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Review

Active targets for the study of nuclei far from stability

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A B S T R A C T

Weakly bound nuclear systems can be considered to represent a good testing-ground of our understanding of non-perturbative quantum systems. Reactions leading to bound and unbound states in systems with very unbalanced neutron-to-proton ratios are used to understand the properties of these systems. Radioactive beams with energies from below the Coulomb barrier up to several hundreds MeV/nucleon are now available, and with these beams, a broad variety of studies of nuclei near the drip-line can be performed. To compensate for the low intensity of secondary beams as compared to primary beams, thick targets and high efficiency detection is necessary. In this context, a new generation of detectors was developed, called active target detectors: the detector gas is used as target, and the determination of the reaction vertex in three dimensions allows for good resolution even with thick targets. The reaction products can be measured over essentially 4π. The physics explored with these detectors together with the technology developed will be described.

Contents

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1. Introduction

Our understanding of non-perturbative quantum systems can be tested with great detail in weakly bound nuclear systems. Non-perturbative systems are those in which small changes, such as adding one nucleon, or a small change in excitation energy or spin, may lead to a complete rearrangement of the system, and can therefore not be treated as perturbation. These systems can be studied by reactions using rare isotope beams. Great progress in this domain has been reached from an increase of many orders of magnitude in rare isotope beam intensities, and by the development of new highly efficient detectors such as active targets. This combination enables the exploration of completely unknown regions of the nuclear chart. It is now possible to study reactions leading to bound and unbound states in systems with very unbalanced neutron-to-proton ratios. A recent review on the progress in this domain can be found in [1].

In active target detectors the counter gas acts as both a target and detector, enabling the investigation of fusion, isobaric analog states, cluster structure of light nuclei and transfer reactions, performed without significant loss in resolution due to the thickness of the target. Active target detectors also allow to investigate fission barriers and giant resonances with rare isotope beams produced via fast fragmentation. Low-energy resonances of astrophysical interest can be explored with active target detectors. Reaction cross sections have been measured to study big-bang nucleosynthesis, seeds of the r process, rp process, and nucleosynthesis in X-ray bursts. Applications of active target detectors to these domains of physics will be illustrated by experiments performed with existing detectors.

Historically one could say that active target detectors go back to the beginning of nuclear physics. Bubble chambers for instance can be considered as the 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. With modern high density electronics, computerized read-out of tracks has become possible, with very complex high-energy detectors such as ATLAS [2,3]. A historic review of the evolution in detector technology can be found in the review of F. Sauli [4].

Many of the technologies that have been developed for high-energy physics have applications in low-energy nuclear physics. However, there are important differences in the requirements between low and high energy. The complexity of nuclear reactions in low to medium energy is much reduced as compared to high energy physics where often several thousands of charged particles emerge from the reaction. This makes analysis at low energy comparatively easier and the number of electronics channels does not need to be as high as in high energy physics, of the order of 10,000 compared to several millions. In addition, 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, whereas in the high energy case essentially all particles are at minimum energy loss. This feature implies that the electronics used for the active target must have a high dynamic range in order to accommodate all possible energy losses. Due to the low energy of the reaction products in many experimental situations, the trigger cannot rely on an external ancillary detector, but must be provided by the detector itself. The development of high-energy detector technology has benefited low-energy nuclear physics, but adaptation to its specific features is necessary.

The development of active target detectors for the study of nuclei far from stability is driven by the combination of these three main features:

1. Inverse kinematics: the use of secondary beams implies the change from direct kinematics to inverse kinematics.
2. Low recoil energies: in inverse kinematics the recoil particles have very low energies in quasi-elastic reactions such as (d, p) and (α, α').
3. Thick targets and high solid angle: to compensate the limited intensity of secondary beam, thick targets and high detection efficiency without loss of resolution are needed.

In the following we discuss and illustrate these statements with more details.

1. Reactions with stable beams and stable targets mostly use light beams such as p, d, ^{3}He, ^{4}He, because they have a simple structure, to bombard targets such as ^{12}C, ^{48}Ca, ^{208}Pb, that are the subject of the study. Let us consider the case of ^{32}Mg as example. The lifetime is too short to prepare this nucleus as a target. However ^{32}Mg can be provided by recent facilities as a beam. Then the equivalent studies imply that the light particles p, d, ^{3}He, ^{4}He and so on have to be the targets. This is what is meant by inverse kinematics. The change from direct to inverse kinematics does not, of course, change the physics of the process to be studied: in the center of mass system, the two are completely equivalent. However, in the laboratory system, several important changes take place. To illustrate this, in Fig. 1 the relative energy variation dE/E for a change of excitation energy of 100 keV, for a reaction ^{32}Mg(d, p) is shown for the most important forward angles in the center of mass system. In normal kinematics, the energy of the beam-like outcoming proton is changed by about 0.6%. This change