A multilayer ΔE-E_R telescope for breakup reactions at energies around the Coulomb barrier *

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Abstract: The breakup reactions of weakly-bound nuclei at energies around the Coulomb barrier and the corresponding coupling effect on the other reaction channels are hot topics nowadays. To overcome the difficulty in identifying both heavier and lighter fragments simultaneously, a new kind of ionization-chamber based detector telescope has been designed and manufactured. It consists of a PCB ionization chamber and three different thickness silicon detectors installed inside the chamber, which form a multilayer ΔE-E_R telescope. The working conditions were surveyed by using an α source. An in-beam test experiment shows that the detector has good particle identification for heavy particles like ^{17}F and ^{16}O as well as light particles like protons and alpha particles. The measured quasi-elastic scattering angular distribution and the related discussions for ^{17}F+^{208}Pb are presented.

Keywords: breakup reaction, weakly-bound nuclei, particle identification, ΔE-E_R telescope, grid ionization chamber

PACS: 07.77.Ka, 25.60.Gc, 29.40.Cs **DOI:** 10.1088/1674-1137/40/11/116004

1 Introduction

The nuclear reaction dynamics induced by light weakly-bound nuclei has been one of the most exciting topics in nuclear physics in the past few decades. A typical feature of weakly-bound nuclei is that they can easily break into smaller fragments and populate the continuum states when approaching the strong Coulomb or nuclear fields of a target nucleus. These continuum states may strongly couple to the low-lying discrete states and change the reaction process greatly, which is the so-called breakup effect.

A number of silicon detector arrays such as MUST2 [1], TIARA [2] and GLORIA [3] have been built in recent years, mainly dedicated to the study of nuclear reactions. However, it is difficult to identify the low-energy heavy fragments by using a silicon detector telescope. For example, in the measurement of ^{17}F breakups, light particles like protons and alpha particles can be easily identified, but very little identification of heavy particles like ^{17}F and ^{16}O has been achieved up to now [4] due to the large thickness of the solid-state detectors. This will inevitably introduce a large uncertainty in the experimental results.

At present, the conclusions for the breakup effects are still contradictory both experimentally and theoretically despite plenty of studies. An important reason for this disaccord can be largely ascribed to the deficiency of the detectors in studying the related reaction mechanisms, which requires discriminating experimentally the different reaction processes, such as elastic, inelastic, transfer, breakup, and so on. Therefore, a new kind of detector setup which can identify simultaneously both the heavy and light fragments is highly desired.

A commonly-used method, the ΔE-E_R telescope [5] identifies different particles from the difference of MZ^2, where M is the mass number and Z is the atomic number of the particle. Particles pass through the first layer detector with an energy loss ΔE, and stop in another layer detector losing the remaining energy E_R. According to

Received 13 May 2016

* Supported by National Key Basic Research Development Program of China (2013CB834404) and National Natural Science Foundation of China (11375268, 11475263, U1432127, U1432246).

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Bethe-Block formula [6]:

$$\Delta E \cdot E_{\mathrm{R}} = kMZ^2, \tag{1}$$

where the total energy $E = \Delta E + E_{\mathrm{R}}$ and k is a constant. It is known that the stopping power in a certain material for heavy particles like ^{17}F and ^{16}O is about two orders of magnitude larger than for light particles like protons and deuterons. In the ΔE-E_{R} telescopes for heavy particle detection, low stopping power detectors like ionization chambers [5, 7, 8] or thin Si detectors [9] usually act as the ΔE detector, which makes the telescope unsuitable for light particle identification. Experimentally, the study of breakup reactions requires particle identification in a large mass range in some cases. To this end, a new kind of detector telescope based on an ionization chamber (IC) is designed and manufactured. This detector telescope is foreseen for the simultaneous identification of both heavy and light reaction fragments produced in the direct reactions around the Coulomb barrier.

