Missing-mass spectroscopy of short-lived nuclei at low-momentum transfer region opened by the MAIKo active target

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Direct reactions with light ions are useful probes to investigate nuclear structures because of the simplicity of reaction mechanisms. In these reactions, measurements at forward angles in the center-of-mass (c.m.) frame are especially important because the experimental results can be less ambiguously analyzed. With the recent technical developments of the new facilities to provide rare isotope (RI) beams, it is now possible to measure the direct reactions of short-lived unstable nuclei and to explore the structures of exotic nuclei far from the β-stability line. Although investigations on such nuclei will allow us to test whether the present knowledge of the nuclear structures established on stable nuclei is valid even in the exotic nuclei, measurements of direct reactions at forward c.m. angles are extremely difficult because they require to detect low-energy ($\sim$1 MeV) recoil particles in missing-mass spectroscopies.

In order to realize the detection of low-energy recoil particles in RI beam experiments, we developed an active target system named MAIKo [1]. MAIKo is based on a time projection chamber (TPC) whose sensitive volume is $100 \times 100 \times 140$ mm^3. In MAIKo, the detection gas is used also as the target gas. In particular, helium gas with a small fraction of quench gas is filled to perform alpha inelastic scattering. Since the scattering occurs inside the sensitive volume of the TPC, the active target enables us to detect low-energy recoil particles.

As the first physics experiment with MAIKo, we performed the measurement of the ^{10}C(α,α') reaction at 68 MeV/u at the RCNP EN beamline [2]. In this experiment, we aimed to examine the magicity of $Z = 6$ in a proton-rich nucleus ^{10}C by deducing the neutron transition matrix element M_n from the ground state to the 2_1^+ state and comparing it with the proton transition matrix element M_p. The $Z = 6$ magicity was recently reported among the neutron-rich carbon isotopes [3].

Figure 1 shows the experimental setup of the measurement. An almost pure ^{10}C secondary beam at 68 MeV/u was produced from the ^{12}C primary beam at 96 MeV/u impinged on the 450-mg/cm^2-thick ^{9}Be target placed at the F0 focal plane. The intensity of the ^{10}C beam was 70 kcps. The alpha elastic and inelastic scatterings were measured with the MAIKo active target installed at the F3 focal plane. The MAIKo TPC was operated with the He(96%)+CO_2(4%) mixture gas at 500 or 1000 hPa. The recoil alpha particles were detected with the MAIKo TPC. High-energy recoil particles which penetrated the TPC were detected with four Si detectors placed outside the TPC.

From the track images obtained with the TPC, the energy and angle of the recoil particles were reconstructed. This information was used to calculate the excitation energy of ^{10}C. The two dimensional scatter plot of kinetic energy versus angle of the recoil alpha particles is given in Fig. 2. Owing to the active target technique, the detection threshold for the recoil alpha particles was successfully lowered down to 0.5 MeV. The excitation energy spectrum at $6.9° < \theta_{\mathrm{c.m.}} < 7.2°$ obtained from the measurement at 1000 hPa gas pressure is given in Fig. 3. The yield of the ground state (blue line) and the 2_1^+ state at $E_x = 3.35$ MeV (green line) were determined by fitting the spectrum with the sum of two Gaussians (red line). The detection and track reconstruction efficiency in the present measurement was determined from a Monte Carlo simulation. Figure 4 shows the obtained differential cross sections of the ^{10}C+α scattering. The solid circles and the open squares represent the elastic scattering and the inelastic scattering to the 2_1^+ state, respectively.

The phenomenological α–N effective interaction and the point-nucleon density distribution in the ^{10}C ground state were determined so that the optical-model calculation (solid line in Fig. 4) reproduced the experimental data of the elastic scattering. We calculated the differential cross section of the inelastic scattering with a distorted-wave Born-approximation (DWBA). In this calculation, the transition potential was obtained by folding the obtained α–N effective interaction with the macroscopic transition density [4]. By comparing the measured inelastic scattering cross section with the DWBA calculation (dashed line in Fig. 4), the neutron

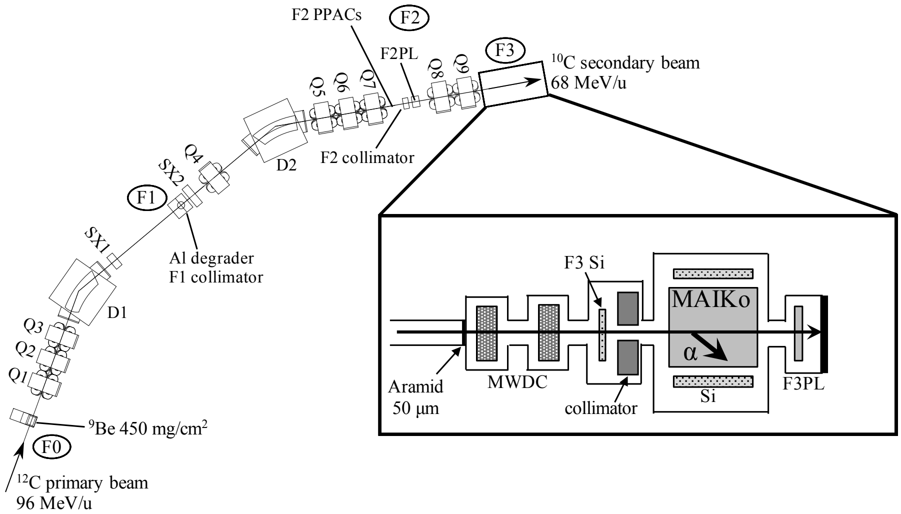

Figure 1: Experimental setup of the ^{10}C(α, α') measurement at the EN beamline.

