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Tracking of ions produced at near barrier energies in nuclear reactions

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Examples of detectors, presently in use, for tracking products from nuclear reactions induced by radioactive ion beams are described. A new tracking detector is being designed to study the binary products from reactions induced by heavy neutron-rich radioactive ion beams on heavy neutron-rich target nuclei. The motivation for such studies and the features designed to accomplish this goal will be presented.

Keywords: Tracking of ion produced; nuclear reaction.

En este trabajo se describen ejemplos de detectores que identifican trazas producidas por productos de reacciones nucleares inducidas por iones radioactivos. Se presenta el diseño de un nuevo detector de trazas para estudiar principalmente reacciones binarias inducidas por iones radioactivos pesados ricos en neutrones en blancos igualmente pesados ricos en neutrones. Se discuten las motivaciones científicas para dichos estudios así como las características principales del detector que permiten cumplir con esta tarea.

Descriptores: Seguimiento de producción de iones; reacciones nucleares.

PACS: 25.60; 25.70.-z; 29.40.Cs; 29.40.Gx

1. Introduction

Tracking in nuclear physics experiments is an old art - photographic emulsions placed at the focal planes of magnetic spectrographs were used to identify light (α, t, d, p) products from nuclear reactions. The magnetic field strength and the location of the track yielded particle momentum and the track thickness and length were used to infer particle ID (and the kinetic energy).

With high-energy physics leading the way in scale and complexity, tracking turned from passive to electronic detection. High-density electronics and fast acquisition made possible almost continuous tracking of a particle in a gas volume. Figure 1 illustrates how a 3-D picture of the particle track can be obtained by sampling the position and arrival times of electrons released along the track of a charged particle passing through the detector. The electron drift time information is combined with the projection of the track in a plane perpendicular to the electron drift direction. In the example shown, the projection is created by image charges collected on small pads viewing an array of proportional wire counters. This “time projection chamber” (TPC) is used for particle detection at high energies. In most designs the TPC surrounds the target (often the detector gas contains the target nuclei) thus yielding good solid angle coverage. With the addition of a magnetic field (Fig. 2) the tracks can yield the momentum of all the charged products emanating from the interaction vertex.

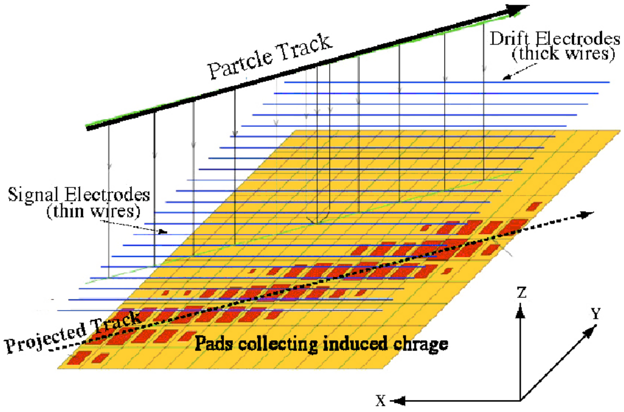


FIGURE 1. Generating a 3D image of a particle track in a TPC.

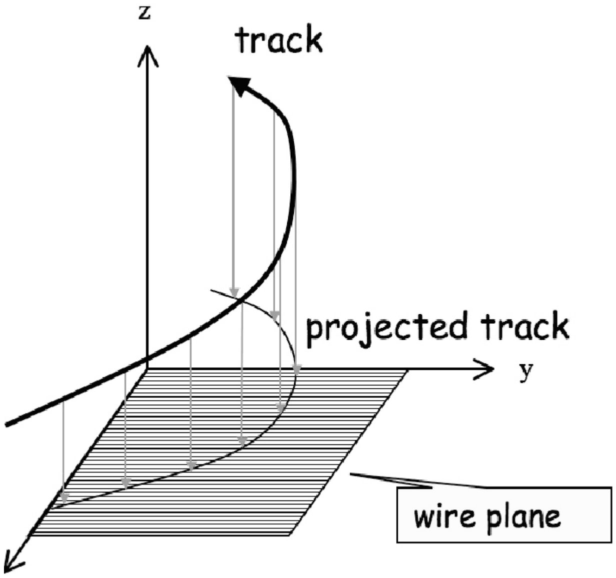


FIGURE 2. The curved track in a magnetic field.

