Nuclear Instruments and Methods in Physics Research B 376 (2016) 156–161

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Large acceptance spectrometers for invariant mass spectroscopy of exotic nuclei and future developments

T. Nakamura, Y. Kondo

2-12-1 O-Okayama, Meguro, Tokyo 152-8551, Japan

ARTICLE INFO

Article history:
Received 10 October 2015
Received in revised form 28 December 2015
Accepted 4 January 2016
Available online 12 February 2016

Keywords:
RI beam
Large acceptance spectrometer
Invariant mass spectroscopy
Neutron detector

ABSTRACT

Large acceptance spectrometers at in-flight RI separators have played significant roles in investigating the structure of exotic nuclei. Such spectrometers are in particular useful for probing unbound states of exotic nuclei, using invariant mass spectroscopy with reactions at intermediate and high energies. We discuss here the key characteristic features of such spectrometers, by introducing the recently commissioned SAMURAI facility at the RIBF, RIKEN. We also investigate the issue of cross talk in the detection of multiple neutrons, which has become crucial for exploring further unbound states and nuclei beyond the neutron drip line. Finally we discuss future perspectives for large acceptance spectrometers at the new-generation RI-beam facilities.

1. Invariant mass spectroscopy in RI-beam experiments

Rare isotope beams available at in-flight separators, at RIKEN (RIBF), MSU, GSI, and GANIL, have expanded physics opportunities to a wider range of *N*–*Z*. Accordingly, more experiments have been performed for nuclei near the drip line or even beyond [1,2]. For such nuclei, most or all of the states are unbound (i.e., in the continuum), thereby decaying by emitting particles. The invariant mass spectroscopy of such unbound states produced with direct reactions and fragmentation of exotic nuclei at intermediate and high energies has thus become a powerful experimental tool in RI-beam physics. Large-acceptance spectrometers play a major role, as we will show, in performing invariant mass spectroscopy experiments.

Let us take an example of the recent experiment on the $1n$ knockout reaction ^{17}C+p at 70 MeV/u by Satou et al. [3] at the RIPS facility [4] at RIKEN, where unbound states of ^{16}C were studied. In this case, decay particles ^{15}C and a neutron emitted in the forward kinematical cone were measured. From the momentum vectors of these two particles, one can reconstruct the invariant mass M_{16*} of a ^{16}C state as,

$$M_{16*} = \sqrt{(E_{15}+E_n)^2 - |\vec{P_{15}} - \vec{P_n}|^2}, \tag{1}$$

where $(E_{15}, \vec{P_{15}})$ and $(E_n, \vec{P_n})$ are the four momenta of the ^{15}C fragment and the neutron. One can extract the relative energy $E_{\rm rel}$ and the excitation energy $E_{\rm x}$ as,

$$E_{\rm rel} = M_{16*} - (M_{15} + M_n), \tag{2}$$

$$E_{\rm x} = E_{\rm rel} + S_{\rm n}, \tag{3}$$

where M_{15}, M_n are the masses of ^{15}C and the neutron, and $S_{\rm n}$ is the neutron separation energy (for ^{16}C, $S_{\rm n}$ = 4.25 MeV). If ^{15}C is produced in a bound excited state, then the γ decay energy ($E_\gamma = 740$ keV for ^{15}C) should also be measured and $E_{\rm x}$ is shifted up by E_γ, since M_{15} is replaced by $M_{15} + E_\gamma$. In the experiment, three states were found at $E_{\rm rel}$ = 0.46(3), 1.29(2), and 1.89 MeV that correspond to $E_{\rm x}$ = 5.45(1), 6.28(2) and 6.11 MeV. The 6.28(2) MeV state was found to be in coincidence with the 740 keV γ ray, and $E_{\rm x}$ is shifted accordingly.

The advantages of invariant mass spectroscopy in the study of exotic nuclei are summarized as follows.

