr. Jianhong, Liang, Mrs. Wen, Tan, Yuhong, Pan, Mr. Wenjun, Ren, Mr. Yuxuan, Kumar Raju, Dr. Mukhi, Prof. Song Guo, Li, Dr. Guangshun, Dr. Yunhua Qiang, Liu, Prof. Min-Liang, Ding, Dr. Bing, Huang, Dr. Minghui, Zhang, Ningtao, Dr. Bingshui Gao, Ma, Mr. Peng, Yang, Dr. Herun, Dr. Ruofu Chen, Haixia Li, Li, Dr. Ronghua, Dr. Xiuhua Wang, Chen, Dr. Cuihong, Yang, Dr. Haibo, Dr. Jian-Song Wang, Sun, Dr. Xiaohui, Li, Dr. Zhihuan, Hua, Prof. Hui 华辉, Prof. Xinxing Xu, Zhou, Prof. Xiaohong, Gan, Zaiguo, Prof. Yuhu Zhang, Dr. Yongde Fang

Date: 2025-06-30T00:00:00+00:00

Abstract

A new multi-detector array named HALIMA (Hybrid Array for LIfetime MeAsurement) has been developed at Lanzhou, for nuclear structure studies in fission. The array comprises eight BGO-shielded High-Purity Germanium (HPGe) detectors and twenty fast Ce-doped Lanthanum Bromide [LaBr3(Ce)] detectors shielded with CsI(Tl). HALIMA is further complemented by two ancillary detector systems: fission fragment (FF) detectors and β detectors. This configuration enables precise sub-nanosecond lifetime measurements using a four-fold FF/β-Ge-LaBr3(Ce)-LaBr3(Ce) coincidence technique. The performance and specifications of the detectors, associated electronics, and data acquisition system are presented in detail. The advantage of FF selectivity is emphasized, which significantly enhances the sensitivity to specific fission channels. Using this approach, lifetimes of nuclear excited states populated in the spontaneous fission of 252Cf have been measured, showing good agreement with established literature values.

Full Text

Preamble

HALIMA: A Hybrid Array for LIfetime MeAsurement of Neutron-Rich Nuclei at IMP Zi-Hao Jia,1, 2 Yong-De Fang,1, 2, ∗ Si-Cheng Wang,1, 2, † Wei Hua,3,

4, ‡ Hong-Yi Wu,5, 6, § Guang-Xin Zhang,3 Cen-Xi Yuan,3 Zhi-Xuan Wang,3 Jun-Hong Xu,1, 2 Jian-Hong Li,1, 2 Wen Liang,1, 2 Yu-Hong Tan,1, 2 Wen-Jun Pan,6 Yu-Xuan Ren,6 M. Kumar Raju,7 Song Guo,1, 2 Guang-Shun Li,1, 2 Yun-Hua Qiang,1, 2 Min-Liang Liu,1, 2 Bing Ding,1, 2 Ming-Hui Huang,1, 2 Ning-Tao Zhang,1, 2 Bing-Shui Gao,1, 2 Peng Ma,1, 2 He-Run Yang,1, 2 Ruo-Fu Chen,1, 2 Hai-Xia Li,1, 2 Rong-Hua Li,1, 2 Xiu-Hua Wang,1, 2 Cui-Hong Chen,1, 2 Hai-Bo Yang,1, 2 Jian-Song Wang,8 Xiao-Hui Sun,8 Zhi-Huan Li,6 Hui Hua,6 Xin-Xing Xu,1, 2 Xiao-Hong Zhou,1, 2 Zai-Guo Gan,1, 2 and Yu-Hu Zhang1, 2 1State Key Laboratory of Heavy Ion Science and Technology, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, 730000, Gansu, China 2School of Nuclear Science and Technology, University of Chinese Academy of Science, Beijing, 100049, China 3Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-Sen University, Zhuhai, 519082, China 4Guangxi Key Laboratory of Nuclear Physics and Nuclear Technology, Guangxi Normal University, Guilin, 541004, China 5Key Laboratory of Nuclear Data, China Institute of Atomic Energy, Beijing, 102413, China 6School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, 100871, China 7Department of Physics, GITAM School of Science, GITAM University, Visakhapatnam, 530045, India 8School of Science, Huzhou University, Huzhou, 313000, China A new multi-detector array named HALIMA (Hybrid Array for LIfetime MeAsurement) has been developed at Lanzhou, for nuclear structure studies in fission. The array comprises eight BGO-shielded High-Purity Germanium (HPGe) detectors and twenty fast Ce-doped Lanthanum Bromide [LaBr3(Ce)] detectors shielded with CsI(Tl). HALIMA is further complemented by two ancillary detector systems: fission fragment (FF) detectors and β detectors. This configuration enables precise sub-nanosecond lifetime measurements using a four-fold FF/β-Ge-LaBr3(Ce)-LaBr3(Ce) coincidence technique. The performance and specifications of the detectors, associated electronics, and data acquisition system are presented in detail. The advantage of FF selectivity is emphasized, which significantly enhances the sensitivity to specific fission channels. Using this approach, lifetimes of nuclear excited states populated in the spontaneous fission of 252Cf have been measured, showing good agreement with established literature values.

