ChinaRxiv

AI translation · View original & related papers at
chinarxiv.org/items/chinaxiv-202505.00037

The heavy-ion time-of-flight spectrometer HiToF

Authors: Wang Haorui, Dr. Chengjian Lin (Nuclear physics), Ma, Dr. Nanru, Yang, Dr. Lei, Yang, Dr. Feng, Jia, Dr. Huiming, Wen, Mr. Peiwei, Luo, Tianpeng, Chang, Mr. Chang, Duan, Hairui, Ms. Songxian Zhu, Huang, Zhijie, Cheng Yin, Zerui Fan, Fu, Lingyi, Li, Huiyan, Mo, Mr. Shaowen, Lu, Mr. Hao, Chenxu Wu, Lin, Dr. Chengjian (Nuclear physics)

Date: 2025-04-27T00:00:00+00:00

Abstract

A heavy-ion time-of-flight spectrometer called HiToF with magnet focusing accomplished by quadrupole triplet lens has been constructed at Beijing Tandem Accelerator National Laboratory, mainly for studies of multi-nucleon transfer reactions at energies near the Coulomb barrier. The spectrometer is equipped a rotating chamber with a diameter of 40 cm and can be rotated in a large angular range from -40° to 160°. The length from target to the focal plane is 2.7 m, enabling high-precision time-of-flight measurements by two micro-channel-plate detectors with 1.9 m apart and typical time resolution of 120 ps. A multi-sampling position-sensitive ionization chamber for ΔE-E measurement is placed on the focal plane, which offers ΔZ/Z resolution of 1/50. The setup provides a maximum solid angle $\Delta\Omega = 20$ msr. An experiment of 32S + 90,94Zr at the beam energy of 135 MeV was performed to test the performance. The projectile-like ions were identified clearly with the mass resolution $\sigma = 0.2$ amu. Results show that the HiToF spectrometer is a powerful setup for studying the heavy-ion reaction mechanisms at low-energies.

Full Text

Preamble

A heavy-ion time-of-flight spectrometer named HiToF, featuring magnetic focusing via a quadrupole triplet lens, has been constructed at the Beijing Tandem Accelerator National Laboratory for studies of multi-nucleon transfer reactions at energies near the Coulomb barrier. The spectrometer is equipped with a rotating chamber 40 cm in diameter that can be positioned across a wide angular range from -40° to 160°. With a flight path length of 2.7 m from target to focal plane, the system enables high-precision time-of-flight measurements using

two micro-channel-plate detectors separated by 1.9 m, achieving a typical time resolution of 120 ps. A multi-sampling position-sensitive ionization chamber for ΔE-E measurements is positioned at the focal plane, providing ΔZ/Z resolution of 1/50. The setup offers a maximum solid angle of $\Delta\Omega = 20$ msr. A test experiment using 32S + 90,94Zr at a beam energy of 135 MeV was performed to evaluate the performance. Projectile-like ions were clearly identified with a mass resolution of $\sigma = 0.2$ amu. The results demonstrate that the HiToF spectrometer is a powerful instrument for investigating heavy-ion reaction mechanisms at low energies.

Keywords: Time-of-flight spectrometer, Heavy-ion, Multi-nucleon transfer reaction, Quadrupole triplet lens

Introduction

Multi-nucleon transfer (MNT) is considered a promising method for producing neutron-rich heavy or super-heavy nuclei and has been studied in low-energy nuclear reactions for several decades. Despite significant theoretical and experimental efforts, the MNT mechanism remains unclear due to the complex phenomena involving the transfer and/or transport of numerous nucleons [**?**, **?**].

Because of the intricacies of the reaction mechanisms, measuring MNT products requires improved precision, placing stringent demands on experimental equipment: (i) good mass (A) and charge (Z) identification to validate various reaction channels; (ii) large acceptance for detecting rare products far from the projectile or target, considering the steep decrease in cross sections with increasing numbers of transferred nucleons; and (iii) good energy resolution to distinguish the numerous energy levels populated in specific reaction channels.

Several detection techniques have been developed for particle identification, such as time-of-flight (ToF) measurement over a known flight distance. The relative uncertainty decreases dramatically with longer flight paths. As a mature method, the E-ToF technique, which simultaneously measures energy and ToF, has been widely used in transfer reaction studies near the Coulomb barrier [**?**]. The mass resolution, determined by energy and ToF measurements, reaches σ = 0.2 amu. For binary reactions, the kinematic coincidences technique effectively enhances energy and mass resolution, such as through simultaneous ToF measurements of projectile-like ions and correlated scattering angles [**?**].

