(p,2p) Reactions on Carbon Isotopes: $p(^{9-16}C,2p)\,^{8-15}B$ at 250AMeV

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Abstract. Proton knockout reactions on carbon isotopes, $p(^{9-16}C,2p)8\text{-}^{15}B$, at 250MeV/A were performed for systematic information on weakly to strongly bound 1p valence protons and deeply bound 1s protons. Various information such as energy gap between 1s and 1p orbits, widths of momentum distributions for 1s and 1p orbits, relative (p,2p) yields are obtained.

Keywords: knockout reaction, single-particle property, momentum distribution.
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INTRODUCTION

Proton knockout reaction, (p,2p), in the inverse kinematics is one of the experimental methods to study the single-particle properties of bound protons [1] in unstable nuclei. Bound proton in the beam is knocked out by quasifree proton-proton scattering, and the hole state is produced. By measuring four-momenta of two protons in the final state, momentum distribution, angular momentum, and separation energy are deduced. Measurement in the inverse kinematics provides additional information. Since hole state is produced in the beam velocity, decay mode of the hole states are measured with high efficiency by detecting particles in the forward direction.

Carbon isotopes, ^{9}C to ^{16}C, are selected as targets. By going from proton-rich side to neutron-rich side, neutron separation energy of valence orbit comes down from 20 MeV to 1 MeV, while proton separation energy (S_p) of the valence orbit ($p_{3/2}$) goes up from 1.3 MeV for ^{9}C to 22.6 MeV for ^{16}C. Protons in core orbit ($s_{1/2}$) are very strongly bound from about 20 MeV to 50 MeV. Therefore (p,2p) reactions on carbon isotopes provide a chance to study the variation of proton single-particle orbits, from weakly bound orbit to strongly bound orbit for $1p_{3/2}$, and very strongly bound orbits for $1s_{1/2}$.

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EXPERIMENT

Measurements were performed at HIMAC (Heavy Ion Medical Accelerator in Chiba) accelerator facility in NIRS (National Institute of Radiological Sciences). ^{12}C and ^{18}O beams accelerated up to 350-400 MeV/A by the synchrotron were used to produce secondary carbon isotope beams at 250MeV/A. Using the secondary beam line (SB2), carbon isotopes are separated and momentum tagged. Beam intensity was 10^4 to 10^5 particles/spill, depending on isotopes. Experimental setup at F3 is shown in Fig. 1. Detector system consists of beam detectors, solid hydrogen target of 5mm thickness, two-arm proton telescopes, and forward magnetic spectrometer. Solid hydrogen target was essential to avoid background and to reduce multiple Coulomb scattering. Proton telescopes are set at 39 degrees to detect protons up to 210 MeV. Forward particles are measured and identified by a combination of magnetic analysis, charge measurement, and TOF measurement.

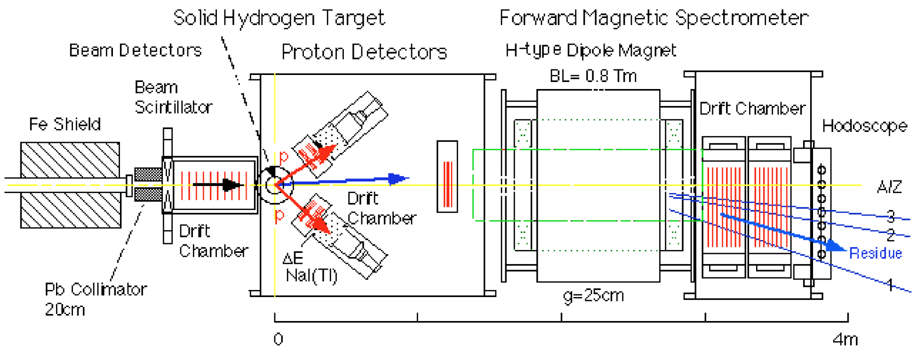

FIGURE 1. Experimental Setup at F3.

Results

Proton separation energy (S_p) distributions are obtained from four momenta of two protons. The spectra consist of sharp peak corresponding to p-hole states and broad bump corresponding to s-hole states. Transitions to Boron ground state are selected by requiring mass-identified Boron isotopes, $^{A-1}$B, detected in the forward direction and setting appropriate gate on S_p spectra. The separation-energy resolution is about 1.3 MeV rms in the present measurement, mainly limited by the angular resolution of the detector system. Transitions to s-hole states are selected by tagging no Boron isotopes in the forward direction and set gate above proton emission threshold on S_p spectra. The latter selection requires that hole states decay by charged-particle emission. Results are shown in Fig. 2. Separation energy distribution for ^{12}C is consistent with that obtained by (p,2p) reactions on ^{12}C using 400MeV proton beams [2].

From present measurement, s-hole states in carbon isotopes are systematically observed. After correcting for the acceptance, S_p distributions are fitted by the functional form, and the peak value and the width of the s-hole states are obtained.

Energy gap between 1p and 1s orbits is shown in Fig. 3. Gap energy has a minimum at around A=12 and becomes wider on both proton-rich and neutron-rich sides. Attractive force between $\nu 1p_{1/2}$ and $\pi 1p_{3/2}$ may explain the increase from ^{12}C to neutron-rich side. Since the identification of s-hole states in ^{9}C has some ambiguities at the moment, and the data for ^{9}C is tentative.