Keywords: FFs/β-γ rays coincidences, Selectivity, Spontaneous fission, LaBr3(Ce), HPGe, Solar cells, Lifetime measurement

INTRODUCTION

The measurement of lifetimes of nuclear excited states is a fundamental aspect of nuclear structure studies. These lifetimes are directly related to reduced transition probabilities, which provide essential information about the underlying nuclear structure, including the degree of overlap between the initial and final nuclear wave functions. Precise lifetime data are crucial for testing nuclear models and understanding collective and single-particle excitations across various regions of the nuclear chart. Over the past two decades, the development of

the fast scintillator LaBr3(Ce) has opened up the possibility to perform fast timing measurements on the lifetimes of nuclear states ranging from the nanosecond down to the picosecond scale [1]. Several dedicated fast-timing arrays have since been developed, including FATIMA [2], KHALA [3], and VESPA [4]. These arrays, when coupled with a Ge array, and used in triple Ge-LaBr3(Ce)-LaBr3(Ce) coincidence measurements, have allowed a wide range of excited-state lifetimes in neutron-rich nuclei to be studied. This method leverages the superior energy resolution of Ge detectors to isolate specific transitions of interest, while the coincident γ-γ events recorded by the LaBr3(Ce) array are used to perform precise fast-timing analyses. More recently, extensive studies for lifetime measurements have been performed using combined setups such as EXILL & FATIMA [5], -ball & FATIMA [6] and GAMMASPHERE & FATIMA [7], using thermal and fast neutron-induced fission, as well as 252Cf spontaneous fission source. However, a major challenge in such studies is achieving high selectivity and effective background suppression. In any fission process, hundreds of different fission fragments are produced, with each fragment typically emitting around seven γ-rays. Accurately associating these γ-rays with their corresponding fission products amid the intense background is experimentally demanding. To obtain clean data, it is essential to enhance selectivity and minimize background contributions.

To overcome the limitations associated with using a Ge array alone, various fission-tagging devices have been developed to enhance selectivity. One notable example is the integration of a liquid scintillator-based active fission target into the FIPPS spectrometer at ILL [8]. This active target enables identification of fission fragments and their temporal correlation with subsequent γ decays, allowing efficient suppression of uncorrelated γ-ray background originating from β-decay. To further improve selectivity and suppress background originating from nonspecific fission products, mass-identified fission fragments FIFI spectrometer with a resolution of about six mass units has been employed in isomer decay spectroscopy studies [9].

To enhance the selectivity and suppress background, a dedicated hybrid setup HALIMA (Hybrid Array for Life-time MeAsurement) was developed at the Institute of Modern Physics, Chinese Academy of Sciences, China. HALIMA is specifically designed for measuring sub-nanosecond lifetimes of neutron-rich nuclei produced via fission. The array consists of eight Compton-suppressed HPGe and twenty LaBr3(Ce) detectors with CsI(Tl)-based anti-Compton shields for γ-ray detection. In addition, two auxiliary detector arrays, 36 solar cell detectors and 36 fast plastic scintillators were integrated into the HALIMA setup for the detection of fission fragments and β particles, respectively. With fragment tagging via solar cells and β-particle tagging via plastic scintillators, HALIMA enables the simultaneous application of both FF-Ge-LaBr3(Ce)-LaBr3(Ce) and β-Ge-LaBr3(Ce)-LaBr3(Ce) fast-timing techniques. A key component of the HALIMA setup is the solar cell array, which registers the implantation of fission fragments, and correlates them spatially and temporally with their subsequent γ decay, effectively serving as a fission tag. As demonstrated later, applying

mass-identified fission tagging reduces background from other fragments by more than a factor of four. In addition to fission tagging, the use of CsI(Tl)-shielded LaBr3(Ce) detectors in the Compton-suppression mode enhances the peak-to-total ratio by a factor of 1.5. To further optimize detection, the LaBr3(Ce) array in HALIMA is designed to have twice the efficiency of the Ge array, thereby maximizing the overall Ge-LaBr3(Ce)-LaBr3(Ce) coincidence efficiency.