More recently TPC-like detectors were built to study nuclear reactions induced by low intensity radioactive ion beams (RIBs). Studies with RIBs are challenging; radioactive nuclear beams are produced via nuclear reactions and the desired beam must be selected from these secondary products. As a result experiments with radioactive ion beams are performed under less favorable conditions then ones using stable beams: low beam intensities, degraded emittance, and possible contaminants which must be tagged or removed from the beam prior to the interactions.

2. Tracking detectors used in the study of nuclear reactions induced by RIBs

TPC-like detectors are well suited to study reactions induced with radioactive ion beams. The high efficiency and good solid-angle coverage are at a premium when beam intensities are low. There are some challenges, though, when applying the standard TPC design as used in high-energy physics.

1. The ions traversing a gas volume can be stripped to multiple charge states. This complicates tracking with magnetic fields.

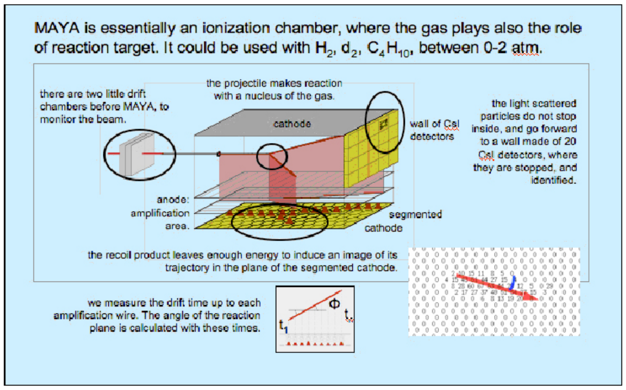
2. Reactions between complex nuclei typically results in products possessing a large range in mass and charge. This may present difficulty in producing a comprehensive characterization of the event due to the different ranges and stopping powers.

Some of these challenges can be addressed in specific circumstances. Eliminating the use of magnetic fields bypasses the problem of multiple charges states of the detected ions and the linear tracking of particles can be accomplished with much coarser sampling.

3. The MAYA detector

Most of our early knowledge of nuclear structure of stable nuclei originated in studies of excitation, resonant capture and direct transfer of neutrons and protons by bombarding stable nuclear targets with beams of light hydrogen and helium isotopes. Extension of such studies to the region of unstable nuclei requires switching beam and target.

A French-led collaboration at GANIL built a detector particularly suited for such studies [1-3]. The layout of this detector is shown in Fig. 3. It is a TPC with a segmented cathode plane. Particles stopped in the detector yield energy loss and total energy data. The fast moving products are stopped in one of the ancillary detectors (the CsI wall) depositing their kinetic energy by exciting or ionizing atoms in the lattice of the solid detector material. The detector gas contains the light nuclear targets thus providing a continuous array of thin targets with which the beam interacts. The MAYA active target has been deployed in several successful studies of resonances in ^{7}H [4,5] and most recently in the study of the two-neutron transfer reaction p (^{11}Li,^{9}Li) t with ^{11}Li beams at the ISAC II facility in Canada [6].



MAYA is essentially an ionization chamber, where the gas plays also the role of reaction target. It could be used with H_2, d_2, C_4H_{10}, between 0-2 atm.

there are two little drift chambers before MAYA, to monitor the beam.

the projectile makes reaction with a nucleus of the gas.

the light scattered particles do not stop inside, and go forward to a wall made of 20 CsI detectors, where they are stopped, and identified.

the recoil product leaves enough energy to induce an image of its trajectory in the plane of the segmented cathode.

we measure the drift time up to each amplification wire. The angle of the reaction plane is calculated with these times.

FIGURE 3. The MAYA presents a continuous array of thin targets for nuclear reaction studies. (Figure from presentation by Barry Davids, TRIUMF, Nov. 2006).