- Good energy resolution: One can reach an energy resolution of about a few hundred keV (1σ) at $E_{\rm rel}$ = 1 MeV even for a momentum resolution of the order of 1% for the fragment and neutron individually. Note that the relative-energy resolution $\Delta E_{\rm rel}$ follows approximately $\Delta E_{\rm rel} \propto \sqrt{E_{\rm rel}}$.
- Kinematic focusing: Since the outgoing particles are boosted by the beam velocity at intermediate and high energies, they are emitted in a narrow kinematical cone. Consequently, one can detect the decay particles with high geometrical efficiency.
- Thick target: Since one uses intermediate and high energy beams, one can use a comparatively thick target of the order of 100 mg/cm^2 at 50–70 MeV/u to 1 g/cm^2 at 200 MeV/u. Hence, one can obtain high reaction yield, which is important for RI-beam experiments since beam intensity is generally week.

http://dx.doi.org/10.1016/j.nimb.2016.01.003
0168-583X/

Owing to these advantages invariant mass spectroscopy has become one of the most useful methods to study the continuum structure of exotic nuclei. There is, however, one disadvantage: One needs to measure all the outgoing beam-velocity particles, which makes the experiment and the analysis more complicated. For instance, if the daughter nucleus is in a high-lying excited state, then this may decay by a cascade of γ rays. In this case, an accurate measurement of the excitation energy requires a high-efficiency γ-ray calorimeter [5].

To realize invariant mass spectroscopy, a large acceptance spectrometer is highly desirable. In the above example [3], a simple dipole magnet was used in combination with the neutron-detector array based on plastic scintillators (see Fig. 1 of Ref. [6], the "RIPS-Dipole setup"), which was a pioneering invariant-mass-spectroscopy setup at the RIPS facility at RIKEN since 1992, for unstable nuclei at about 70 MeV/u. This dipole magnet has a relatively large gap (25 cm), so that the outgoing particles including neutrons have a large acceptance. On the other hand, the momentum resolution is moderate (1%) since focusing elements such as quadrupole magnets are not used. A momentum resolution of 1% is already sufficient to obtain a good $E_{\rm rel}$ resolution, and a simple dipole magnet has an advantage of having large acceptance. The use of such a magnet is also necessary to "sweep" the charged particles away from the neutron detectors.

A large momentum acceptance of the magnet is advantageous in studying a variety of final states with a single setup. Let us consider the incident beam of the drip-line nucleus ^{22}C on a carbon target. In this case, one can study its reaction cross section of ^{22}C to study its size, 1n removal to study the unbound ^{21}C states ($\rightarrow^{20}$C+n), low-lying excited states ^{22}C with the inelastic scattering, and other unbound states such as in ^{16,17,18,19}B with proton-removal fragmentation reactions, for example.

2. SAMURAI facility at RIBF

At the RIBF, RIKEN, the advanced invariant-mass-spectrometer setup, SAMURAI was constructed and commissioned in 2012 [7–9]. SAMURAI stands for **S**uperconducting **A**nalyser for **MU**lti particles from **RA**dio **I**sotope Beams. The SAMURAI setup for the invariant mass spectroscopy of neutron-rich nuclei is schematically shown in Fig. 1(a). This setup was used, as shown, for the recent kinematically complete measurement of the unbound system ^{26}O by 1p knockout from ^{27}F with a carbon target at 201 MeV/u [10].