In this paper, a comprehensive description of the HALIMA detection system is presented, including its detector components, readout electronics, and fully digital data acquisition system. Results from the first experiment using a 252Cf spontaneous fission source are discussed to illustrate the performance of the setup. Section II details the detector hardware and data acquisition system. Section III describes the data analysis techniques employed for fast-timing measurements across different time ranges. A summary and outlook are provided in Section IV.

INSTRUMENTS

An overview of the HALIMA detection system is provided in Fig. 1 [Figure 1: see original paper], which illustrates the arrangement of the HPGe and LaBr3(Ce) detectors, along with the data acquisition setup. The following sections describe the configuration and integration of each component in detail.

A. HPGe detectors

The HALIMA setup includes eight n-type coaxial HPGe detectors, each equipped with BGO shielding, mounted on the central ring perpendicular to the fission axis. The distance between the entrance window of the HPGe detectors and the center of the array is 17.5 cm. Each detector offers a relative efficiency of 70% compared to a standard 3 $\times$ 3 inch NaI(Tl) detector, with a typical energy resolution of 2.5 keV (FWHM) at 1332 keV. The full-energy peak (FEP) efficiency at 1 MeV was measured to be 1.05%, using standard 152Eu, 133Ba and 60Co radioactive sources. The resulting absolute efficiency curve is shown in Fig. 2 [Figure 2: see original paper], along with a fit using the empirical formula described in [10].

Each HPGe detector in the HALIMA setup is surrounded by a BGO anti-Compton shield composed of eight optically isolated BGO crystals, each coupled to a photomultiplier tube (PMT). For each BGO anti-Compton shield, the PMTs are daisy-chained to obtain a single summed output signal. These BGO Compton suppressors significantly reduce background, providing a suppression of approximately 77% in the 400–800 keV energy range when tested with a 60Co source.

B. LaBr3(Ce) detectors

To facilitate lifetime measurements, twenty individual LaBr3(Ce) detectors were incorporated into the HALIMA setup, all configured identically. Each detector consists of a cylindrical LaBr3(Ce) crystal being 2 inches in diameter and 3 inches in length, coupled to a Hamamatsu R13089 photomultiplier tube. As shown in Fig. 1, two rings consisting of eight LaBr3(Ce) detectors each have been mounted on both sides of the central ring of HPGe detectors, positioned at angles of 56° and 124° relative to the fission axis. The distance from the detector face to the center of the array is 16.5 cm. Additionally, a third ring composed of four LaBr3(Ce) detectors is mounted at the topmost layer of the array, with each detector located 22 cm from the center and oriented at an angle of 29° with respect to the fission axis. This configuration provides a solid angle coverage of approximately 13% for an isotropic source located at the center of the array.

Due to the compact size of LaBr3(Ce) crystals, Compton scattering is significant, resulting in a pronounced Compton continuum that reduces the peak-to-total ratio, particularly for low energy γ rays [11]. To reduce the Compton continuums, Régis [12] and Gierlik [13] et al. developed BGO-based Compton suppressors for LaBr3(Ce) detectors and achieved significant improvements in peak-to-total ratio [12] and peak-to-Compton ratios [13].

In the present work, a more cost-effective, compact and novel CsI(Tl)-based anti-Compton shield has been developed and equipped in the HALIMA setup. Figure 3 shows the technical drawing of a single LaBr3(Ce) detector housed within a CsI(Tl) anti-Compton shield supported by an aluminum shell. Each LaBr3(Ce) detector is enclosed by a CsI(Tl) anti-Compton shield, composed of four separated CsI(Tl) crystals. The scintillation signals from these crystals are read out using twenty-eight 6.4 mm $\times$ 6.4 mm silicon photomultipliers (SiPMs), with seven SiPMs coupled to each crystal. These signals are summed and read out as a single channel. A comparative study using a calibrated 152Eu source (Fig. 4 [Figure 4: see original paper]) demonstrates that the intense Compton background is significantly reduced when the CsI(Tl) anti-Compton shield is applied. A more detailed characterization and performance analysis will be presented in a forthcoming publication.

To optimize the time resolution of LaBr3(Ce) detectors in γ-γ coincidence mode, the PMTs of the LaBr3(Ce) detectors were operated at a bias voltage of approximately -1070 V. At this voltage, the 662 keV γ-rays from a 137Cs source produce a uniform output signal amplitude of 200 mV across all detectors. Due to the inherent non-linearity in the energy response of LaBr3(Ce) detectors largely attributed to the voltage sensitivity of PMTs, a second-order polynomial function was employed for energy calibration. Standard γ-ray sources, 133Ba and 152Eu, were used for this calibration, covering an energy range from 81 keV to 1408 keV. The energy resolution of the LaBr3(Ce) detectors was found to be 2.67% at the 1332 keV line of a 60Co source. The absolute full-energy peak (FEP)

efficiency at 1 MeV for the entire LaBr3(Ce) array was measured to be 2.74%. The corresponding absolute efficiency curve, along with the fitting results, is shown in Fig. 2.

