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In-flight recoil separators RITU and MARA and the standard detector setups

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ABSTRACT

In-flight recoil separators RITU and MARA at Jyväskylä Accelerator Laboratory are complementary devices to separate the fusion-evaporation residues from the primary beam and other reaction products. The nuclear-structure-research program at Jyväskylä utilizes these separators and the detector setups shared between the separators to identify weak reaction channels and extract nuclear-structure information via decay experiments and in-beam spectroscopic studies. For example the very weak N∼Z nuclei are studied in-beam by using β-decay tagging method (Tuike scintillator) enhanced with the mass selection (MARA) and charge particle-evaporation veto (JYTube).

1. Introduction

Studies of the weak reaction channels in nuclear physics experiments with in-flight recoil separators require advanced and specialized detector setups together with powerful data-acquisition systems. Detectors around the target observe the prompt radiation like γ rays and light reaction products while the detectors at the focal plane are used to record implantation energy, position and angle of the products and background particles, time of flight, energy losses and radioactive decay products like αs, protons and βs. Digitized data collected from the detector channels can be used to set complicated conditions for inter-detector coincidences to reveal signals from reaction channels having cross section of one millionth or even less from the overall nuclear reaction cross section.

The most typical nuclear-structure experiments utilizing RITU or MARA in-flight separators are either in-beam experiments observing the level transitions with the germanium-detector array around the target or decay experiments measuring the decay properties of poorly known or yet unobserved isotopes in the vicinity of the proton drip line, for example [1,2]. The method of recoil-decay tagging [3,4] is used in the in-beam experiments to select the weak channels enabling one to reach the level of few tens of nanobarns in cross section [5].

In the following the operation of the in-flight recoil separators RITU and MARA at Jyväskylä and the most commonly used detector setups around the separators will be introduced. The aim is to highlight how the different detector setups are used in a variety of experiments with different goals.

2. Separators

The most important function of the in-flight separators is to separate the interesting reaction products from the intense primary beam passing a target. The selection between the separator to be used for an experiment is made according to the reaction kinematics or due to some constraints specific to an experiment. MARA is typically used in studies of fusion products below mass number ∼150 and in reactions using inverse or symmetric kinematics whereas RITU is mostly used in the heavier element region utilizing asymmetric kinematics. The layout of the separators together with the JUROGAM-3 rail system is shown in Fig. 1.

2.1. RITU

RITU is a gas-filled separator [6,7] consisting of three magnetic quadrupoles and a dipole magnet in the configuration $Q_\mathrm{v} D Q_\mathrm{h} Q_\mathrm{v}$ where the subscripts v and h stands for vertical and horizontal focusing, respectively. The angular acceptance of RITU is $\pm 25 \cdot \pm 85$ mrad^2 in horizontal and vertical directions, respectively.

The trajectory of an ion in the magnetic field is defined by the magnetic rigidity, $B\rho = p/q$, where B is the magnetic field flux density, ρ is the radius of curvature, p is the momentum and q is the charge of the ion. The average charge state of a flying recoil fluctuates due to frequent charge-exchange collisions with the filling gas. The mean-free path calculated from charge-exchange-collision cross sections, given by the model defined in Ref. [8], is typically of the order of a millimetre. Since this is short relative to the radius of curvature, the charge-exchange collisions result an ion to have a well-defined average charge.

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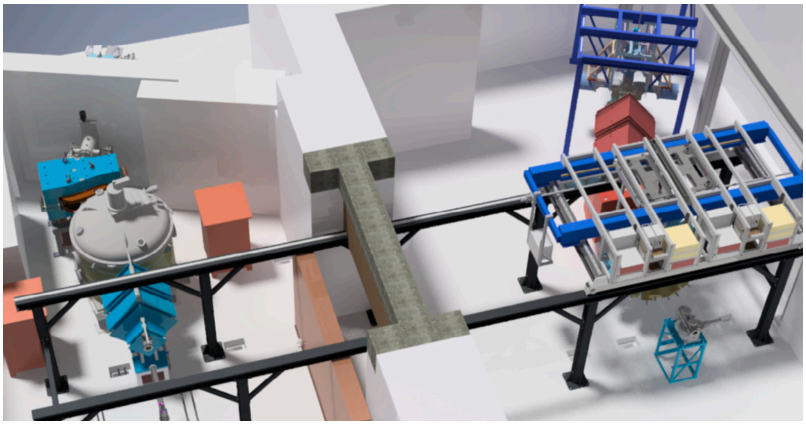

Fig. 1. Layout of the MARA (left) and RITU (right) in-flight separators in the experimental area. The rail system drawn in black is used to move JUROGAM 3 germanium array between the separators.

This average charge is almost directly proportional to the velocity of an ion [9] leading to the magnetic rigidity being independent of the ion velocity. Thus, inside a gas-filled-recoil separator the trajectories of products are independent of their kinetic energy and initial charge state which leads to RITU having a high transportation efficiency.

In RITU, Helium is used as a filling gas with pressures between 20 to 160 Pa depending on the kinematics. More symmetric reactions leading to higher fusion-evaporation residue (recoil) velocities require higher pressures to reach the optimal image size and to increase the suppression factor for the scattered primary beam. The suppression factor is typically better than $5 \cdot 10^{10}$ in experiments studying translead fusion products.

2.2. MARA

One of the most important reasons to construct the vacuum-mode recoil-mass spectrometer MARA [10] was to extend the local nuclear-structure research program to lighter fusion products near the proton-drip line and especially for studies of nuclei around N = Z line. The fusion-evaporation reactions used for studies of these nuclei are often very symmetric for projectile and target masses or sometimes in inverse kinematics, where the projectile is heavier, is preferred. In MARA the separation of primary beam and products takes place in the electric field between the cathode and anode of an electrostatic deflector. The electric rigidity for a non-relativistic ion is $E\rho = 2K/q$, where E is the electric field, ρ is the radius of curvature, K is the kinetic energy and q is the charge. The electric rigidity for a primary-beam particle is always higher than that of the fusion products and therefore the primary-beam particles bend much less in the deflector. The anode is equipped with a long 15 mm tall horizontal gap, through which the primary beam particles drift to a dedicated beam dump.

MARA consists of a quadrupole triplet followed by the electrostatic deflector. The deflector and the dipole bend particles to opposite directions which causes the energy dispersion to vanish at the focal point of the separator. However, since the magnetic and electric rigidity depend differently on mass and energy of an particle, there is nonzero mass dispersion left. The mass dispersion of MARA is about 8 mm/(1% in m/q). The function of the quadrupole triplet is to create a point-to-point focus from the target to the focal plane. The quadrupole component of the magnetic dipole can be changed with surface coils and therefore the position of the focal point of MARA can be adjusted. The total length of the separator from target to the focal point is 7.0 m.

The angular acceptance of MARA is $\pm 45 \cdot \pm 55$ mrad^2 in horizontal and vertical directions, respectively. Adjustable apertures installed at the entrance and exit of the deflector can be used to increase the mass resolution but are more commonly used to provide a safe opening of the separator at the beginning of an experiment. However, the mass slits, which are located 10 cm before and after the focal point, are used in many experiments to admit only two charge states of one mass to enter the implantation detector. The m/q focal plane is heavily tilted, which causes the focal point to be earlier or later for the particles with different m/q values. The typical mass resolving power of MARA is around 170 u^{-1} and the transmission through the separator is between 10–70% depending on the reaction asymmetry and number of collected charge states.

3. Target area detectors

3.1. JUROGAM 3

The JUROGAM 3 [11] is a germanium-detector setup consisting of 24 Clover and 15 tapered single-crystal Phase1 detectors. The array has 111 crystals in total. Each of the detectors are surrounded by BGO shields to improve the peak-to-total value. JUROGAM 3, including its essential electronics, are installed in a rail system which can move the fully biased array between the RITU and MARA separators as shown in Fig. 1. The Clover detectors are installed in two rings around 90 degrees relative to the optical axis while the Phase1 detectors form two rings at backward angles. A new frame able to support Phase1 detectors while the Clover detectors are in use at other laboratories has been constructed recently. This smaller Ge-array is used, for example, in plunger-lifetime experiments (see Section 3.4) where the detectors around 90 degrees are not needed.

