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Multi-Sampling Ionization Chamber (MUSIC) for measurements of fusion reactions with radioactive beams

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ABSTRACT

A detection technique for high-efficiency measurements of fusion reactions with low-intensity radioactive beams was developed. The technique is based on a Multi-Sampling Ionization Chamber (MUSIC) operating as an active target and detection system, where the ionization gas acts as both target and counting gas. In this way, we can sample an excitation function in an energy range determined by the gas pressure, without changing the beam energy. The detector provides internal normalization to the incident beam and drastically reduces the measuring time. In a first experiment we tested the performance of the technique by measuring the $^{10,13,15}C+^{12}C$ fusion reactions at energies around the Coulomb barrier.

1. Introduction

Fusion reactions play an important role in nature, starting from the creation of the light elements in the Big Bang. They are crucial for the production of heavier elements in the stars' quiescent burning phase as well as in stellar explosions. Fusion processes also generate the energy in the Sun that created and maintains life as we know it. In nuclear physics, fusion reactions can produce exotic nuclei away from stability on the proton-rich side of the mass valley and they are crucial for the production of very heavy nuclei. The availability of radioactive beams at first-generation facilities over the last 20 years has opened many new possibilities for the study of fusion reactions. Particularly, for nuclear structure studies reactions with unstable nuclei offer the possibility to reach even further away from the valley of stability.

Fusion between carbon isotopes has attracted the attention of physicists and astronomers for the last 50 years. From fundamental nuclear structure effects to recent discoveries in stellar phenomena, there are still many open questions. One of them is the presence of oscillations in the $^{12}C+^{12}C$ fusion cross sections that are not observed in neighboring systems and are not completely understood yet [1]. In nuclear astrophysics, fusion reactions involving neutron-rich carbon isotopes may play a fundamental role opening new paths for nucleosynthesis in x-ray binaries, where new explosive phenomena called superbursts have recently been observed [2].

In most cases, fusion reactions in the laboratory are studied via the identification of the evaporation residues (ERs) using a variety of experimental techniques. The identification of the ERs can be achieved by detecting the decay radiation from characteristic energy levels or by direct particle detection. For the first case, γ- (e.g., Refs. [3–5]), β- (e.g., Ref. [6]), or x-ray measurements (e.g., Refs. [7–9]) are frequently employed. For the second case, the ERs can be directly detected in ΔE–E_{res} detector telescopes mounted at small scattering angles. For that, thin Si ΔE detectors or ionization chambers have been used (see, for example, Refs. [1,10]). Time-of-flight (ToF)

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techniques, i.e. measuring the velocities and the energy of the ERs, or gas-filled separators [11] have also been employed in the past.

By using one of these methods, excitation functions are obtained by varying the energy of the beam and using large high-efficiency detector arrays (in the decay radiation case), or measuring angular distributions of the ERs (in direct measurements). These experiments require a good relative normalization between the measurements made at different energies. For experiments with low-intensity radioactive beams the measurements can be very time consuming since typically only one cross section is obtained at each bombarding energy.

As an alternative, a Multi-Sampling Ionization Chamber (MUSIC) is presented here. The MUSIC is a small gas-filled detector which operates at low beam intensities ($\sim 10^4$ particles/s), counting both incident particles and reaction products. It is also capable of measuring several energy points of an excitation function at once. The detector operates as an active target, i.e. the ionization gas serves as target for the reaction and as detection medium at the same time. The projectile loses energy along its path inside the detector and fusion occurs with different energies depending on the position inside the detector. Since an ER is heavier than a beam particle, it will suffer a significantly larger energy loss. Therefore, the detected energy loss ΔE will suddenly increase at the position where a fusion reaction occurred and the ER will stop inside the detector, which is the signature of a fusion event.

Multi-sampling detectors have been employed in the past for the study of heavy-ion reactions. A multi-sampling ionization chamber was first developed for measurements with relativistic heavy ions [12]. Later multi-sampling proportional counters [13,14] were built for experiments with relativistic as well as with low-energy heavy ions. All these detectors, however, are generally quite large (typically 1 m long) which can lead to complications when isotopically enriched gases are to be used as an active target.

This paper is organized as follows: in Section 2 we give details of the main design features and the operational principle of the MUSIC detector. In Section 3 we describe the experimental setup for using the detector at the ATLAS facility at Argonne National Laboratory and the general procedure for its operation, whereas the performance of the technique under real experimental conditions is given in Section 4. A summary and future perspectives are presented in Section 5.