The two primary timing characteristics of the LaBr3(Ce) detector array are the time resolution and time walk. Time resolution is determined from the summed time-difference spectra of all pairwise combinations among the 20 LaBr3(Ce) detectors. To achieve this, the individual time spectra are aligned by applying appropriate time shifts to each detector relative to a chosen reference detector, after which the summed time difference spectrum is obtained using 60Co source. Time information was extracted using the TSINC digital algorithm [14] and Constant Fraction Discrimination (CFD). Figure 5 [Figure 5: see original paper] displays the resulting time difference distribution for 20 LaBr3(Ce) detectors with 1173 keV-1332 keV γ-ray of 60Co source. The time resolution is 348.9(2) ps in FWHM, which is comparable to the resolution of FATIMA [2] despite the larger crystal volume of the LaBr3(Ce) detectors used in our setup.

To extract lifetimes shorter than the intrinsic time resolution of LaBr3(Ce) detectors down to a few picoseconds (ps), it is essential to determine the Prompt Response Difference (PRD) as a function of energy. The PRD calibration is used to describe the time walk characteristics using the coincident γ-ray cascade emitted by 152Eu source over the energy range between 200 keV and 1400 keV. The PRD was measured using Leading-Edge Discrimination (LED) in conjunction with the TSINC interpolation algorithm [14]. The resulting PRD curve is shown in the top panel of Fig. 6 [Figure 6: see original paper] and was fitted using the following equation:

$$PRD(E_\gamma) = \sqrt{E_\gamma} + b + cE_\gamma + d.$$

From the residual shown in the lower panel of Fig. 6, the uncertainty in the PRD is estimated to be $\pm$ 5.5 ps. With the PRD, the generalized centroid difference (GCD) method [15] can be applied for precise lifetime measurements down to tens of picoseconds (ps). A detailed account of the PRD calibration and its application in this setup will be presented in a forthcoming publication.

C. FFs detectors: Solar cells

The detection of fission fragments (FFs) in intense background dominated by light charged particles remains a major challenge in fission experiments. Solar cells, originally developed for photovoltaic energy conversion, were first introduced by Siegert in 1979 for detection of FFs at the Institut Laue-Langevin (ILL) facility [16]. Subsequently, Ajitanand et al. demonstrated their radiation hardness during a 252Cf experiment, confirming their suitability for use in high-background environments [17]. Owing to its low cost, flexible geometry and insensitivity to alpha particle, solar cells have been effectively employed in fission detection arrays, such as SAPHIR [18, 19] and DEATH-STAR [20, 21].

In the present work, the rise time and pulse height characteristics of three commercially available solar cell types were evaluated. Among them, TOPCON-type solar cells were selected as the FF detectors due to their high signal amplitude (400–600 mV) and relatively fast rise time (200–800 ns). These solar cells have a thickness of 130 µm and a very small depletion depth (1 µm), making them largely insensitive to light charged particles such as alpha particles due to their charge collection mechanism, specifically the funneling mechanism [22]. As illustrated in Fig. 7 [Figure 7: see original paper], the solar cells array, consisting of thirty six 11 × 11 mm^2 solar cells, is mounted on a printed circuit board (PCB) positioned at the center of HALIMA setup. The raw pulse height spectrum of FFs from a 252Cf source detected by a solar cell is presented in Fig. 8 [Figure 8: see original paper].

To assess the mass resolution of the TOPCON solar cells, the 2E method [23] which is based on conservation laws of mass and momentum, was applied using an open 252Cf source. Schmitt calibration [24] was used in this analysis, with the primary equation expressed as:

$$E = (a + a'M)x + b + b'M,$$

where a, a', b, and b' are constants using the values in [25], while E, x and M represents the energy, pulse height and the mass of FFs, respectively. Subsequently, the iterative process based on the neutron emission distribution [26] is performed to determine both the pre-neutron and post-neutron mass distribution. The resulting FF mass distribution is shown in Fig. 9 [Figure 9: see original paper] and compared with the data from [26], demonstrating good agreement. The typical time resolution of solar cells in the present work is approximately 20 ns, using the standard Charge Sensitive Preamplifier.