3.2. SAGE

The SAGE electron spectrometer [12] is a powerful tool to study the structure of heavy isotopes where many of the transitions are mainly internally converted or where no γ-ray emission is allowed i.e. transitions between 0^+ states. The unique feature of SAGE is that it fits inside the JUROGAM 3 array when the outermost Phase1 ring is removed, allowing the observation of γ rays in cascade with the emission of an electron. The coils of SAGE create a solenoidal magnetic field which focuses the electrons upstream to a high-resolution silicon detector through a high-voltage barrier for delta-electron suppression. The SAGE is slightly tilted to allow the primary beam to pass the detector.

3.3. JYTube

In the experiments where the fusion channel cannot be identified with high certainty at the focal plane, a charged-particle veto detector JYTube can be utilized around the target. JYTube and its predecessor UoYTube have been proven to be very useful in the experiments around

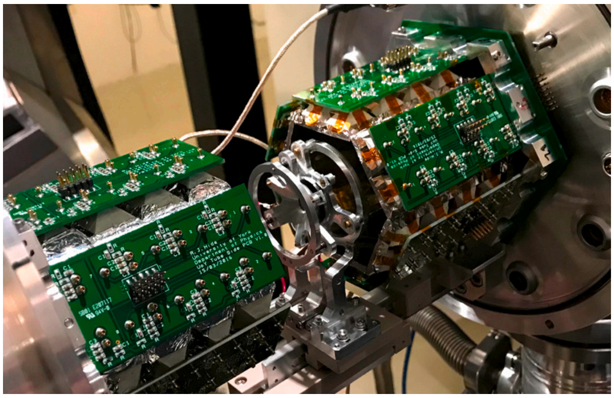

Fig. 2. The APPA plunger device for lifetime measurements in the middle of the opened charge-particle detector JYTube.

the N~Z line where the isotope under interest is produced in channels with zero or one proton evaporation. In these experiments the yield of other evaporation channels of the same mass can be millions times higher and the nuclei-of-interest are β emitters which do not generally provide a clear identification. JYTube fits inside the JUROGAM 3 array and it consists mostly of low-Z elements thus being relatively transparent for γ rays.

A photograph of JYTube is shown in Fig. 2. JYTube has two hemispheres which can be slid along the optical axis to allow the change of target or access to an instrumentation around the target. One hemisphere has hexagonal barrel of 48 individual $20 \cdot 20 \cdot 2$ mm^3 plastic-scintillator squares and a bottom plate of 12 scintillators of two different shapes. In total, these 120 scintillators have a 70% observation efficiency for a single proton, which can be transformed to veto efficiencies around 91% and 97% for two and three proton evaporation channels, respectively. Light output is read individually from the scintillators by $6 \cdot 6$ mm^2 Silicon PhotoMultipliers (SiPMs).

3.4. APPA

APPA is the newest plunger-lifetime instrument in use at Jyväskylä. The device has a stretched degrader foil after the stretched target foil and can precisely change the distance between the foils. In the Fig. 2 APPA is shown inside JYTube but it can be used also alone. Since the observed energy of a γ ray emitted in backward angles is sensitive to the recoil velocity, the intensity ratio of unshifted and shifted components of a γ-ray peak represents the ratio of emissions before and after the degrader. This then gives direct information about the lifetime of a level for a known recoil velocity and foil distance. In addition to traditional lifetime measurements using degrader foil and γ rays, the degrader can be replaced by a thin charge-reset foil and the atomic charge-state distribution, which depends on the emission time of an conversion electron, can be measured with MARA. This so called charge-plunger method to access lifetimes of the highly-converted excitation levels has been demonstrated to work [13].

4. Focal plane instrumentation

After the recent update of the RITU focal plane, the same silicon, transmission and germanium detectors can be used at the end of both separators. Multiple vacuum chambers containing the detectors are back-to-back on sliding tracks allowing one to access different parts at ease. The very last vacuum chamber has different sized lids available and an ethanol-cooled mounting plate inside for versatile detector setups.

4.1. MWPC

A Multi Wire Proportional Counter (MWPC) is placed 40 cm upstream from the implantation detector in most of the experiments. Isobutane in 200–400 Pa pressure is used as an ionization gas. The gas volume of about 5 cm in thickness is confined by the pair of thin mylar windows. The active width and height of all the MWPCs in use are 160 mm and 60 mm, respectively. The MWPCs available consist of three or five planes of wires stacked close to each other and the wire pitch is between 1.0–1.6 mm.