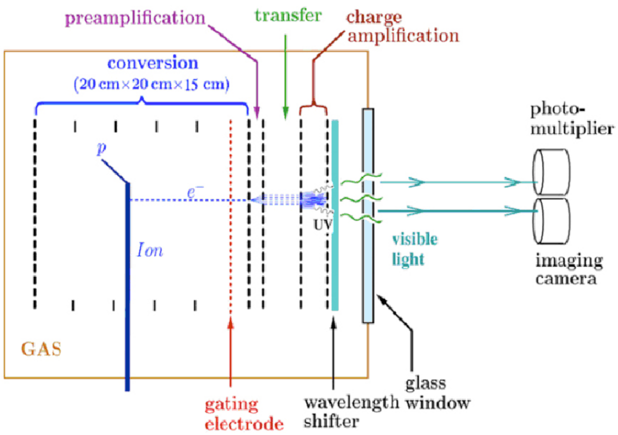


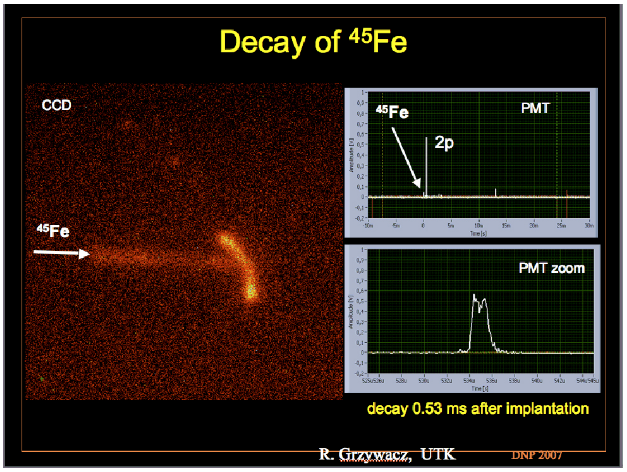
FIGURE 4. The OTPC – the gas fill is 49%Ar + 49%He and 1% each of N_2 and CH_4.

4. Optical TPC for imaging nuclear decays

The TPC shown in Fig. 4, built by a collaboration led by a group from Warsaw, presents one elegant solution to the limited dynamic range problem. The detector was developed to study the rare direct two-proton decay mode expected in some proton rich nuclei where single proton decay is energetically prohibited [7]. The detector design exploits the fact that the 2p decay occurs long after the emitting nucleus enters the detector. A gate electrode inhibits electron multiplication. When, in a rare occurrence, a ^{45}Fe enters the chamber and is stopped within, the gate is opened and the detector is now sensitive to the low-density tracks of light particles (p or α). Another novel idea employed here is the use of scintillation light in the gas to project the particle tracks in a plane perpendicular to the drift direction. The projection plane is defined by a thin sheet of wavelength shifter that converts the UV scintillations to visible light that can be recorded by a CCD camera. That light is also viewed by a fast photomultiplier tube (PMT) which records the arrival time of electrons to the charge amplification region. While this solution may be limited in its capabilities it was ideal at the task it was designed to perform and costs a fraction of an equivalent more standard setup with electronic signal processing. The OTPC was deployed to study the 2p decay [8] and the β delayed 3p decay [9] of ^{45}Fe. The tracks of the stopped ^{45}Fe and the two protons are shown in Fig. 5.

5. Tracking products from reactions induced by neutron-rich radioactive nuclei

The study of reactions between heavy nuclei is an area that should benefit from the availability of radioactive ion beams. Much of the systematic work that went into determining nucleus-nucleus potentials and interaction barriers was based on measurements done with stable nuclei. The same is true for the fusion hindrance in heavy systems that prevents the dinuclear system from fusing even after it has penetrated past the interaction barrier. Data on quasi-elastic scattering, deep inelastic scattering, nucleus-nucleus capture, and fusion are needed to test our semi empirical models and broaden their range of applicability. As Fig. 6 shows, the few cases where nucleus-nucleus barriers were deduced from data, measured with neutron-rich unstable beams, it reveals a marked difference between measured barriers and ones calculated with the best available semi-empirical model [10]. The shaded data in Fig. 6 were taken at the HRIBF with radioactive Sn beams formed from the fission products created in the bombardment of ^{238}U with protons [11]. The accelerated fission products span a large range of isotopes that can be used in reaction studies. Most of the interesting beams (more neutron-rich) are produced at intensities below 10^5 ions/sec. To study the interactions of these radioactive nuclei with other heavy targets a detector system that is efficient and has low detection threshold is necessary. Such a detector can yield data on most if not all the products from binary collisions. An ORNL-led collaboration designed such a detector system [12]. Figures 7 and 8 show two orthogonal views of the active detector volume.