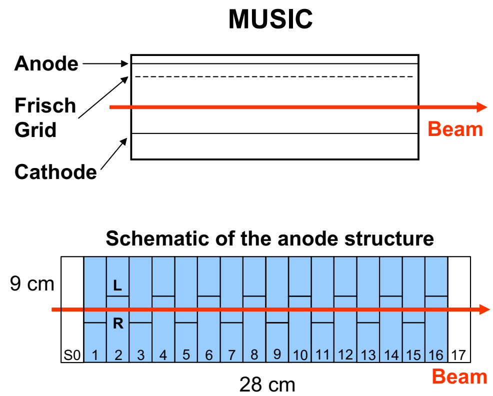

Fig. 1. Schematic of the Multi-Sampling Ionization Chamber (MUSIC). In the upper panel there is a lateral view of the detector and in the lower panel the structure of the anode. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

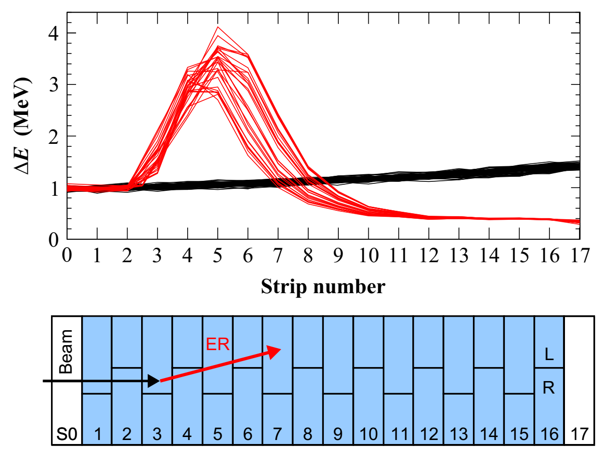

Fig. 2. Experimental traces measured with the MUSIC detector. Black lines correspond to beam particles interacting with the gas target only by ionization. The red lines correspond to fusion events occurring in strip number 3. Note the presence of the fusion features described in the text, meaning a jump in ΔE followed by zero pulse height in strips higher than 10. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Schematic and operational principle

The schematic of the multi-sampling ionization chamber MUSIC is shown in Fig. 1. The ionization chamber is mounted inside a 30 cm (L) × 10 cm (W) × 20 cm (H) aluminum box that can be filled with a suitable counting gas (He, CH_4, Ne, Ar). In the following we discuss as an example the fusion reactions between ^{10,13,15}C and ^{12}C studied by detecting the evaporation residues in MUSIC, which was filled with CH_4 at 200 mbar thus providing the ^{12}C target. The beams, ^{10,13,15}C, were obtained from the heavy ion accelerator ATLAS. Beams of the stable ^{13}C were accelerated in a tandem Van de Graaff accelerator, while beams of radioactive ^{10,15}C, with half-lives of 19.3 s and 2.46 s, respectively, were obtained via the in-flight method [15]. The beam production technique is discussed in Section 3.3 and more details can be found in Ref. [15]. The ^{10,13,15}C beams enter and exit the detector through 1.45 mg/cm^2 thick titanium windows. Titanium was chosen to minimize the production of ERs in the window material. In this experiment we have used non-enriched methane (CH_4) gas as active target, for its good counting properties and because reactions with the hydrogen do not interfere with the events of interest at the energies studied in this experiment. The correction for the 1% contamination from ^{13}C was in all cases smaller than the statistical uncertainty of the measured fusion cross sections.

In order to obtain the multi-sampling capabilities of the MUSIC detector, the anode of the ionization chamber is segmented in a pattern shown in the lower part of Fig. 1. There are a total of 18 strips numbered from 0 to 17, with each strip being 1.58 cm long. The "active strips" are numbered from 1 to 16, while the first and last strips, S_0 and S_{17}, serve as so-called "control strips". While the segmentation chosen for this detector does not allow a full tracking of the individual particles, it allows a clean identification of fusion events as well as the elimination of elastic and inelastic scattering events based on their multiplicity. This will be discussed below.

The energy signals from the anode were read out using Mesytec MPR-16 preamplifiers and Mesytec MSCF-16 shaper amplifiers [16]. In addition there were four more energy signals from the control strips S_0 and S_{17}, from the Frisch grid and from the cathode of the ionization chamber that were read out with standard NIM electronics.

The information provided by the MUSIC detector for a single incoming particle is best represented in a plot of ΔE vs. *strip number*, which is called a "trace". As an example, Fig. 2 shows some experimental traces measured for the ^{13}C+^{12}C system with a ^{13}C beam at E_{lab}=45 MeV. The beam reaches the first active strip (S_1) with an energy of 39 MeV and loses a total of 19 MeV in the active volume of gas providing the signals S_1-S_{16}. Thus, at this