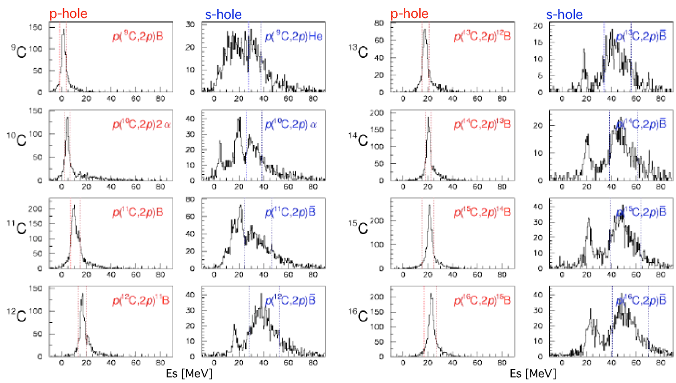

FIGURE 2. Separation-energy distributions for p-hole states (left) and s-hole states (right).

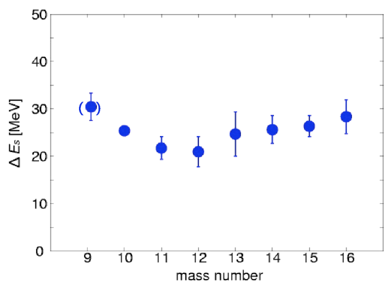

FIGURE 3. Energy gap between 1s and 1p orbits in carbon isotopes.

Momentum distributions of bound protons in 1s and 1p orbit are obtained by setting appropriate gates on S_p spectra as shown in Fig. 2. Effects of finite geometrical acceptance are corrected for by selecting regions in the momentum space. Two kinds of momentum distributions, $d\sigma/dq$ and $d\sigma/dq_z$, are obtained after correcting for the acceptance, and fitted by using the functional form, $d^3\sigma/d\vec{q}^3 \propto q^{2l} \exp\left(-q^2/\sigma_l^2\right)$ for l=0 and 1, assuming Harmonic-oscillator-type wave functions, where z and l are beam direction and angular momentum, respectively. Angular momentum l can be uniquely identified, except few cases, by comparing reduced χ^2 of the fitting. Although momentum widths of s-hole states for ^{13}C to ^{15}C can not be deduced from $d\sigma/dq$ distribution due to statistics, momentum widths for other cases are consistent with each other from two methods. The widths σ_l are summarized in Fig. 4. The momentum widths for ^{12}C are consistent with those obtained by $^{12}C(e,e'p)$ reactions [3].

Momentum width of p-orbit increases monotonically from proton-rich to neutron-rich side, reflecting weak binding nature of valence protons in the proton-rich side. Momentum width of s-orbit is rather constant below A=12, and starts to increase above A=12. Simple potential model after adjusting the proton separation energy qualitatively reproduces the tendency of momentum widths of p-orbits. On the other hand, the same model gives constant momentum width, independent of the separation energy, for s-orbits, contradicting with the experimental widths.

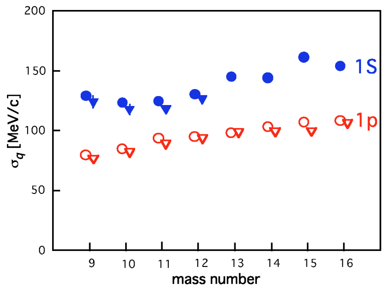

FIGURE 4. Momentum width σ_l (Harmonic oscillator-type) of p-orbits (open) and s-orbits (closed). Triangles are obtained from $d\sigma/dq$ distributions, and circles from $d\sigma/dq_z$ distributions.

From the momentum widths of s-orbit, root mean square charge radius of 1s protons in the carbon isotopes can be deduced, by assuming Harmonic oscillator-type wave function. The charge radius decreases from 2.0 fm in the proton-rich side to 1.5 fm in the neutron-rich side. The present observation indicates that the proton radius of the core is shrinking towards neutron-rich side.

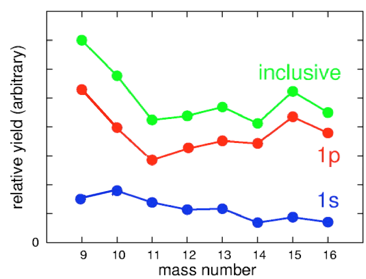

FIGURE 5. Relative (p,2p) yield .

Relative (p,2p) yields are obtained after the acceptance correction. The results are summarized in Fig. 5. Total yield is rather constant between ^{11}C and ^{16}C, and the yield is about 50% larger for ^{9}C. When yields are divided into p orbit and s orbit contributions, it is the p orbit contribution, which is increasing at ^{9}C. Since the yield is expected to be proportional to the spectroscopic factor, present observation also indicates that the spectroscopic factor for the weakly bound valence proton is larger, as in the case of knockout reactions [4]. There is a tendency that the yield for s-orbits are decreasing towards neutron-rich side. Since very-strongly bound s orbit is involved, it is not clear that the reason for the reduction is due to the variation of the spectroscopic factor of deeply bound protons or due to the reaction mechanism.

Summary

Proton knockout (p,2p) reactions from $^{9\text{-}16}$C isotopes at 250 MeV/ were performed for systematic information on weakly to strongly bound 1p protons and deeply bound 1s protons. Separation-energy distributions are measured with 1.3 MeV (rms) resolutions. S and p hole states are identified and separated by tagging the decay mode of the hole states. Energy gap between 1s and 1p orbits are rather constant at about 20 MeV, and tends to become wider on both proton and neutron-rich sides. Momentum distribution widths for 1p valence orbit are roughly consistent with simple calculations. On the other hand, momentum distribution widths of 1s protons show increase toward neutron-rich side, indicating that the charge radii of 1s protons are shrinking towards the neutron-rich side. Relative (p,2p) yields indicate weakly-bund valence proton in ^{9}C have larger spectroscopic factors compared with the valence protons in other carbon isotopes.

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