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Design and construction of a multi-layer CsI(Tl) telescope for high-energy reaction studies

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ABSTRACT

A prototype of a new CsI(Tl) telescope, which will be used in the reaction studies of light isotopes with energy of several hundred AMeV, was constructed and tested at the Institute of Modern Physics, Chinese Academy of Sciences. The telescope has a multi-layer structure, and the range information was obtained to improve the particle identification performance. This prototype has seven layers of different thickness. An energy resolution of 5.0% (FWHM) was obtained for one of the layers in a beam test experiment. Positive improvement for the identification of ^{14}O and ^{15}O isotopes was achieved using the range information.

1. Introduction

Particle identification (PID) is one of the most essential tasks in nuclear physics experiments, especially for reaction studies. Various methods have been developed for this purpose, such as the $\Delta E - E$ method and range information [1,2] as well as the Bragg peak amplitude [3] and the time-of-flight (TOF) measurements [4]. Each method has its advantages and limitations. For example, the energy loss (ΔE) combined with the residual energy (E) measurement ($\Delta E - E$ method) can identify isotopes of light ions easily but fails to identify heavy ions because of the limited resolution of the detectors [5]. It is often difficult to know a priori the most efficient method for PID when designing a new experiment.

Normally, the atomic number Z of a nucleus is easy to be determined by the partial energy deposit (ΔE) measurement in a thin detector, but it is slightly difficult to determine mass number A, especially for this high-energy cases. Magnetic spectrometer combined with TOF measurements may be a good solution for this, but it is quite complicated for some simple measurements such as charge-changing cross-section (CCCS) or one-nucleon knockout.

A Calorimeter Telescope (CATE) was developed at GSI [6,7] and used in a series of high-energy experiments to identify the secondary reaction products after the reaction target [8–11] by using the $\Delta E - E$ method. Although this telescope met the demands in those experiments, the overlap between neighbouring isotopes in the identified mass spectrum is not negligible. In Fig. 10 of Ref. [12], the difficulty of performing PID using $\Delta E - E$ information at high energies is illustrated. The figure-of-merit (FoM) decreases with particle energy, and at about 600 MeV, the FoM for carbon isotopes becomes smaller than 0.5. This indicates that the traditional $\Delta E - E$ method could not meet our demands, and an additional observable parameter should be considered.

Simple calculations performed with LISE++ [13,14] show that for high-energy particles with the same velocity, even neighbouring isotopes will have an obvious difference in their particle ranges in materials. In this paper, a prototype of a multi-layer telescope, which combines range information with the traditional $\Delta E - E$ method, was introduced for studying direct reactions such as single-nucleon knockout. Positive PID performance was achieved with this simple experimental setup for light nuclei ($Z < 10$) at around 300 AMeV at the Cooler Storage Ring of the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR) [15].

2. Design and manufacture of the new telescope

2.1. Design

To stop heavy ions with energy of several hundred AMeV, the detector material should have high density, high stopping power and large volume. CsI(Tl), an inorganic scintillating material, was chosen as the detector material for this new telescope because it not only meets the above requirements, but also has other advantages such as

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relatively good energy resolution, ease of manufacturing and lower price.

This new detector prototype was designed according to the range of oxygen isotopes with energy around 250 AMeV, which is about 36.6 mm for ^{16}O from simple calculations. The active area of the prototype is 7×7 cm^2 and the photomultiplier tubes (PMTs) are used as a readout device. With regard to the thickness of the layers, although a thinner layer can yield better resolution for a range, it is not recommended for practical use, mainly because the light collection of a thin plate will strongly depend on the incident position, which may influence the energy resolution of the detector. Hence, we decided to construct a prototype with 7 layers, with thickness of 7, 7, 7, 5, 5, 10 and 10 mm in that order. The main isotopes of oxygen and nitrogen can be stopped in the 4th and 5th layers. In addition to the extraction of the ΔE information, the first three layers can also used to reduce the reaction background in the crystals by the coincidence method. The 6th and 7th layers are aimed to stop the lighter nuclei. Further, the last layer can be used to veto the lighter nuclei that penetrate the detector.

A Monte Carlo simulation based on Geant4 [16] was developed to evaluate the performance of the detector. In the simulation, a 300 AMeV ^{14}O beam bombards a 6 g/cm^{2}Al target, and the products are detected using this telescope. The obtained ΔE–E spectrum is shown in Fig. 1. An energy resolution of 2% is assumed for each detector layer, and the first layer of the telescope is used as the ΔE detector. Although different elements can be distinguished clearly from the spectrum, the isotopes cannot be differentiated clearly. Moreover, there is an intense background that originates from the reactions with crystal lattices and some other sources. True coincidences between each layer of crystals were used to suppress this background. Fig. 2a is the ΔE–E spectrum for carbon isotopes selected in Fig. 1. The curves in Fig. 2a are obtained by fitting the datum with the empirical formula given in Ref. [17], which is illustrated as follows:

$$\Delta E = \left[(gE)^{\mu+1} + \left(\lambda Z^{\frac{2}{\mu+1}} A^{\frac{\mu}{\mu+1}} \right)^{\mu+1} \right]^{\frac{1}{\mu+1}} - gE. \tag{1}$$

The parameters are defined in Ref. [17]. Furthermore, the mass of the incident ions, which is shown in the inset picture, can be deduced from Eq. (1). Following Refs. [18,19], we can define a FoM as follows:

$$FoM = \frac{|p_1 - p_2|}{FWHM_1 + FWHM_2} \tag{2}$$

Although Refs. [18,19] give a lower limit of FoM, which is the adjacent peak that could be separated clearly if the FoM was greater than 0.7, Ref. [5] states that the isotopes can still be separated when the FoM is as low as 0.5. The FoM is slightly lower than 0.5 for our