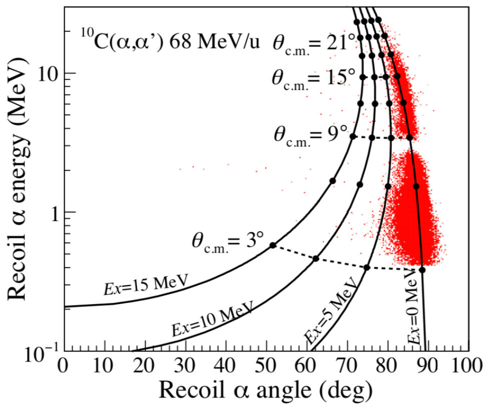

Figure 2: Scatter plot of kinetic energy versus angle of the recoil alpha particles.

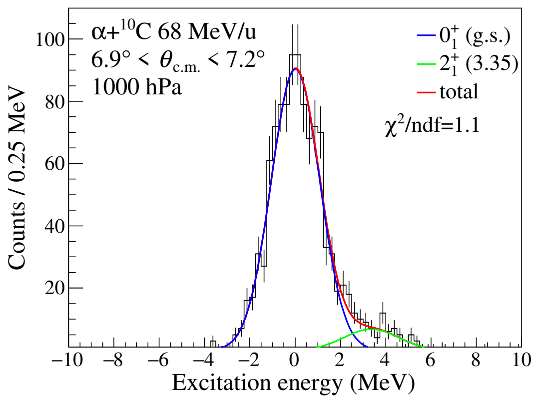

Figure 3: Excitation energy spectrum of ^{10}C.

transition matrix element from the ground state to the 2^+_1 state in ^{10}C was deduced as $M_n = 6.9 \pm 0.7(\text{fit}) \pm 1.2(\text{sys})$ fm^2.

The obtained M_n value in ^{10}C is close to the M_p value in ^{10}Be of 6.78 ± 0.11 fm^2 [5]. This shows that the charge symmetry in the $A = 10$ system is almost conserved. By combining the M_p value in ^{10}C [6], we obtained the ratio of the neutron and proton transition matrix elements in ^{10}C as $M_n/M_p = 1.05 \pm 0.11(\text{fit}) \pm 0.17(\text{sys})$. This ratio is close to unity whereas a large M_n/M_p ratio of 3.2 ± 0.7 was reported in neutron-rich ^{16}C [7]. This result indicates that the $Z = 6$ shell closure is less evident in ^{10}C compared to the neutron-rich carbon isotopes.

After the long-standing challenge to develop a new active target system in RCNP since 2011, the first RI beam experiment has been successfully completed. We are going to launch a new project to upgrade MAIKo from FY2020. In this project, the MAIKo TPC will be enlarged from $100 \times 100 \times 140$ mm^3 to $300 \times 300 \times 200$ mm^3 to achieve 10 times higher statistics and explore more proton/neutron-rich nuclei. The upgraded detector will be used in many incoming RI beam experiments at RCNP and RIBF in the near future.

For details of the present work, the readers are referred to Refs. [1, 8, 9].

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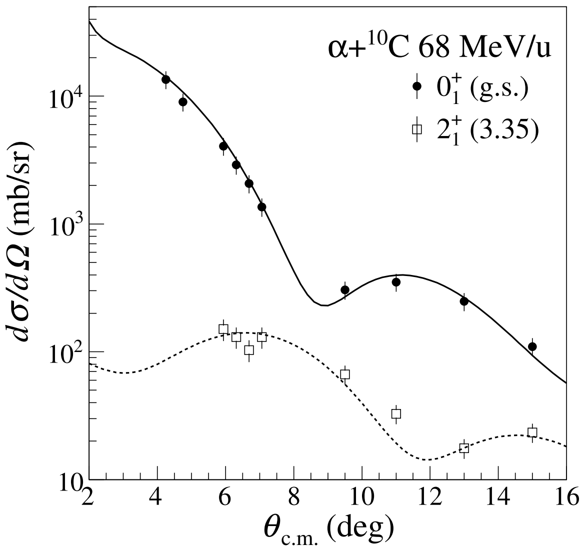

Figure 4: Differential cross sections of the ^{10}C+α elastic (solid circles) and inelastic scattering to the 2_1^+ state (open squares). The solid line and dashed line represent the optical model and DWBA calculations, respectively.

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