2 Structure of the multilayer ΔE-E_{R} detector telescope

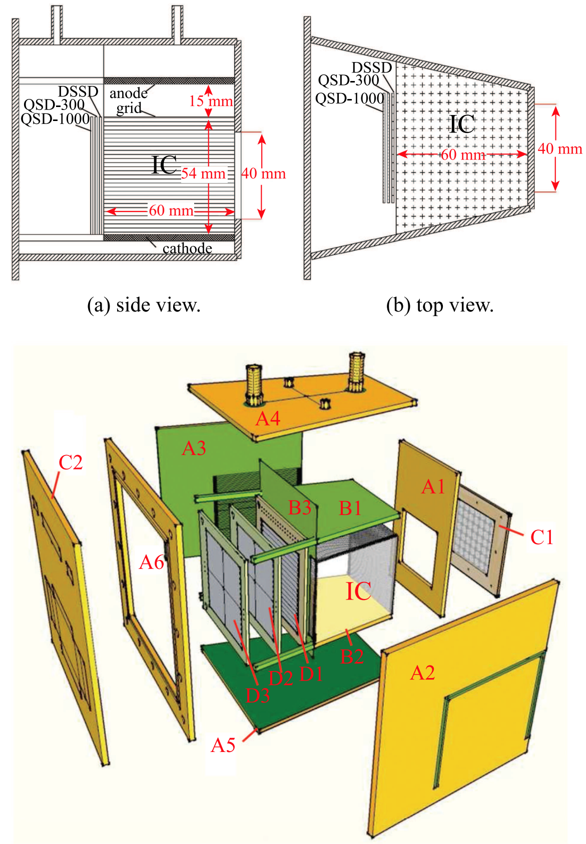
To identify the breakup fragments of a weakly-bound nucleus simultaneously in an experiment, coincident measurement is needed. To achieve this coincidental experimental detection and facilitate theoretical explanation, with a high detection efficiency, a compact detector structure with a small dead-zone is critical.

2.1 The overall structure

The newly developed multilayer ΔE-E_{R} telescope has a compact structure, as shown in Fig. 1(a) and Fig. 1(b). The IC has an effective working-gas length of 60 mm, followed by three layers of silicon detectors inside the chamber, one 60 μm thick double-sided silicon-strip detector (DSSD) followed by two quadrant silicon detectors (QSDs) with thicknesses of 300 μm and 1000 μm, respectively. The IC and the DSSD constitute the first telescope for heavy-particle identification, and the DSSD and the QSDs, including QSD-300 and QSD-1000, constitute other telescopes for light-particle identification.

In order to reduce the weight, the IC was made of printed circuit board (PCB). As shown in Fig. 1(c), it consists of eleven PCBs. The front window has an active area of 40 mm×40 mm and is equipped with a 1.5 μm thick Mylar film. The back window has an active area of 50 mm×50 mm and is equipped with a 0.5 μm thick Mylar film to protect the silicon detectors from the influence of the IC electric field.

The silicon detectors work in the IC gas environment, so it is important to reduce the gaps between different detectors to reduce additional energy losses. All the silicon detectors were mounted on the back plate and close to each other with a distance of about 1.5 mm. The distance between the IC and DSSD is about 1.0 mm. An interior photo of the IC-based detector telescope is shown in Fig. 2.



(a) side view. (b) top view.

(c) exploded view.

Fig. 1. (color online) General assembly diagram of the IC-based detector telescope.

A1-front plate A2-left plate A3-right plate A4-roof plate A5-floor plate A6-screw-hole plate B1-anode plate B2-cathode plate B3-back window plate C1-front window plate C2-back plate D1-64 μm DSSD D2-300 μm QSD D3-1000 μm QSD.

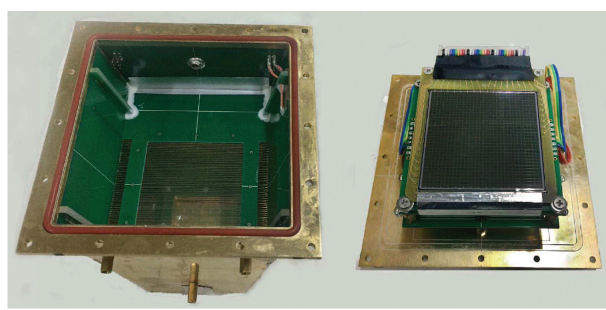


Fig. 2. (color online) Interior photo of the IC-based telescope detector.

(left: internal view of the IC; right: the Si detectors installed on the back plate.)

2.2 The IC structure

The internal structure of the ionization chamber includes the trapezoid-shaped anode and cathode with areas of $60\times(52+79)/2$ mm^2. The anode-cathode distance is 69 mm and they are separated by the grid electrode with a distance of 15 mm to the anode, as shown in Fig. 1. In order to generate a uniform electric field to direct the drift of the ionization electrons toward the anode, a total of 54 equipotential rings between cathode electrode and grid electrode are employed. All rings have the same separation of 1 mm and are connected in series with 1 MΩ resistance. Both the anode-grid distance and electric field strength can affect electron drift and collection times, which will in turn affect the energy resolution. The grid electrode screens the anode electrode and protects the pulse amplitude of the energy-loss from the affection of the ionization position. The shielding failure rate σ, which is used to evaluate the shielding effect, is defined as the ratio of electron induced anode electric charge corresponding to field intensity E_p to the positive ion produced field intensity E_q, i.e. $\sigma = dE_p/dE_q$. According to Bunemann theory [10]:

$$\sigma = \frac{d}{2\pi C}\ln\frac{d}{2\pi r}, \tag{2}$$

where d is the grid-wire spacing, r is the grid-wire radius and the anode-grid distance $C = 15$ mm. Generally, a good shielding can be obtained only if σ is small enough. Gilded tungsten wire with a radius of 50 μm was chosen as the grid electrode. Grid wires were welded to the left and right PCB plate with a separation $d\approx 0.977$ mm, so that the grid transitivity is about 89.8%. Accordingly, the shielding failure rate σ is about 1.18%.

3 α-source test

An ^{241}Am α source was used for testing the working conditions, that is, to select the optimum working voltages of the grid as well as the anode. During the test, CF_4 was selected as the working gas with a pressure of 13.3 kPa (100 Torr). The corresponding energy loss for 5.486 MeV alpha particles passing the IC is about 700 keV.

One selection principle for the grid voltage is that the electric field intensity E_{gc} (between grid and cathode) shall guarantee the electrons can get the maximum drift velocity. In the case of CF_4, if reduced field strength E_{gc}/P (P means air pressure) is about 0.3—0.5 V/cm·Torr, the best electron drift velocity is about 8 cm/μs. Here the grid-cathode distance d_{gc} is 5.4 cm, so given $E_{gc}/P = 0.3$ V/cm·Torr, the grid voltage should be:

$$V_g = V_{gc} = E_{gc}\cdot a = 0.3\times 5.4P = 1.62P, \tag{3}$$

where a is a distance-related parameter. The corresponding calculation result is $V_g = 162$ V.

For the anode voltage, to make sure that the electrons which arrive at the grid electrode will keep drifting to the anode instead of being collected by the grid wires, the electric potential of the anode should be higher than that of the grid. As is given by Bunemann, the relationship between anode-grid electric field E_{ag} and grid-cathode electric field E_{gc} should be [10]:

$$\frac{E_{ag}}{E_{gc}} = \frac{1+\rho}{1-\rho}, \tag{4}$$

where $\rho = 2\pi r/d$, grid-wire radius $r = 0.050$ mm, and $d \approx 0.977$ mm, thus $E_{ag}/E_{gc} \geqslant 1.95$. Therefore, the anode voltage should be:

$$\begin{aligned} V_a &= V_{ag} + V_{gc} = E_{ag}\cdot C + V_{gc} \\ &\geqslant 1.95E_{gc}\cdot C + V_{gc} = (1.95C/a+1)V_{gc} \approx 250 \text{ V}. \end{aligned} \tag{5}$$

In order to determine the applied grid voltage V_g and the matching anode voltage V_a in the actual experimental measurement, the pulse height and energy resolution varied with anode voltage V_a under different grid voltage V_g were measured. The measured results for 5.486 MeV α particles are shown in Fig. 3. At a certain grid voltage, as the V_a grows the output pulse height increases and reaches its maximum somewhere; meanwhile the energy resolution decreases and reaches its minimum. The grid/anode voltage of 150/450 V, corresponding to 90% of the maximum output amplitude and the best energy resolution of about 8%, was selected as the working voltages. These voltages are close to the calculated values.

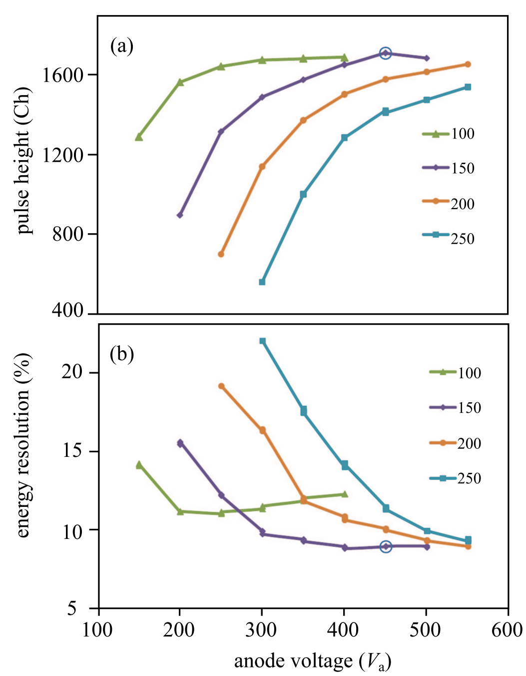


Fig. 3. (color online) Variation of the pulse height (a) and energy resolution (b) with the anode voltage (V_a) at different grid voltages (V_g).

4 In-beam measurement

The IC-based telescope has been tested with ^{17}F beam at the Radioactive Ion Beam Line at the Heavy Ion Research Facility in Lanzhou (HIRFL-RIBLL1) [11]. The ^{17}F beam was produced by a primary beam of ^{16}O with an intensity of ∼2 eμA. The primary beam bombarded the hydrogen gas target [12] which is cooled down to about −70 ℃ with an alcohol-cooled refrigeration device. The secondary beam of ^{17}F was produced via the ^{1}H(^{16}O, ^{17}F) reaction and then separated, purified, and transported to the secondary target chamber. At last, a ^{17}F beam with about 63% purity and 1×10^5 pps intensity was achieved.

The ^{17}F ion bombarding on ^{208}Pb target produced many kinds of particles, like the elastic scattering particle ^{17}F, its breakup products ^{16}O and protons. All these particles can be identified by the present multi-layer ΔE-$E_{\rm R}$ telescope. In the two-dimensional particle identification (PID) plot of the first layer ΔE-$E_{\rm R}$ telescope formed by IC and DSSD, heavy particles can be identified. As shown in Fig. 4(a), two bands can be seen, the upper from the secondary beam ^{17}F and the lower from ^{16}O, and these two bands are separated clearly. The following two layers of telescopes can help us to identify the light particles. As shown in Fig. 4(b), in the PID plot of ΔE-$E_{\rm R}$ telescope formed by QSD-300 and QSD-1000, light particles like protons and alpha particles can be clearly identified.

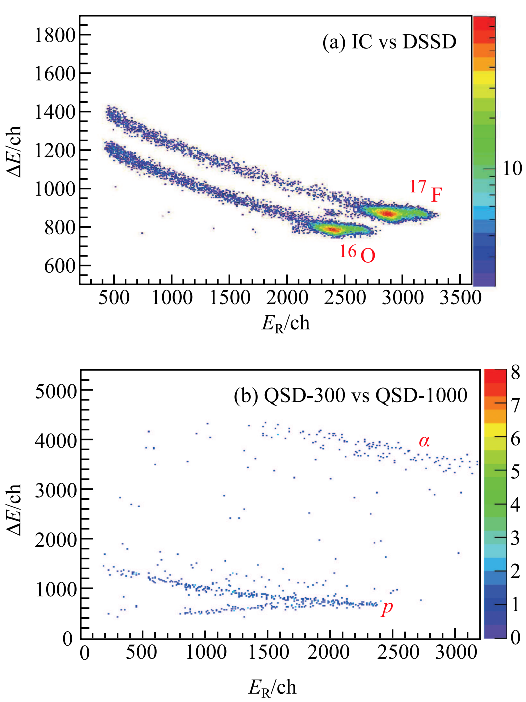


Fig. 4. (color online) Two-dimensional particle identification of the heavy particles (a) and light particles (b) by using the ΔE-$E_{\rm R}$ method.

For ^{17}F, the excitation energy of the first excited state is too low (0.51 MeV) to be separated from the ground state. So the measured result is quasielastic scattering, i.e. the sum of the elastic and the first excitation state. The measured quasielastic angular distribution of ^{17}F+^{208}Pb is shown in Fig. 5. By fitting the experimental data with an optical model, the parameters of the optical model potential (OMP) were extracted as V = 155.37 MeV, $r_{\rm V}$ = 1.11 fm, $a_{\rm V}$ = 0.50 fm, W = 18.43 MeV, $r_{\rm W}$ = 1.26 fm and $a_{\rm W}$ = 0.70 fm, where the V and W represent the real and imaginary parts, respectively. In the fitting procedure, the standard Woods-Saxon form was adopted for the OMP, and the code FRESCO was used for the optical model calculations. The fitting result is shown in Fig. 5 by the red curve. The radius and diffuseness parameters of the imaginary potential are obviously larger than those of the real part, indicating that the absorption of flux from the elastic channel starts to occur at longer distance, as should be expected from the loose structure of the projectile. Moreover, the total reaction cross section of ^{17}F+^{208}Pb derived from the optical model calculation (with the above extracted parameters) is 322.5 mb, which is far larger than that of ^{16}O+^{208}Pb at the similar reduced energy $E_{\rm c.m.}/V_{\rm B}$, 113 mb [13]. These results demonstrate quite a loose structure of the ^{17}F nucleus, which is in agreement with the previous results [9, 14]. The breakup reaction mechanism is of great importance in the study of reactions induced by radioactive beams, and we are looking forward to a good performance of our multilayer ΔE-$E_{\rm R}$ telescope in coincident measurement of the breakup fragments.

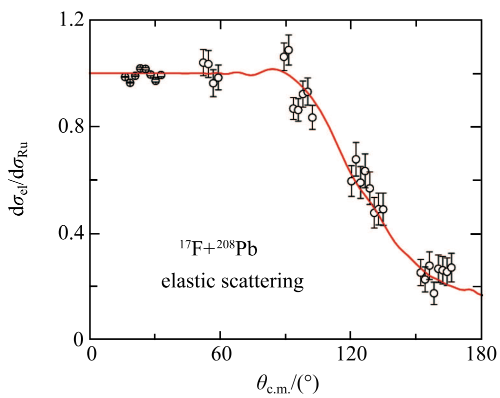


Fig. 5. (color online) The quasielastic angular distribution of ^{17}F+^{208}Pb at $E_{\rm lab}(^{17}{\rm F})$ = 95.1 MeV. The fitting result with optical model is shown by the red curve.

5 Summary

For identifying both the heavier and the lighter breakup fragments produced in weakly-bound nucleus-induced nuclear reactions at energies near the Coulomb barrier, an innovative detector telescope system based on IC and silicon detectors has been developed.

The grid IC telescope system uses a flow-gas design. Under the pressure of 150 Torr it can work stably and an energy resolution of the IC of about 8% is achieved for alpha testing. The ionization chamber telescope system and the related flange are all made of printed circuit board to achieve a compact structure with smaller volume and lower weight.

The combination of the grid IC and the three layers of silicon detectors which are installed inside the chamber form the multilayer telescope system for particle identification. Among them, the heavier fragments are identified by the first layer telescope (IC vs DSSD), and the lighter fragments can be identified by another layer telescope (QSD-300 vs QSD-1000).

Additionally, in the ^{17}F+^{208}Pb experiment this IC-based telescope allows particle identification in a wide mass range, from light particles like protons and deuterium to heavy particles like ^{16}O and ^{17}F, which is of great significance for the study of elastic scattering and breakup reactions of loosely-bound nuclei at energies around the Coulomb Barrier.

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