To further investigate MNT reaction mechanisms, a ToF spectrometer for heavy-ion reactions called HiToF was constructed at the HI-13 tandem accelerator of the Beijing Tandem Accelerator National Laboratory. Its design resembles the PISOLO spectrometer [**?**] at Laboratori Nazionali di Legnaro but incorporates a focusing system with a quadrupole triplet lens. The maximum solid angle covered by HiToF reaches 20 msr. HiToF is equipped with two micro-channel-plate detectors dedicated to time-of-flight measurement and a specially designed ionization chamber for energy measurement and charge identification at the focal plane. A test experiment has been successfully conducted recently, establishing a solid foundation for further investigation of multi-nucleon transfer reactions.

This paper is organized as follows: Section II describes the detection systems and ion optical elements; Section III presents results from the recent 32S + 90,94Zr test experiment; and Section IV summarizes the results and conclusions.

II. Spectrometer

The HiToF spectrometer consists primarily of an adjustable detection system and an ion-optical system. It is connected to a steel-tape sealed rotating chamber 40 cm in diameter. The spectrometer can rotate about the chamber center, covering an angular range from -40° to 160°. A schematic view of the spectrometer is presented in Fig. 1 [Figure 1: see original paper].

A. The Detection System

The detection system includes ToF measurement using two micro-channel plates (MCP1 and MCP2) and energy measurement using a multi-sampling position-sensitive ionization chamber (IC) installed at the focal plane. A v-E detector comprising an MCP and a double-sided silicon-strip detector (DSSD) is also installed at the complementary angle in the rotating chamber for velocity and energy measurements of target-like particles.

The ToF measurement employs two transmission-type detectors with excellent timing properties, such as timing detectors made of micro-channel plates [**?**]. Each timing detector uses a pair of micro-channel plates 45 mm in diameter to provide start and stop signals along the flight path. The stop detector is positioned 40 cm from the focal plane. In the test experiment described in Section III, the start detector was placed 40 cm from the target, though it can be positioned closer to targets to reduce relative uncertainty with a longer flight distance. Both MCP detectors, which define the geometrical solid angle for the entire spectrometer, can be replaced with position-sensitive MCPs to provide position information for reconstructing the trajectory of projectile-like ions after magnetic focusing. The energy resolution can be further improved using the ToF information for specific particles. Fig. 2 [Figure 2: see original paper] shows the result of an offline test over a short flight distance of 5 mm using a standard α source containing the isotope 241Am, demonstrating a typical timing resolution of 120 ps.

To meet experimental demands for improved energy resolution, a special IC with a transverse electric field has been designed, drawing on conventional ionization chambers and active target time projection chambers [**?**, **?**]. The IC is constructed from printed circuit boards with dimensions of 300 mm × 200 mm × 200 mm and is located at the focal plane. The 300 mm length provides a broad energy range for Z identification. The circular entrance window, 100 mm in diameter, is positioned 18.3 cm from MCP2 and equipped with a 2 µm thick mylar foil. The large entrance window area provides substantial acceptance for energy measurement. The grid consists of gold-plated tungsten wires 0.08 mm in radius, soldered 1 mm apart. The distance from grid to anode is 22 mm, while the spacing between grid and cathode is 136 mm. Sixty-seven equipotential rectangular loop electrodes are evenly distributed along the plate, with 1 MΩ resistors connecting adjacent electrodes.

This IC features three-dimensional position resolution capabilities, enabling precise ΔE-E and position detection. Energy resolution can be improved through track reconstruction provided by the IC. Fig. 3 [Figure 3: see original paper] shows design details. The IC anode is divided into seven sections, providing not only energy loss ΔE and residual energy ER but also the trajectory (z-direction) of incident ions. Each section is divided into two wedge-shaped parts to determine the x-position via the charge division method. The y-position is obtained from the drift-time difference between anode and cathode, with the timing signal from MCP2 serving as the reference for drift-time measurement. Typical x, y, and z position resolutions are approximately 1.0, 0.5, and 2.0 mm, respectively, depending primarily on the properties of the incident ion, the working gas, and the applied high voltage. The smart preamplifier (SPA) [**?**] is used for IC signal readout.

Fig. 4 [Figure 4: see original paper] shows offline test results using a 252Cf fission source. The fission fragments from this source have a continuous energy spectrum distributed primarily around 105Mo and 140Xe. The energies of heavier fragments are typically lower than the Bragg peak energy, causing the corresponding ΔE-E spectrum to exhibit an upward trend. Lighter fragments with energies above the Bragg peak energy produce a flatter spectrum. The working gas is 99.9% pure propane at a pressure of 30 Torr, with an anode operating voltage of 110 V and a cathode voltage of -308 V.