When using solar cells as FF detectors in fission experiments, it is essential to evaluate their radiation damage tolerance. For this purpose, a comparative radiation damage test was carried out using a 20 × 20 mm^2 silicon detector and a solar cell of the same size. Both these detectors were placed 8 cm away from a 252Cf source with an activity of 100 µCi (3.7 MBq). The variation in pulse height as a function of incident flux is presented in Fig. 10 [Figure 10: see original paper]. For an integrated flux of approximately 10^9 particles/cm^2, the FFs detected by solar cell exhibited only a 10%–15% reduction in pulse height, indicating a minor degradation. In contrast, the silicon detector exhibited a complete loss of signal, demonstrating its significantly lower radiation tolerance under similar conditions.

D. β detectors: Fast plastic scintillators

An auxiliary detector array comprising 36 fast plastic scintillators (11 × 11 mm^2) has been integrated into the HALIMA setup for β-particle tagging. Each scintillator, fabricated from EJ-series plastic scintillator material and 3 mm

in thickness, is optically coupled to a Hamamatsu S14160 Multi-Pixel Photon Counter (MPPC) with a sensitive area of 6.4 × 6.4 mm^2. These scintillators and MPPCs are mounted on a PCB, positioned 5 mm downstream from the center of HALIMA setup. The configuration of β ancillary array is shown in Fig. 11 [Figure 11: see original paper]. The time resolution of each β detector has been measured to be 942 ps.

E. Electronics and DAQ system

The electronics and data acquisition (DAQ) system of HALIMA is based on a Pixie-16 developed by XIA LLC, USA. Energy signals from the HPGe detectors, BGO and CsI(Tl) anti-Compton shields and solar cells are digitized by 16 channel, 100 MHz, 14-bit modules, while the energy signals from LaBr3(Ce) detectors, β detectors are digitized by 16 channel, 500 MHz, 14-bit modules wherein the rise time can be accurately measured. The data is recorded using a general-purpose digital data acquisition system (GDDAQ) [27, 28], and operated in a triggerless mode, which means all live events are recorded without predefined conditions. This triggerless architecture provides significant flexibility for offline data analysis and event reconstruction [29].

To optimize the fast-timing performance of LaBr3(Ce) detectors, particularly time resolution and time walk, the waveforms of LaBr3(Ce) detectors are recorded on an event-by-event basis for offline analysis. The waveform recording length is set to 0.2 µs, providing sufficient temporal detail for precise timing studies. The high-voltage supply system is segmented into two parts: two CAEN N1470 are used for powering the HPGe detectors, while three ISEG EHS modules are dedicated to supplying the LaBr3(Ce) detectors, CsI(Tl) anti-Compton shields, and BGO detectors.

III. COMMISSIONING WITH A 252CF SOURCE

A commissioning measurement was carried out using a semi-closed 252Cf source with an activity of 100 µCi. The source was encapsulated with a 50 $\mu g/cm^2$ Au sputter and mounted on a 0.127 mm thick platinum-clad nickel backing. This configuration ensures that, in each spontaneous fission (SF) event, one fission fragment (FF) recoils into the vacuum chamber while the complementary FF is absorbed in the backing. Figure 12 [Figure 12: see original paper] illustrates the technical layout of the HALIMA setup during this commissioning phase. The 252Cf source is positioned at the bottom of vacuum chamber and surrounded by a 40 mm-thick tungsten shield with a cone angle of 18°. This shielding configuration effectively blocks prompt γ rays emitted during the fission from the source. Following fission, the recoiling FF traverses the 8 cm vacuum gap and is detected by the centrally located solar cell array. In this configuration, the solar cells function as implantation detectors, enabling event-by-event correlation between FFs and their associated γ rays. Since FFs of different masses possess varying velocities, their time-of-flight (TOF) over the 8 cm path introduces a

measurable spread, which can be utilized for isomer selection. By gating on signals from the solar cells, isomer-specific events are effectively selected, and the overwhelming background is significantly suppressed. A total of approximately 4400 hours of data acquisition was completed during this commissioning run yielding around 1.3×10^{11} fission events.

In the present work, two complementary approaches have been employed to measure the lifetimes of excited states of interest produced by fission, as illustrated in Fig. 13 [Figure 13: see original paper]. The first method, shown in Fig. 13(a), utilizes the FF-Ge-LaBr3(Ce)-LaBr3(Ce) coincidence technique. In this configuration, a fission event is initially detected by the solar cell array, followed by the observation of an isomeric decay involving three or more γ rays. The excited state of interest, with lifetime denoted by τ is fed and decayed via γ_2 and γ_3, which are detected in coincidence by two LaBr3(Ce) detectors. The preceding transition γ_1 is recorded using a HPGe detector.

The second approach, illustrated in Fig. 13(b), involves a β-Ge-LaBr3(Ce)-LaBr3(Ce) coincidence technique based on the fast plastic scintillator array. In this case, the γ rays are emitted following β decay of fission fragments, with the triple γ-ray detection configuration remaining similar to that of the first method.

Prior to coincidence analysis, time alignment of all detectors was performed relative to a reference LaBr3(Ce) detector to ensure precise timing. Based on this preliminary data analysis, the validation of FFs selectivity has been evaluated by comparing γ-ray spectra gated with and without FF detection. This comparison clearly demonstrated the advantage of FF gating in terms of significant background suppression and improved peak-to-background ratios. The lifetimes of three excited states ranging from a few picoseconds to several hundred nanoseconds have been determined by implementing distinct coincidence and lifetime extraction methods. The extracted values show good agreement with literature data, confirming the capability of the HALIMA setup to perform precise lifetime measurements over a broad temporal range.

A. Time alignment

Due to variations in electronics, cable lengths, and the use of digitizer cards with different sampling frequencies and bit resolutions, each detector type within the HALIMA setup exhibits a unique timing offset. These offsets lead to misalignments in the time distributions of detectors when referenced to a reference LaBr3(Ce) detector. To correct this, the timing information including the initial timestamp and the timing information provided by the CFD filter algorithm is extracted, allowing for implementation of time alignment for each detector on a run-by-run basis. For each detector, the relative time difference with respect to the reference LaBr3(Ce) detector is determined by performing a Gaussian fit on the time distribution. The centroid of each distribution is then shifted to 0 ns to achieve synchronization. Figure 14 [Figure 14: see original paper]

shows the time difference as a function of detector ID matrices before and after time alignment. Each unit on the horizontal axis represents individual detector IDs with the HPGe detectors, solar cells, LaBr3(Ce) detectors and fast plastic scintillators represented from IDs 0–7, 8–43, 44–55 and 60–67, 56–59 and 68–99, respectively. As illustrated in Fig. 14(a), the centroids of the time distributions are scattered due to inherent offsets. After applying the alignment procedure, all time distributions are successfully centered around 0 ns, as shown in Fig. 14(b), indicating a uniform timing response across all detectors in the array.

B. Validation of FFs Selectivity

The γ-ray spectrum originating from the spontaneous fission of 252Cf is notably complex due to the presence of emission lines from hundreds of neutron-rich fission fragments. To enhance the selectivity of γ-ray events and suppress background, the HALIMA setup utilizes the solar cell array to detect fission fragments (FFs), which are then used as a trigger for implementing FF-γ coincidence measurements. To evaluate the improvement in selectivity, HPGe-HPGe coincidence spectra were generated under different gating conditions and compared, as shown in Fig. 15 [Figure 15: see original paper]. Figure 15(a) shows the HPGe coincidence spectrum of Ge-Ge double events, which is generated by using a Ge gate on the 314 keV transition. The γ rays originated from both isomeric decay and β decay are shown in the spectrum. In contrast, Fig. 15(b) shows the coincidence spectrum obtained by applying an additional gate on the solar cells, thereby selecting events correlated with fission fragments. With this condition, the isomeric state ($19/2^-$, 10 ns) in ^{137}Xe is selectively tagged, and its subsequent γ-ray transitions are prominently visible. As a result, unwanted γ rays from β-decay processes are effectively suppressed, yielding a significantly cleaner spectrum dominated by the 400 keV and 1220 keV transitions.

Beyond its role in enhancing isomer selectivity, gating on FFs offers a significant advantage in suppressing Compton background, which is particularly critical in fast-timing measurements using LaBr3(Ce)-LaBr3(Ce) coincidences. In such measurements, the background beneath the full energy peaks can introduce considerable uncertainties, thereby diminishing the precision of lifetime extraction. Furthermore, scattered γ rays originating primarily from neutron-induced inelastic scattering and Compton scattering of prompt γ-rays within the surrounding components of the HALIMA setup contribute substantially to the background in LaBr3(Ce) spectra. By utilizing FF selectivity, this intense background is reduced, thereby improving the peak-to-background ratio. To quantify the performance of this selectivity, a comparative analysis was conducted for the nucleus ^{134}Te and obtained the LaBr3(Ce)-LaBr3(Ce) coincidence spectra under different gating conditions. In Fig. 16 [Figure 16: see original paper], the LaBr3(Ce) coincidence spectrum was obtained by using a double gate on both 115 and 297 keV, respectively, for Ge and LaBr3(Ce). The peak-to-background ratio as obtained for the energy width corresponding to the width of full width at half maximum of 1279 keV was measured to be 1.6, as shown in the inset

of Fig. 16. Upon applying an additional gate on solar cell signals (gating on FFs), a noticeable reduction in background, particularly below 600 keV, was observed. Under this condition, the P/B ratio for the 1279 keV peak increased substantially to 4.3. The third case is the LaBr3(Ce) coincidence spectrum employing an additional gate on the specific mass of ^{134}Te. Compared to the Ge-LaBr3(Ce)-LaBr3(Ce) coincidence events, the background in the LaBr3(Ce) spectrum was further suppressed, resulting in a more than fourfold improvement in the P/B ratio.