Decay of ^{45}Fe

decay 0.53 ms after implantation

R. Grzywacz, UTK DNP 2007

FIGURE 5. Image of the 2p decay of ^{45}Fe. The inset shows the PMT signal used to construct the 3D tracks. The zoomed in figures show the two way split in arrival time of the electrons from the two tracks, which are not parallel to the projection plain. The proton energies are inferred from track length.

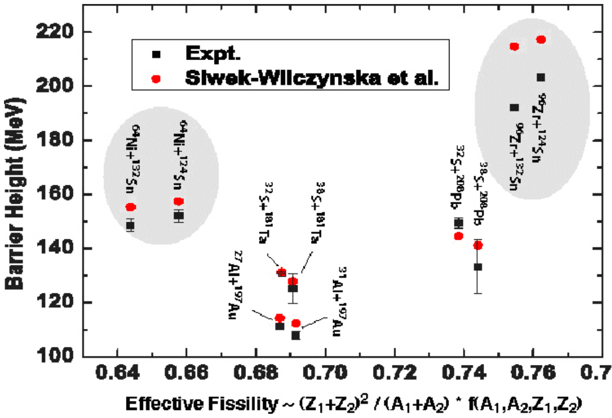


FIGURE 6. Comparison of measured and calculated barriers.

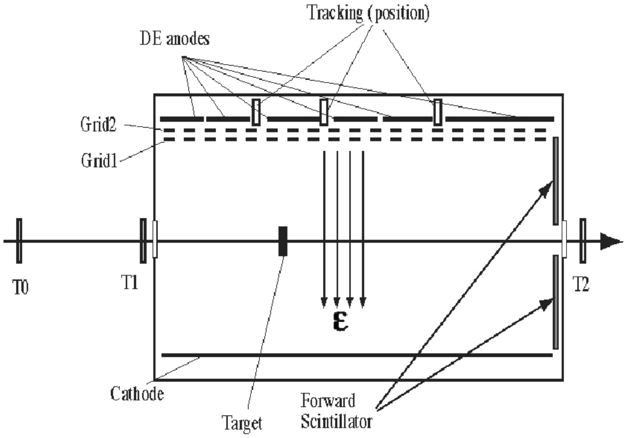


FIGURE 7. A view of the detector in a plane cut in a direction parallel to the drift direction of the ions and electrons.

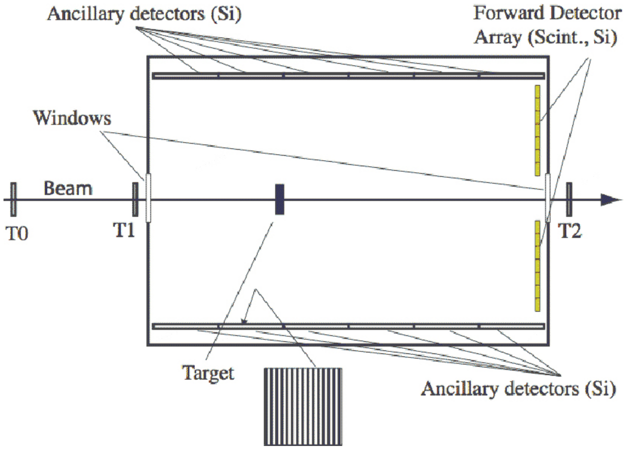


FIGURE 8. A view of the detector in a plane perpendicular to the drift direction.

The two views show the layout of a detector system that consists of a gas-filled ionization chamber with the reaction target placed inside the detector volume. This choice is dictated by the fact that we would like to have the maximum available solid angle coverage and that we are mostly interested in using heavy targets (Sn, Pb, U). Differentiating products from collisions of the beam with the nuclei in the detector gas and the real target will rely mostly on tracking the products to the target location and partly on the topology of the reaction. The electrons generated along the tracks of the beam and the heavy reaction products drift toward a highly segmented anode plane (shown in Fig. 9) where the projection of the ion track on the anode plane will be determined by position-sensitive proportional wire counters embedded in the anode plane structure. Scattered beam particles that do not stop inside the gas volume of the detector will deposit their energy in the ancillary detectors that line the front and the sidewalls of the ionization chamber. Two thin timing detectors [Sha05], T0 and T1, measure flight time, intensity, and position of the beam particles before they enter the gas filled chamber. T3 detects beam like particles that pass through.