B. The Ion-Optical System

The ion-optical system uses a quadrupole triplet lens (Q1-Q2-Q3) to transport incident ions to the focal plane approximately 2.70 m from the target. Three quadrupole magnets Q1, Q2, and Q3 are positioned at 0.85, 1.35, and 1.85 m from the target, respectively. Q1 and Q3 have identical structures with an aperture of Φape = 100 mm and maximum magnetic flux density of Bmax = 0.373 T. Q2, located in the middle with reverse-phase current, has an aperture of Φape = 130 mm and maximum magnetic flux density of Bmax = 0.636 T. Ions with magnetic rigidity up to B = 0.95 T · m can be analyzed at maximum angular acceptance of Δ = 3.3° and Δ = 7.3°.

The HiToF spectrometer can operate in three modes: (a) both x and y focusing (double-focusing), (b) x focusing and y parallel, and (c) x parallel and y focusing. The double-focusing mode provides maximum solid angle and enhances transmission efficiency, while mode (c) preserves scattering angle information by focusing only perpendicular to the reaction plane [**?**, **?**]. The spectrometer' s solid angle was confirmed through measurements of quasi-elastic event yields on the focal plane as a function of quadrupole field. Corresponding ion trajectories calculated by the GICOSY code [?] are shown in Fig. 5 [Figure 5: see original paper]. The quadrupole triplet lens settings are determined primarily by the mass, energy, and charge state of incident ions.

Practical flight distances are constrained by many technical considerations, particularly solid angle requirements [?]. Due to optical focusing by the quadrupole triplet lens, the actual flight distance of projectile-like ions may deviate from the designated length between start and stop detectors. For this reason, x-y position information at the focal plane and the trajectory of incident ions provided by the IC can be used to correct the flight distance, thereby partially reducing the relative uncertainty of ToF measurements.

III. Performance of HiToF

An experiment using 32S + 90,94Zr at ELab = 135 MeV (approximately 15% above the Coulomb barrier) was conducted to test the spectrometer' s performance. Two targets were prepared: 90ZrO2 and 94ZrO2 evaporated onto 25 µg/cm2 carbon backings with thicknesses of 104 µg/cm2 and 120 µg/cm2, respectively. The experiment tested magnet focusing performance, detection system capabilities, and particle identification.

Transmission efficiencies were determined by measuring product ions on the focal plane with and without magnetic fields. Magnetic fields for maximum transmission efficiency B0 were set based on GICOSY calculations, with several nearby field values also tested. As shown in Fig. 6 [Figure 6: see original paper], enhancement factors from yield ratios with and without quadrupole fields for charge states of 11+, 12+, and 13+ in double-focusing mode agreed well with GICOSY calculations. The magnetic field setting for maximum transmission efficiency is BQ2/BQ1 = 1.678 with BQ1 = BQ3.

In the experiment, ToF was measured between two MCP detectors at a flight distance of 1.9 m. ToF measurement is influenced by factors including spectrometer isochronism, target thickness inhomogeneity, energy straggling in the target, imperfect software corrections, and finite ToF detector resolutions [?]. As shown in Fig. 7 [Figure 7: see original paper], the FWHM of the main peak for 32S particles without magnetic field is 500 ps. The ToF of focused ions is also affected by flight distance uncertainty due to the large solid angle.

Different magnetic fields are required for particles with different energies, masses, and charge states, and all three focusing modes were tested. For the test experiment, we reorganized the seven sections of the IC anode into three groups of two, two, and three sections respectively. Propane was used as the working gas for ionization at pressures from 50 to 70 Torr. Fig. 8 [Figure 8: see original paper] shows IC tracking results, which are useful for more precise energy detection. Using the method described in Section II, x-y distribution images on the focal plane for three focusing modes are shown in Fig. 9 [Figure 9: see original paper], consistent with GICOSY calculations. The magnetic field settings

BQ2/BQ1 for modes (a), (b), and (c) are 1.678, 1.32, and 1.577 respectively, with BQ1 = BQ3. These results verify the IC' s position resolution capability and the focusing performance of the quadrupole triplet lens.

The large effective solid angle and good charge and mass resolution enable measurement of cross sections for weak reaction channels. The ΔE-E measurement shown in Fig. 10 [Figure 10: see original paper] precisely identifies different elements. Populated product isotopes at Ebeam = 135 MeV extend from Z = 12 (4-proton stripping) to Z = 16. Lower energy particles observed correspond to carbon (Z = 6) and oxygen (Z = 8) from the target backings.

The HiToF spectrometer' s resolution enables unambiguous identification of numerous projectile-like reaction products. Mass-charge two-dimensional spectra for the reaction 32S + 90,94Zr at Lab = 55° (near the grazing angle) are shown in Fig. 11 [Figure 11: see original paper]. Multiple reaction channels were measured, including proton stripping, neutron stripping, and neutron pick-up reactions. Reaction products were clearly identified up to two-neutron pick-up and four-proton stripping, with rare events from -5p channels also observed.