The logical signal generated by the ionization charge collected from a centre plane of wires is used as a delayed stop for the Time-of-Flight (ToF) measurement where the start is generated by the implantation detector. ToF between the detectors combined with the implantation energy is the key identification method used for recoil selection from other implanted particles. The absence of a time-correlated MWPC signal is a necessary condition for a decay event in the implantation detector.

At the MARA focal plane the signals are taken from both ends of the horizontal and vertical wirings equipped with delay lines and fed into analogue TAC units. The position of the transmission is then calculated from the measured time difference. The MWPC in MARA is installed at the centre of the mass-focal plane to provide the m/q information. Position sensitive MWPC is not needed at RITU.

4.2. DSSD, punch-through and tunnel detectors

A Double-Sided silicon-Strip Detector (DSSD), the BB20 model from Micron Semiconductor Ltd, is used as an implantation detector at both focal planes. It consists of 172 and 72 0.67 mm wide strips in vertical and horizontal directions, respectively. Its active size is $128 \cdot 48$ mm^2. Three different thicknesses, 150 μm, 300 μm and 700 μm, are available. A thin detector provides lower β background for proton-emission studies while thicker ones give higher observation efficiencies for βs and conversion electrons.

Charge signals from the DSSD are conducted via thin wires outside the vacuum chamber to 17 (5 in y and 12 in x) Mesytec MPRT-16 preamplifiers. These preamplifiers have four linear gain settings and adjustable threshold for NIM-timing signal. Typically the full range of 35 or 70 MeV are applied on x-side to reach a reasonable energy resolution for decay products and a lower gain of 70 or 120 MeV is applied on y-side strips to cover the fusion-recoil energies without saturation. A low energy threshold around 40 keV and energy resolution better than 20 keV are typically reached for new detectors. NIM-timing signal is a leading-edge triggered and is common for all 16 channels in a preamplifier. These signals are collected from the 12 x-side units to act as a start for ToF.

Light particles, typically protons and αs created in direct reactions, are observed to punch through the DSSD in every experiment. These particles do not ionize isobutane enough to trigger the MWPC and therefore can be erroneously classified as decay products. To address this, a pair of simple silicon detectors are installed few millimetres behind the DSSD and act as additional veto detectors for such events.

A rectangular tunnel-like detector setup just upstream from the DSSD is used in some experiments to detect escaping decay products and conversion electrons. The geometrical efficiency of these escape detectors is about 20% in total.

4.3. Germanium detectors

The standard focal plane setup includes four γ-ray detectors. The largest Mirion Broad Energy Germanium Detectors, BEGe 6530, are installed behind, top of and on one side of the DSSD. A standard Clover detector, similar to those in the JUROGAM 3, is placed on the other side of the DSSD. The maximum efficiency is measured to be between 20–25% at 150 keV. The germanium detectors are mounted on a floor-supported stand on wheels.

4.4. Tuike

Tuike [14] is a position-sensitive β detector made of plastic scintillators. It consists of two layers of light-isolated scintillator bars installed perpendicularly. The first layer has 14 vertical bars having the cross section of $10 \cdot 80\ \mathrm{mm}^2$ while the thicker second layer has eight horizontal bars with the cross section of $140 \cdot 10\ \mathrm{mm}^2$. The thicknesses of the vertical and horizontal layers are 6 mm and 24 mm, respectively. The light signals are read by 22 SiPM chips.

Tuike is the newest detector built for β-tagging (for the method, see [15]) experiments at MARA. In the β-tagging experiments, where Tuike is utilized, the β-decay half life of the isotope of interest is relatively short and the end-point energy is high since the nucleus will undergo a Fermi-superallowed β decay between isobaric-analogue states. These decays are selected with Tuike by setting an energy threshold for β particles between 2–6 MeV depending on the required cleanliness of the identification. The highest possible threshold is set by the electron energy loss in plastic which is about 6 MeV for 30 mm.

5. Conclusions

The in-flight recoil separators are essential instruments to extract the extremely weak reaction channels. However, the modern studies of nuclear structure at the boundaries of known nuclei requires special detector setups both before and after the separator. In this article we have described the key instrumentation around the RITU and MARA separators at Jyväskylä for nuclear-structure studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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