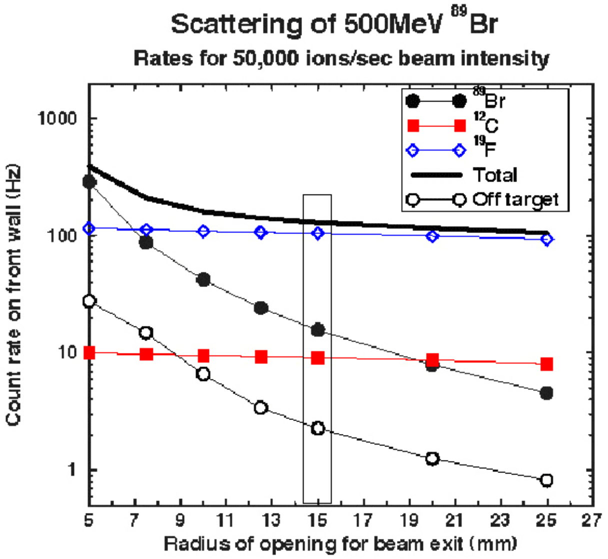


FIGURE 9. A proposed design of the anode plane on which particle tracks will be projected. The embedded wire planes provide position and time of arrival information. Two hits generate a track.

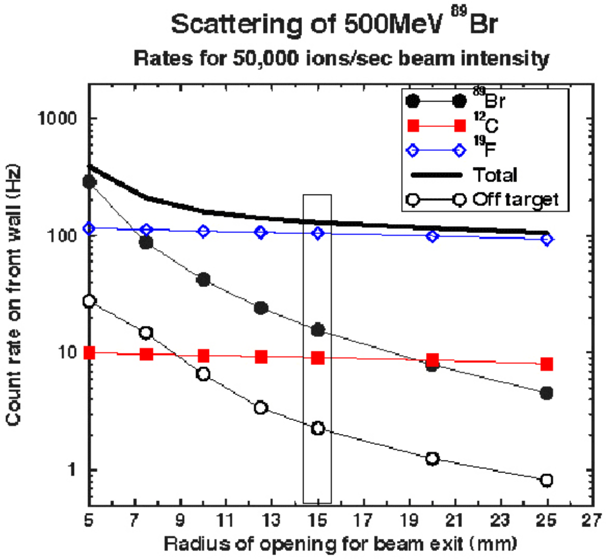


FIGURE 10. Predicted rates of ions hitting the front wall of the detector. The background from interaction with the detector gas is large but manageable at 50 kHz beam rates.

Although this detector relies on electron drift time for 3-D tracking it differs from other TPC designs in two respects.

1. It detects the energy loss without amplification of the signal since the fragments detected are heavy and produce plenty of primary electrons along a track. Energy loss determined in this way is compromised only by detector noise and straggling and is superior to what is attained following electron multiplication.

2. Since the ions move in straight lines, tracking can be done by measuring as little as two positions along the particles track. The anode plane design shown in Fig. 9 has position sensitive wire counters embedded at several positions.

The intent is to provide all the tracking information using the signals from these wire counters. Lateral (in plane) position can be determined by charge division and the vertical position can be determined by measuring drift time relative to the start signal from the T1 timing detector placed near the entrance to the chamber. A similar, though less elaborate scheme worked in a detector built to track heavy reaction products at the focal plane of a magnetic spectrograph [Sha75]. The detector will be exposed to the direct beam limiting the usable beam intensities to ∼50 kHz (both beam and contaminants). Since the detector system has been designed expressly to address aspects of collisions between heavy unstable and very neutron-rich nuclei this is not a serious drawback. Some studies can be done with beam intensities as low as a few hundred ions a second. The event trigger may combine a beam trigger in coincidence with a hit in one of the ancillary detectors lining the walls of the chamber or a signal from one of the electrodes in the anode plane. Figure 10 shows that the expected trigger rates for the highest beam intensities the detector can withstand will result in a trigger rate that can be easily handled by present day data acquisition systems. The figure shows these rates as a function of the opening exit window for a counter having active dimensions of $20\times20\times30$ cm^3. The vertical “box” drawn around 15 mm-radius corresponds to an opening angle of a 4.3 degree cone around the beam direction.

Our collaboration secured funds for the first stage in which the ion chamber will be constructed. If it meets the expected performance criteria of providing good tracking information and high quality energy loss signals we will proceed to pave the walls with silicon detectors and scintillators so that this becomes a fully functional detector system. We hope to complete this project within 3 years.

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