For this reaction system, the IC provides nuclear charge resolution ΔZ/Z = 1/50. The achieved mass resolution is $\sigma = 0.2$ amu, primarily limited by the IC' s energy resolution. Mass spectra for various Z selections are shown in Fig. 12 [Figure 12: see original paper] and Fig. 13 [Figure 13: see original paper]. For Z = 16, an exponential decline in ion yield with increasing transferred neutrons is observed. Fig. 13 clearly shows multiple channels from Z = 12 to Z = 15, with the peak at Z = 12, A = 26 corresponding to the -4p-2n channel.

IV. Summary and Outlook

Based on the test experiment, the HiToF spectrometer—a simple, high-precision instrument providing a large solid angle of 20 msr and excellent resolution for mass, energy, and position—has been adequately prepared for multi-nucleon transfer reaction studies. The achieved resolutions are $\sigma = 0.2$ amu for mass, ΔZ/Z = 1/50 for charge, and 1.0, 0.5, and 2.0 mm for x, y, and z position dimensions, respectively.

Different focusing modes of the quadrupole triplet lens provide versatility for various investigations. Energy and mass measurements are limited primarily by the detection system' s resolving power, which fundamentally determines spectrometer performance.

In the near future, the improved IC and track reconstruction via the ToF timing detector and IC will be combined to enhance energy resolution with more precise magnetic fields. Higher-precision angular distributions will be obtained through coincidence measurements between the IC for projectile-like ions and the v-E detector for target-like ions.

For low-energy nuclear reaction studies, HiToF provides excellent opportunities for experimental investigation of reaction mechanisms. Its robust particle identification capability is crucial for identifying reaction products and channels in MNT processes. The spectrometer' s broad detection range enables observation of a greater number of reaction channels, facilitating deeper understanding of reaction mechanisms. Superior device performance is required for frontier research, so efforts will focus on improving the detection system, particularly enhancing energy and position resolution.

References

[1] L. Corradi, A. M. Stefanini, C. J. Lin et al., Multinucleon transfer processes in 64Ni+ 238U. Phys. Rev. C 59, 261 (1999). doi: 10.1103/PhysRevC.59.261

[2] T. Niwase, Y. X. Watanabe, Y. Hirayama et al., Discovery of New Isotope 241U and Systematic High-Precision Atomic Mass Measurements of Neutron-Rich Pa-Pu Nuclei Produced via Multinucleon Transfer Reactions. Phys. Rev. Lett. 130, 132502 (2023). doi: 10.1103/PhysRevLett.130.132502

[3] R.R. Betts, Time of flight detectors for heavy ions. Nucl. Instrum. Methods 162, 531 (1979). doi: 10.1016/0029-554X(79)90731-6

[4] L. Corradi, G. Montagnoli, D. R. Napoli et al., A kinematic coincidence technique for the study of low-energy heavy-ion reactions. Nucl. Instrum. Methods A 297, 461 (1990). doi: 10.1016/0168-9002(90)91330-E

[5] G. Montagnoli et al., The time-of-flight spectrometer for heavy ions PISOLO. Nucl. Instrum. Methods A 454, 306 (2000). doi: 10.1016/S0168-9002(00)00482-4

[6] W. Starzecki, A.M. Stefanini, S. Lunardii et al., A compact time-zero detector for mass identification of heavy ions. Nucl. Instrum. Methods 193, 499 (1982). doi: 10.1016/0029-554X(82)90242-7

[7] Wu, HK., Wang, XY., Wang, YM. et al. Fudan multi-purpose active target time projection chamber (fMeta-TPC) for photonuclear reaction experiments. NUCL SCI TECH 35, 200 (2024). doi: 10.1007/s41365-024-01576-1

[8] Tian, J., Sun, ZP., Chang, SB. et al. Studies of an event-building algorithm of the readout system for the twin TPCs in HFRS. NUCL SCI TECH 35, 73 (2024). doi: 10.1007/s41365-024-01434-8

[9] Wang, DX., Lin, CJ., Yang, L. et al., Compact 16-channel integrated charge-sensitive preamplifier module for silicon strip detectors. NUCL SCI TECH 31, 48 (2020). doi: 10.1007/s41365-020-00755-0

[10] R. Bass, J.v. Czarnecki and R. Zitzmann, Design study of a magnetically focussed time-of-flight spectrometer for heavy ions. Nucl. Instrum. Methods 130, 125 (1975). doi: 10.1016/0029-554X(75)90164-0

[11] M. Berz, H. C. Hoffmann, H. Wollnik, et al., COSY 5.0 - The fifth order code for corpuscular optical systems. Nucl. Instrum. Methods A 258, 402 (1987). doi: 10.1016/0168-9002(87)90920-X

ChinaRxiv 中X

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

Source: ChinaXiv —Machine translation. Verify with original.