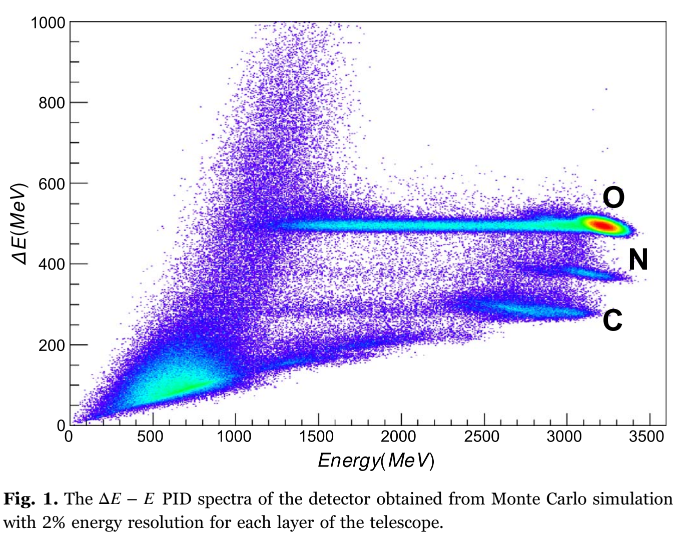

Fig. 1. The $\Delta E - E$ PID spectra of the detector obtained from Monte Carlo simulation with 2% energy resolution for each layer of the telescope.

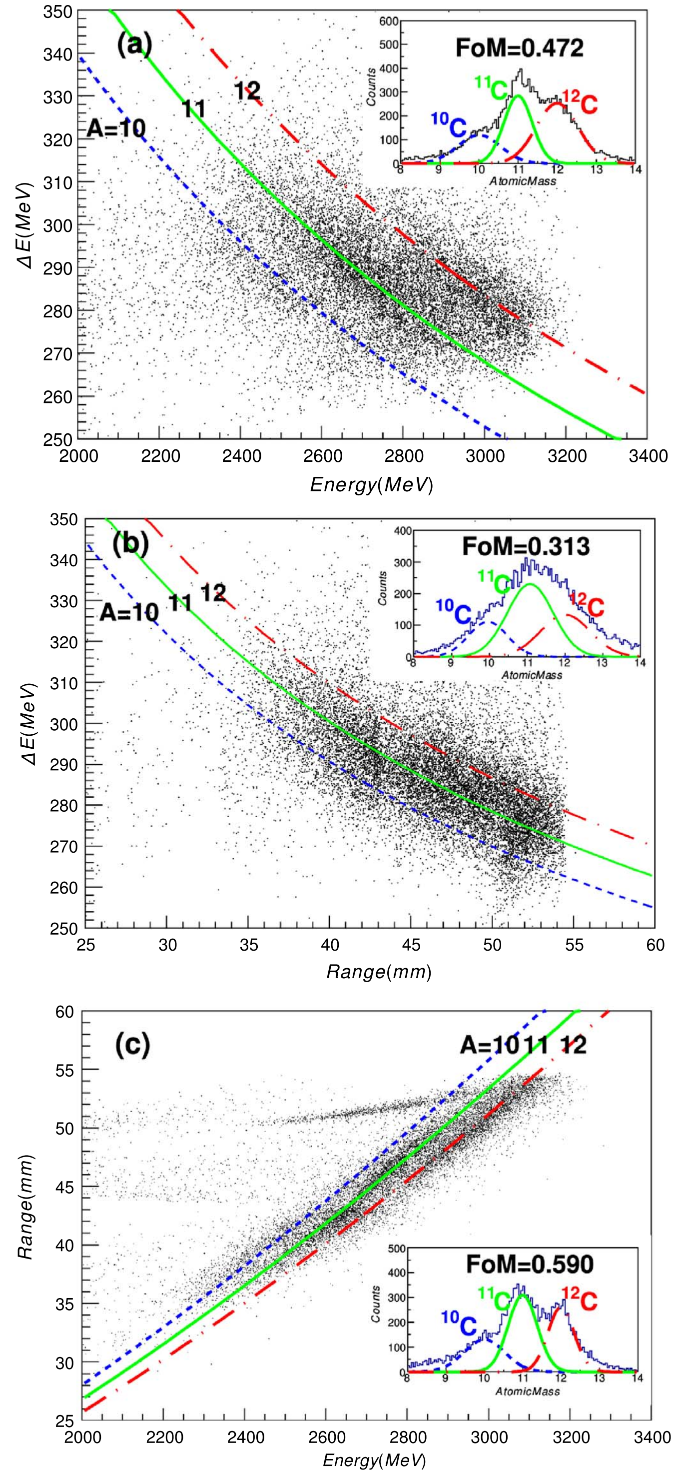

Fig. 2. The PID spectra for carbon isotopes obtained from Monte Carlo simulation with 2% energy resolution for each layer of the telescope. (a) The PID spectrum using the $\Delta E - Etotal$ method, (b) is the PID spectrum through the $\Delta E - Range$ method, and (c) is the PID spectrum through the $Range - Etotal$ method. The FoM are calculated for ^{11}C and ^{12}C.

detector, which demonstrates that using only ΔE–E information is not sufficient to identify heavy ions in such energy region.

Fig. 2b and c shows the PID spectra for carbon isotopes with range information. The range of one particle stopped in layer n of the telescope is calculated as follows: