Discovery of Z=6 magic number in $^{13-20}$C and new evidence on tensor-force effect in ^{16}O

H. J. Ong[1], S. Terashima[2], D. T. Tran[1], L. Yu[2], I. Tanihata[1,2], N. Aoi[1] for RCNP-E372 and RCNP-E443 Collaborations

[1] *Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan*

[2] *School of Physics and Nuclear Energy Engineering, Beihang University, Beijing, 100191, China*

We report on results from two experimental studies on the structure of neutron-rich carbon isotopes and the stable ^{16}O nucleus. In the first experiment, we measured the charge-changing cross section (CCCS) of $^{12-18}$C on a natural carbon ($^{\mathrm{nat}}$C) target, and determined their point-proton distribution radii (denoted as "proton radii" hereinafter). From systematic analyses on the proton radii, electromagnetic transition rates and atomic masses of these carbon isotopes as well as the neighboring nuclei, we found clear evidence for a prevalent magic number (subshell closure) at proton number Z=6 in $^{13-20}$C. In the second experiment, we bombarded an ice target with a proton beam, and measured simultaneously a deuteron and a recoiled proton produced in a proton-induced neutron-pickup (p,dp) reaction. We observed, for the first time, a strong isospin dependence of the cross sections populating several low-lying states in ^{14}N. The results, in particular the overwhelmingly strong population of isospin T=0 states as opposed to a T=1 state in ^{14}N, indicate dominant tensor-force correlation in the removed proton-neutron pair in the ^{16}O nucleus. The results were published in Nature Communications [1] and Physical Review Letters [2], respectively.

The experiments were performed at the extended exotic nuclei (EN) beam line and at the West-South (WS) beam line using the the GRAF (Grand-RAiden Forward mode) beam line, respectively. It is worth noting that both the GRAF and the extended EN beam lines were completed as recent as in 2014, and these two experiments were some of the earliest experiments performed at the beam lines. In the following, we describe both studies in more detail.

1 CCCS measurement and discovery of a prevalent Z=6 magic number in $^{13-20}$C

The charge or proton radii of nuclei are important observables not only for understanding nuclear structure, but also for extracting information relevant to the equation of state (EOS) of asymmetric nuclear matter. Although experiments using electromagnetic probes such as the electron scattering, x-ray spectroscopy of muonic atoms, and optical and K_α x-ray isotope-shift (IS) have been successfully applied to determine the charge radii of stable as well as scores of unstable nuclei, it is extremely challenging to apply the IS method to nuclei within $10> Z >4$ due mainly to insufficient precision in the atomic physics calculations and difficulty of production of low-energy isotopes. To determine proton radii of neutron-rich boron and carbon isotopes, we have measured the charge-changing cross sections of $^{10-15}$B and $^{12-18}$C using secondary beams at around 50 MeV/nucleon.

The experiment was performed at the EN beam line using the radioactive isotope (RI) beams produced in separate runs by projectile-fragmentation reactions of a 80-MeV/nucleon ^{22}Ne on a ^{9}Be target. Thanks to the newly constructed third focal plane, up to six times better purity was achieved for most of the radioactive beams. The RI beam was identified and counted using a plastic scintillator and two tracking detectors, before being incident on a 450-mg/cm^2-thick natural carbon target. We measured the CCCS employing the transmission method. In this method, we detected and counted the Z-unchanged particles after the target. The outgoing particles were detected and identified using an ionization chamber and a 7-cm-thick NaI(Tl) scintillator.

To extract proton radii from the measured CCCS's, we formulated an extended Glauber model within the finite-range optical limit approximation, taking into account energy dependence of the range parameter [3]. Assuming harmonic-oscillator type density distributions, we applied our Glauber model and determined the range parameters of the proton density distributions so as to reproduce the experimental CCCS's for $^{12-18}$C measured at RCNP as well as the CCCS's for $^{12-19}$C from Ref. [4]. The density distributions were later used to determine the proton radii for $^{12-19}$C. The proton radii for $^{12-16}$C thus extracted are consistent with the literature. Comparing the isotopic dependence of proton radii, we found that the proton radii for $^{12-19}$C are almost constant, which indicates an inert proton core in these isotopes (see Fig. 1(a)). Further systematic analyses of the proton radii, electric quadrupole transition rates and atomic masses along various isotonic chains revealed a prevalent Z=6 magic number (Fig.1(b)) in $^{13-20}$C. For details, see Ref.[1].

