Direct reaction experiments with fast RI beams for studying properties of exotic nuclei and astrophysical nuclear processes

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One of the first experiments using fast radioactive isotope (RI) beams, which RIKEN started to provide in the early 1990s, was on the Coulomb dissociation of ^{14}O. The experiment was performed with ^{14}O beams and a ^{208}Pb target by a group mainly composed of researchers from Rikkyo University, ISN Grenoble, RIKEN, and University of Tokyo.[1] The ^{13}N(p, γ)^{14}O reaction in the hot CNO cycle was indirectly studied. The Grenoble team brought an array of CsI(Tl) scintillators, which was used together with a position-sensitive silicon detector array and associated electronics developed by the Rikkyo group for detecting outgoing particles in coincidence.

This study has unique properties: it is the first experiment for astrophysical reactions involving short-lived nuclei, the first Coulomb dissociation measurement for explosive nuclear burning, an international collaboration that combines experimental devices developed by respective groups, and a good example of direct reaction studies using fast (87.5 MeV/nucleon in this case) RI beams in inverse kinematics, where the nuclei in the beam are of interest and the target serves as the reaction probe.

The radiative width of the first 1^- state in ^{14}O, the key parameter for evaluating astrophysical reaction rates, was successfully extracted, and it agreed with a direct measurement at the laboratory of Louvain-la-Neuve with slow ^{13}N beams performed in a similar period. These pioneering experiments resolved a long-standing question on the ^{13}N(p, γ)^{14}O astrophysical reaction rate.

Another direct reaction experiment in inverse kinematics was on the neutron-rich $N = 20$ nucleus ^{32}Mg performed at RIKEN in 1994. The reduced transition probability $B(\mathrm{E2}: 0^+ - 2^+_1)$ was successfully determined by Coulomb excitation.[2] Again, the inverse kinematics, where fast radioactive ^{32}Mg beams were incident on a ^{208}Pb target, was employed. The population of the first 2^+ state in ^{32}Mg was identified by measuring its deexcitation γ rays, in contrast to the above-mentioned Coulomb dissociation, in which the particle decay from the unbound 1^- state in ^{14}O was measured by detecting the proton and ^{13}N in coincidence.

The extracted large B(E2) value of 454 ± 78 e^2fm^4 supports the idea of disappearance of the $N = 20$ shell closure in ^{32}Mg. This B(E2) measurement was performed for the first time long after the study determining the low 2^+ energy of 895 keV in the late 1970s.

For this type of experiments, a γ detector array, DALI, was built. It consists of $\approx$60 NaI(Tl) scintillators and has a large efficiency with sensitivity to the γ-ray emission angle, which is indispensable for correcting a large Doppler shift of photons from fast-moving nuclei. To adopt higher-energy beams of RIBF, a new array called DALI2 with $\approx$170 crystals was developed to cope with larger Doppler shifts. DALI and DALI2 have been and are still used in various experiments.[3]

The successes of these studies demonstrated the usefulness of direct reaction with fast RI beams, and triggered extensive studies of the structure of exotic nuclei and astrophysical reactions in explosive burning. They were performed at RIKEN and other facilities such as NSCL-MSU, GANIL, and GSI.

Coulomb dissociation was also applied to the ^{7}Be(p, γ)^{8}B reaction, the major process of producing high-energy neutrinos in the sun. Several experiments provided new independent results free from systematic problems caused by the radioactive ^{7}Be target used in (p, γ) measurements in normal kinematics. These studies contributed to make the ^{7}Be(p, γ)^{8}B reaction rates more reliable and, therefore, to place the discussions of the solar neutrino problem on firmer ground.[4]

In addition to the Coulomb excitation, various direct reactions have been studied. The inelastic scattering of light particles such as proton, deuteron, or α in this energy regime is dominated by the nuclear interaction and have different sensitivities to the final states. For example, for finding the 1^- state in ^{12}Be, the Coulomb excitation and proton inelastic scattering are compared, where the former is more sensitive to the $\ell = 1$ excitation.[5] We also found that the inelastic proton scattering is one of the most efficient probes to observe unknown low-lying levels. Nucleon removal reactions are commonly used, since they populate more states compared with the inelastic scattering.

Many new properties in exotic nuclei were discovered by these direct reactions in inverse kinematics. Recent examples at RIKEN are findings of a "soft" nature of ^{32}Mg by the proton inelastic scattering populating its first 4^+ state[6] and a large $N = 34$ shell gap in ^{54}Ca expected form the location of the 2^+ state populated by nucleon removal reactions.[7]

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