Feasibility study of pionic atom spectroscopy with the (p,^{2}He) reaction

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Spectroscopic studies of deeply bound pionic atoms provide information on partial restoration of chiral symmetry in medium [1]. The experimental research with the (d,^{3}He) reaction is in progress at RIBF. Historically, the (p,^{2}He) reaction was used to search deeply bound pionic states at RCNP by Matsuoka et al.[2] The result of this experiment suggests that pionic atoms can be formed in this reaction. However, the binding energy could not be determined due to insufficient resolution. We plan to investigate the same reaction with an improved resolution.

Spectroscopy of pionic atoms using the (p,^{2}He) reaction will be improved in the following way. In order to improve the resolution, Grand Raiden will be used for momentum analysis of two protons instead of LAS, which was used in the previous experiment. In addition, we will adopt the GRAF mode, by which much more intense beam ($\sim$30 nA) can be delivered. It will compensate the reduction of the acceptance. In the previous experiment, an incident beam was extracted from the side port of dipole magnet of LAS and was dumped at the beam dump located near the focal plane detectors. The beam intensity was limited to about 1.0 nA or less because of the instrumental background. In the GRAF mode, an incident beam is transported to a beam dump at the wall, which is far from the focal plane detectors, and an intense beam will not cause background even in a forward angle measurement.

In order to confirm the feasibility of the upgraded measurement with Grand Raiden, we performed a test experiment (E451) in November 2015 and April 2016. The main purposes are the transportation of an intense beam through the GRAF beamline at the Bρ ratio (the magnetic rigidity of Grand Raiden divided by that of the beamline) of 0.53 for the (p,^{2}He) observation, and the measurement of two correlated protons with Grand Raiden. We succeeded in transporting 30 nA beam with the transmission rate more than 90%. For the ^{2}He measurement, the ^{12}C(p,^{2}He)^{11}B reaction was employed. A CH_2 target was irradiated with 30 nA beam, and two protons were momentum-analyzed by Grand Raiden. We observed narrow peaks due to the transition to the ground state and the excited states of ^{11}B in a 20-minute measurement (Fig. 1). The resolution in this spectrum was 420 keV (FWHM), in which the contribution from the thickness of the target (50 mg/cm^2) was estimated to be about 320 keV. Thereby, we confirmed that a sufficient resolution will be achieved when a thin target is used.

The background rate was also evaluated in the test experiment. The main background is an accidental coincidence event such that the (p,p') reaction takes places twice in a single bunch. For this purpose, 392 MeV proton beam impinged on a ^{120}Sn target, and protons with their momentum around 500 MeV/c was measured. The double differential cross section of the ^{120}Sn(p,p') reaction was 1.5 mb/sr/MeV, and it follows that the effective double differential cross section, with the two (p,p') reactions in a bunch regarded as a single (p,^{2}He) reaction, will be 6 μb/sr/MeV. It should be noted that the cross section of a continuum background without π production is approximately 2 μb/sr/MeV, by interpolating those for ^{12}C and ^{208}Pb targets [2], and that their strength are of the same order of magnitude. The background due to accidental coincidence can be subtracted by the event mixing technique [3].

In the (p,^{2}He) measurement, a calibration measurement for the determination of the beam energy is needed. We utilize beam-energy dependence of the momentum of an ejectile particles. By measuring the ejectile for several reactions, the beam energy can be deduced from the ratio of the momenta of the ejectile for two different reactions. Furthermore, the fluctuation of the beam energy has to be continuously monitored during the production run, since there is no reference peak within the acceptance of Grand Raiden. For this purpose, the π^+ from the H(p,π^+)d reaction will be momentum-analyzed by the LAS spectrometer simultaneously.

In the test experiment, we also investigated these calibration methods. For the determination of the beam energy, we measured candidate reactions such as p(p,d)π^+, ^{12}C(p,p). The optimization of the calibration scheme is under way. We also studied the H(p,π^+)d reaction with a CH_2 target. The yield was consistent with the expectation from the known differential cross section, and the energy resolution of π^+ was 570 keV (FWHM). Therefore, we decided to use this reaction for the beam energy monitor.

Moreover, aiming at reduction of the accidental coincidence background, we also performed an ion-optics study, mainly paying attention to the y direction. The y position of the reaction vertex is reconstructed by using optical properties. A large fraction of uncorrelated proton pairs are expected to be removed in the offline analysis, by looking into the correlation of the y coordinates, which should coincide with each other for ^{2}He. In order to relate the coordinates (x, y, θ, ϕ) at the target and those at the focal plane, we utilized elastic scattering at a horizontally stretched gold wire target with the sieve slit. We examined the ion-optics in two cases: with and without the sextupole (SX). The resolution of the reconstructed y position is 200 μm (FWHM) with SX and it was found that the rejection of the uncorrelated event to be effective. However, the aberration due to the angle is too large without SX, hence this method is not practical in the GRAF mode with SX removed from the spectrometer.

Based on the outcome of the test experiment, we proposed an experiment for the production run. We use a 30 mg/cm^2 ^{124}Sn as the target, which has the largest neutron number among the stable Sn isotopes so that the cross section of pionic atom formation will be large. The target will be coated with a thin CH_2 foil for the calibration measurement. As in the test experiment, we will use 30 nA beam in the GRAF mode. The experiment (E483) has been approved with 12.4-day beamtime.

The preparation for E483 is in progress. After the spectroscopy with Grand Raiden is established in the E483 experiment, we will start systematic studies with other nuclides, including xenon isotopes.

References

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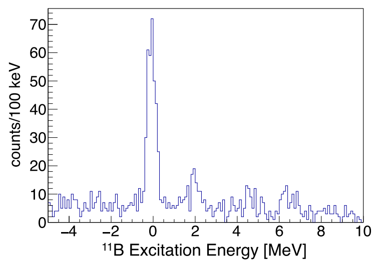

Figure 1: ^{11}B excitation energy spectrum in the ^{12}C(p,^{2}He)^{11}B reaction.