It should be emphasized that the 252Cf source employed in the present work is a semi-closed source, disabling the employment of 2E method for determining the masses of FFs detected by solar cells. Therefore, an alternative approach known as the M-V method [30] was exploited, where M and V are the mass and velocity of FFs. The method is based on conservation laws of mass and momentum. Combining the Eq. 2 and the following formulas:

$$MV^2 = V(M),$$

the velocity distribution as a function of the mass was determined using an open 252Cf source developed by self-transfer technique [31]. The post-neutron mass distribution then can be obtained using the iteration process. Using this method, a mass resolution of approximately 7 atomic mass units (u) (FWHM) was achieved.

C. Preliminary results

This subsection presents the lifetime measurements of three nuclear excited states, ranging from a few picoseconds to several hundred nanoseconds. Specifically, the lifetimes of two isomers in ^{134}Te and ^{138}Ba were measured using FFs-Ge-Ge/FFs-LaBr3(Ce)-LaBr3(Ce) and β-Ge-LaBr3(Ce)-LaBr3(Ce) coincidence techniques. Additionally, the lifetime of an excited state in ^{132}Te was extracted using the Generalized Centroid Difference (GCD) method, based on FFs-Ge-LaBr3(Ce)-LaBr3(Ce) coincidences. The measured lifetimes were found to be in good agreement with previously reported literature values, validating the reliability of the experimental techniques and analysis methods employed in the present work.

In the case of ^{134}Te, the 6^+ state has been identified as a relatively long-lived isomer [32]. As illustrated in Fig. 17 [Figure 17: see original paper], the FFs-Ge-Ge and FFs-LaBr3(Ce)-LaBr3(Ce) coincidence techniques were employed to measure its lifetime. The time difference spectra of both HPGe and LaBr3(Ce) were obtained using a Ge/LaBr3(Ce) gate on both 115 and 297 keV transitions. The coincidence time windows between two γ rays were set to $\pm$ 200 ns for Ge-Ge and $\pm$ 4 ns for LaBr3(Ce)-LaBr3(Ce), respectively. Using the slope method, the extracted lifetimes were determined to be 164.04(95) ns from the FFs-Ge-Ge data and 164.7(7) ns from the FFs-LaBr3(Ce)-LaBr3(Ce) data. Both values are

in excellent agreement with the previously reported literature value of 164.1(9) ns [32].

The primary objective of present work is to measure the sub-nanosecond lifetimes of nuclear excited states. In the case of ^{138}Ba, the 4^+ state was identified as a short-lived isomer [33], and its lifetime was determined using the β-Ge-LaBr3(Ce)-LaBr3(Ce) coincidence technique. The coincidence time window for detecting the feeder (547 keV) and decay (463 keV) γ-ray transitions with LaBr3(Ce) detectors was set to $\pm$ 4 ns, while a third γ-ray detected by HPGe was gated on the 1436 keV transition. The coincidence time windows between β and triple γ rays were determined based on the correlated prompt time difference distribution. The γ-γ coincidence matrix from the LaBr3(Ce) is shown in the top panel of Fig. 18 [Figure 18: see original paper]. This matrix clearly reveals the 463 keV and 547 keV transition, confirming the correlated decay pathway of the 4^+ state in ^{138}Ba. The time difference spectrum was obtained using one LaBr3(Ce) gate on 463 keV and another LaBr3(Ce) gate on 547 keV respectively, as illustrated in the bottom panel of Fig. 18. A convolution function consisting of the Gaussian and exponential distributions was used for fitting the time distribution. The extracted half-life of the 4^+ state in ^{138}Ba was found to be 2.02(9) ns, which is in good agreement with the previously reported value of 2.08(6) ns [33].

