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Active Target detectors for studies with exotic beams: Present and next future

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ABSTRACT

Reaccelerated radioactive beams near the Coulomb barrier, which are starting to be available from the ReA3 accelerator at NSCL and in next future at FRIB, will open up new opportunities for the study of nuclear structure near the drip lines. Efficient measurement techniques must be developed to compensate for the limited intensity of the most exotic beams. The Active-Target Time Projection Chamber (AT-TPC) constructed at MSU solves this problem by providing the increased luminosity of a thick target while maintaining a good energy resolution by tracking the reaction vertex over an essentially 4π solid angle. The AT-TPC and similar detectors allow us to take full advantage of the radioactive ion beams at present and future nuclear physics facilities to explore the frontier of rare isotopes.

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1. Active Targets in the context of exotic beams

The scientific motivation for the construction of special detectors for the use with secondary beams is identical to the general justification for FRIB [1], as described for example in the long range plans of the NSAC [2]. Active Targets, with their high intrinsic efficiency, are well suited to study nuclei very far from stability, approaching the drip line, where secondary beam intensities become low. A first-principles description of nuclear systems along the drip lines presents a substantial theoretical and computational challenge [3]. One of the more specific questions we want to answer with this type of detector, is related to the question, as formulated in the 2013 NSAC report [2] concerning the simplicity of complexity. The relevant overarching question addressing the origin and nature of the nuclear emergent behavior is “How does subatomic matter organize itself and what phenomena emerge?”. In loosely bound systems, coexistence of normal shell-model like states with very different configurations, such as low density quasi-molecular states, is expected [4]. This can be considered as phase transitions between different ordering principles. Highly efficient detectors with good resolution are necessary to characterize these states near continuum and near the drip line.

2. Specificities of Active Target detectors

Bubble chambers can be considered as a first example of an Active Target detector: the liquid hydrogen served as target and at the same time to reveal the tracks as visible bubbles. A historic review can be found in the talk of Becchetti [5]. With modern high density electronics, computerized read-out of tracks has become possible, with very complex high energy detectors such as ATLAS [6]. The complexity of nuclear reactions in low to medium energy is much reduced as compared to high energy physics, with often several thousands of charged particles emerging from the reaction. However, the energy loss of charged particles in a low energy detector varies by several orders of magnitude, as a function of the atomic number of the reaction partners and their energy.

3. Operation principles of an Active Target for radioactive beams

An Active Target serves both as target and detector for the nuclear reactions.

The detection is made using the Time Projection Chamber (TPC) principles: the volume is filled with a gas, that is ionized by a

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charged particle traveling through the gas. The number of electrons freed during this process is proportional to the energy loss of the particle in the gas. Once the electrons are free in the gas, an electric field across the chamber makes them drift towards an electron amplifier that collects and amplifies them. This electron amplifier is segmented allowing for the reconstruction of the position in two dimensions. The third spacial dimension is obtained by measuring the electron drift time in the chamber. With these combined measurements we get a 3D reconstruction of the tracks together with a determination of total kinetic energy of particles that stop in the detector. To obtain the energy of particles that do not stop in the volume, two possibilities exist: use of ancillary detectors (e.g. silicon and/or CsI detectors), or a magnetic field that allows us to obtain the magnetic rigidity. The particle identification can be derived by the ΔE–E characteristics of the tracks.

Another important feature is that the detection gas must also be used as target. Hence a key question for this technology is to find the appropriate gas mixture that provides the desired nuclei for the target *and* good conditions for the detection in the TPC mode. When using an Active Target, the pressure of the gas determines the thickness of the target. The pressure must be chosen to optimize: the range of the reaction products, the range of the beam, and the reaction probability. For low energy beams, the gas pressure can be sufficiently high to stop the beam in the chamber, thus providing the excitation function of the reactions of interest from energy below the barrier up to the incident beam energy. This implies a large range of pressures depending on the experiment.

4. Active Target Time Projection Chamber (AT-TPC)

The AT-TPC was designed and built at NSCL, where it is installed coupled to one of the beam lines of the reacceleration ReA3 facility [7]. Reaccelerated exotic beams of up to 3 MeV/u can be transmitted to the detector to be studied. We decided to build a half scale prototype with a small number of electronic channels to test the technology. For both the prototype and the full detector, in order to collect the freed electrons coming from the energy loss of the particles traveling through the gas, we need an electron amplification device. We have tested two different technologies: GEMS and Micromegas. The Micromegas technology was chosen, as it turned out to be more tolerant to the gas and pressure variations.