The principal element is the superconducting SAMURAI magnet with a maximum field of 3.1 Tesla (Field integral 7.1 Tm) with a large effective gap of 80 cm. One characteristic feature of the SAMURAI facility is its relatively high momentum resolution for the charged fragment, of the order of 10^3 (1σ). This was realized by designing the magnet to have a large bending angle of about 60 degrees, as well as the tracking using four multi-wire drift chambers with high position resolutions [7]. A simple tracking analysis using a polynomial fit and the calculated field map, combined with a time-of-flight measurement between the target and the hodoscope (HODF), can already provide $P/\Delta P \sim 700(\sigma)$, the design value of SAMURAI. With detailed tracking and restricted acceptance, the momentum resolution can reach about 1500 [7]. The interest of high-momentum resolution is that it provides for high mass resolution in the particle-identification. When one needs sufficient separation in the mass distribution $\sim 5\sigma$ separation may be necessary when a particular isotope has a much larger yield compared to the neighbors. Such a high separation (5σ) is indeed achieved for charged fragments with $A \sim 100$ when the momentum resolution is $P/\Delta P = 700$. Fig. 2(left) shows the particle identification spectrum obtained in the ^{26}O experiment. The mass spectrum extracted for the oxygen isotopes is shown in Fig. 2 (right), where better than 10σ separation is reached in this mass region. Recently, an experiment on ^{132}Sn was performed where masses are clearly separated even in this mass region [11].

Neutrons emitted in the forward direction go through the gap of the magnet and their positions and time-of-flight are measured by the neutron detector array NEBULA (**NE**utron-detection system for **B**reakup of **U**nstable-Nuclei with **L**arge **A**cceptance), which is shown schematically in Fig. 1(b). The NEBULA array consists of 120 modules of plastic scintillator, each of which is 12(W) $\times$ 12 (D) $\times$ 180(H) cm^3. These modules are arranged into two walls, each of which is composed of two layers of 30 modules. The total thickness is thus 48 cm [7], and the area amounts to 360 $\times$ 180 cm^2. In the ^{26}O experiment, the front faces of these two walls were 11.12 m and 11.96 m downstream of the reaction target. Each wall is equipped with a charged-particle veto array of 1 cm thickness. A wide acceptance is required since neutrons are emitted with much larger angles than the charged fragment, as discussed below.

The other important feature of SAMURAI as an advanced large-acceptance facility is that it offers a variety of experimental modes, which are owing to the rotatable stage on which the magnet is installed. The range of rotation is −5–95° (0° corresponds to the setup where the entrance and exit faces are 90° to the beam axis). The setup in Fig. 1(a) is at 30°. SAMURAI thus offers a variety of experimental setups, e.g., for (1) Invariant mass spectroscopy by HI(Heavy-ion fragment) + neutron(s) coincidence as in the example of ^{26}O, (2) Invariant mass spectroscopy by HI + proton coincidence at the 90° setting, where the hole in the yoke is used as a beam port, (3) Missing mass spectroscopy by measuring recoil particles primarily from the target, (4) Polarized deuteron-induced reactions, and (5) Heavy-ion collisions to measure $\pi^{\pm}$ using the

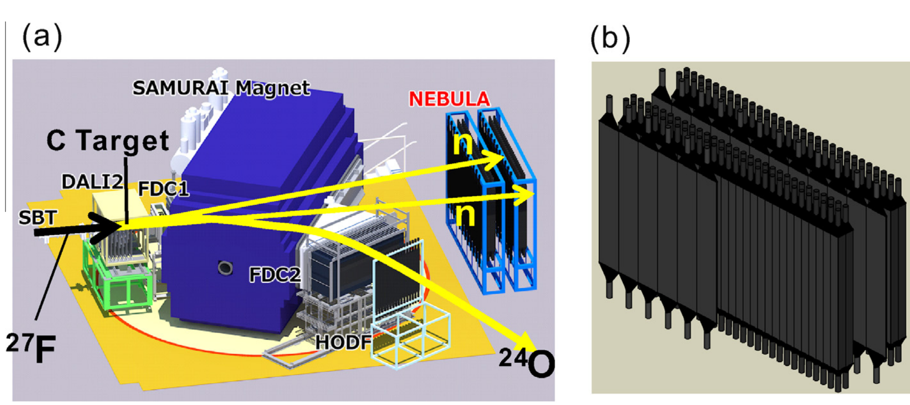

Fig. 1. (a) The SAMURAI setup for the invariant mass spectroscopy of neutron-rich nuclei, as used for the study of the unbound states of ^{26}O[10]. (b) The NEBULA neutron detector array. The first veto layer is partially removed for display purposes.