For excited states with lifetimes shorter than the intrinsic time resolution of LaBr3(Ce) detectors, the Generalized Centroid Difference (GCD) method provides a more suitable approach. The lifetime of 2^+_1 state of ^{132}Te was determined to be 5(3) ps implementing γ-γ fast timing methods based on mass separator [34]. In the present work, this short-lived excited state was measured using the M(FFs)-γ-γ-γ coincidence technique, where M(FFs) refers to gating on the known mass of ^{132}Te. The top panel of Fig. 19 [Figure 19: see original paper] presents the γ-γ coincidence matrix of LaBr3(Ce) after background subtraction using HPGe gates on the 103 keV and 151 keV transitions and background gates on either side of the peaks. A strong correlation is observed between the 974 keV and 697 keV transitions. In the GCD method, the centroid difference between delayed and anti-delayed time distributions is measured. The delayed and anti-delayed time difference spectra for 2^+_1 state of ^{132}Te are presented in the bottom panel of Fig. 19. The time distribution in blue line is "Delayed" , corresponds to the start detector is gated on 697 keV (feeder) and the stop detector is gated on 974 keV (decay). Conversely, the red line represents the "Anti-delayed" distribution, with the stop detector gated on 697 keV (feeder) and the start detector gated on 974 keV (decay). The background-corrected centroid difference between "Delayed" and "Anti-delayed" was measured to be -769(12) ps. The lifetime was then calculated using the following formula:

$$2\tau = \Delta C - PRD.$$

The lifetime was determined to be 9(7) ps, which is in agreement with the

values of 5(3) ps in [34] and $2.15^{+25}{}_{20}$ ps in [35]. While the uncertainty in the present measurement is somewhat larger, this is likely attributable to the absence of precise positional calibration among the 36 solar cells used for fission fragment detection. Minor spatial misalignments between the solar cells and the 252Cf source may have introduced additional timing uncertainties, thus affecting the precision of the centroid determination. Nonetheless, the close agreement with earlier results validates the reliability of the HALIMA setup and demonstrates its capability to perform accurate sub-nanosecond lifetime measurements in complex fission environments.

IV. SUMMARY

A novel hybrid detection system, named HALIMA, has been developed and installed at the Institute of Modern Physics to facilitate the measurement of sub-nanosecond lifetimes of neutron-rich nuclei produced via fission. This system is composed of eight BGO-shielded HPGe detectors and twenty fast LaBr3(Ce) detectors, each shielded with CsI(Tl), offering high-resolution γ-ray energy and timing capabilities. To enhance event selectivity, two specialized ancillary detector arrays were incorporated: a solar cell detector array for detecting fission fragments (FFs), and a fast plastic scintillator array for β-particle detection. These additions enable advanced coincidence techniques such as FFs/β-Ge-LaBr3(Ce)-LaBr3(Ce), significantly improving the spectral quality and peak-to-background ratio, hence allowing precise lifetime measurements. In particular, the implementation of FF gating proved critical in isolating γ-ray cascades of interest by effectively suppressing background contributions from unrelated fission products and β decays. This additional selectivity not only reduced the intense background but also improved the peak-to-background ratio by more than a factor of four, thereby increasing the accuracy of lifetime measurements. A comprehensive overview of HALIMA' s components has been provided, detailing the energy and timing performance of the detectors, the data acquisition (DAQ) system, and associated electronics architecture.

A commissioning experiment with a 252Cf source was conducted to validate the performance of the HALIMA setup. By applying combined gating on FFs and fast plastic scintillators, the lifetimes of three excited nuclear states in ^{134}Te, ^{138}Ba and ^{132}Te were measured, covering a range from a few picoseconds to several hundred nanoseconds. The results are in good agreement with the literature values, demonstrating the capability and precision of the HALIMA setup. Furthermore, several excited states with previously unmeasured lifetimes produced by 252Cf fission were identified for the first time, opening new avenues for nuclear structure studies of neutron-rich nuclei.

Looking ahead, the HALIMA system will be used not only for measuring lifetimes of excited states following isomeric or β decay, but also for the lifetimes of prompt γ rays directly emitted by FFs of 252Cf and the source will be placed at the center of the HALIMA array without shielding. To enhance mass resolution of fission fragments, new ancillary detectors based on Silicon Carbide (SiC)

are being developed as next-generation fission detectors. With its advanced detection capabilities, HALIMA will significantly contribute to the systematic study of neutron-rich nuclei produced via neutron-induced fission, extending our understanding of nuclear structure in regions far from stability.

V. ACKNOWLEDGMENTS

This work has been supported by the National Natural Science Foundation of China (Grants No. 12275321, 12335009, 12475129, No. 12121005, No. 2025A1515012112), Natural Science Foundation of Guangdong Province, China, the International Atomic Energy Agency Coordinatated Research Project F41034 (Contract No. 28649), the computational resources from Sun Yat-sen University and the National Supercomputer Center in Guangzhou, the Open Project of Guangxi Key Laboratory of Nuclear Physics and Nuclear Technology (No. NLK2023-08), the Central Government Guidance Funds for Local Scientific and Technological Development, China (No. Guike ZY22096024), the Guangdong Major Project of Basic and Applied Basic Research (Grant No. 2021B0301030006), Young Scientists Fund of the National Natural Science Foundation of China (No. 12405144) and the National Key Research and Development program (MOST 2022YFA1602304).

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