4.1. Electron amplification system: Micromegas

Micromegas stands for MICRO-MEsh-GAseous Structure [8] and consists of a micromesh held over a segmented anode readout plane. Each pad has its own dedicated readout electronic channel. In our device [9] gain can be varied pad by pad by applying a specific voltage to each pad. The mesh is held at a uniform distance of 128 μm above the anode plane with the help of insulated pillars placed 2 mm apart. The mesh itself is made of 18 μm thick stainless steel wire woven at a pitch of 63 μm. The electric field between the micromesh and the anode plane is about 50 times higher than that found in the space between the cathode and anode. The number of electrons is amplified in this high field producing a signal that then can be read out. Typical amplification factors can reach up to 10,000, depending on the gas, the gas pressure, and the electric field.

The pad plane can be segmented in different configurations depending on the resolution needed and the number of electronic channels available. In the next section we will show the different options we have used in the AT-TPC.

So far we have worked with several gas mixtures and a wide range of pressures: P10, isobutane, Ar:H_2 (90:10), He:CO_2, pure H_2, etc., at pressures ranging from 10 Torr with isobutane to 1 atm for He:CO_2 (90:10) achieving electron amplification gains higher than 10^3 in both cases. In Fig. 1 we show the gain curves obtained for different pressures and bias applied to the Micromegas for a pure H_2 gas. Most of the gas mixtures need voltage of the order of 1 kV/cm atm to achieve reasonable drift velocities, of the order of several cm/μs. As a consequence, very high voltage on the cathode is necessary, 50 kV for the prototype and 100 kV for the full size AT-TPC.

4.2. Prototype AT-TPC

The prototype [11] has a cylindrical volume 50 cm long and 28 cm in diameter with a Micromegas of 253 pads (see Fig. 2). This smaller granularity makes it impossible to measure the curvature of particles in a magnetic field, thus it is designed to be used without the superconducting magnet.

The design was optimized to study binary reactions and the readout plane is segmented in 253 2 mm thick concentric pads separated into quadrants. The radial resolution is then 2 mm, achieving good precision in determining the range and thus kinetic energy of charged particles in the device. This configuration does not allow for a measurement of the azimuthal angle. In the case of a binary reaction this is not needed.

For more complex reactions such as 3-body decay, we redesigned the pad plane as a backgammon-like structure. In this case we have a central pad and 126 concentric rings subdivided into quadrants. Each of these rings is then subdivided azimuthally, creating a radial backgammon structure. An example of the determination of the azimuthal angle from this charge division is shown in Fig. 3.

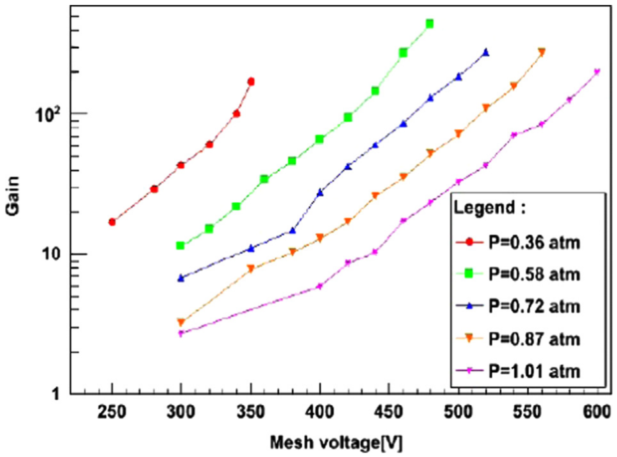

Fig. 1. Micromegas gain as a function of the applied voltage for different pressures in pure H_2 gas. From [10].

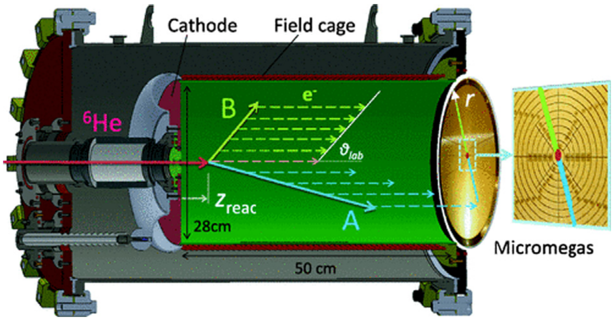

Fig. 2. Schematic drawing of the prototype AT-TPC. From [12].

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