2 Observation of tensor-force effect in ^{16}O via high-momentum neutron pickup reaction

The tensor force, which is one of the components of the nuclear forces acting between two nucleons, plays important roles in atomic nuclei as well as in neutron stars. The tensor forces are essential to reproduce/explain

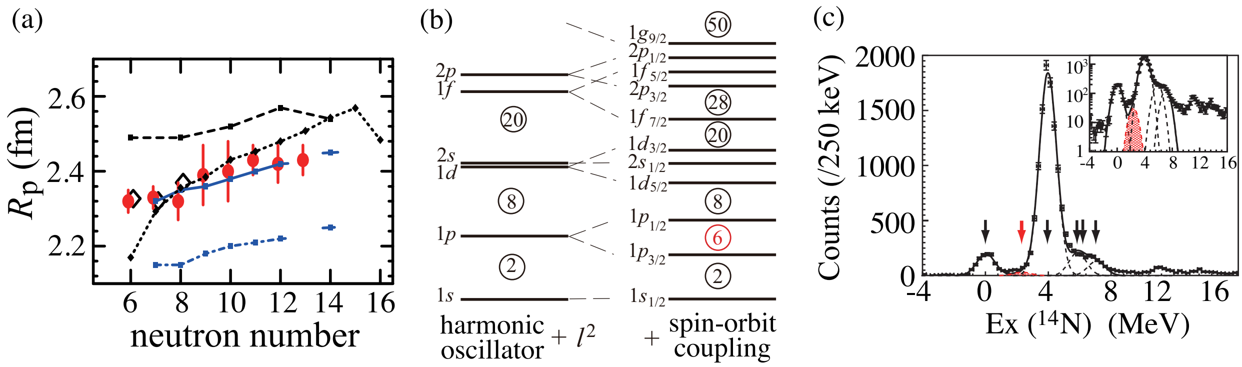

Figure 1: (a) Extracted proton radii of $^{12-19}$C in comparison with several theoretical calculations. For details, see Ref.[1]. (b) Schematic drawing of single-particle orbitals of nuclei without (left) and with (right) spin-orbit coupling force. The latter nuclear-force component gives rise to $Z = 6$ magic number. (c) Reconstructed excitation energy spectrum of ^{14}N. The arrows show known states; the black (red) bumps correspond to the states with isospin $T = 0$ (1). See Ref.[2] for details.

the binding energies of deuteron and the alpha particle, and the non-zero quadrupole moment of deuteron. In heavier nuclei, while the tensor force has been suggested to account for the evolution of magic numbers in light neutron-rich nuclei [5], no direct experimental evidence has been reported. To search for a direct evidence of the effect of the tensor forces in nuclei heavier than ^{4}He, we performed ^{16}O(p,d) reaction at relatively high-momentum transfers, and found a marked enhancement of the ratio for the positive-parity state. The results indicate the existence of large components of high-momentum neutrons in the ground-state configurations of ^{16}O due possibly to the tensor force [6]. To examine whether or not, at high-momentum transfer, the neutron is predominantly picked up from a neutron-proton pair, we measured simultaneously scattered deuterons at forward angles and the recoiled protons at backward angles in the ^{16}O(p,dp) reaction where the neutron pickup reaction mechanism is dominant.

The experiment was performed at the WS-GRAF beam line. A 392-MeV proton beam was directed onto a 56-mg/cm^2-thick ice target [7]. The scattered deuteron particles were momentum analyzed and transported to the focal plane of the high-resolution Grand Raiden (GR) spectrometer [8], where they were detected by two drift chambers and two 10-cm-thick plastic scintillators. The recoiled protons were detected by two 3-mm-thick (ΔE) plastic scintillators and four horizontally segmented 60-mm-thick (E) and 240×60-mm^2 plastic scintillator blocks. The excitation energy spectra for the ^{16}O(p,dp)^{14}N* reaction were reconstructed using the information of the proton beam energy, the scattering angles and measured momenta of the deuterons and recoiled protons. We found a strong population of the 3.95-MeV excited state with $J,T = 1,\ 0$, and a markedly weak population of the 2.31-MeV excited state with $J,T = 0,\ 1$ in ^{14}N (see Fig.1(c)). Comparing with data from an earlier work [9] at 75-MeV proton energy and with a kinematical setting that favors knockout reaction, we found marked reduction in the $J,T = 0,\ 1$ to $J,\ T = 1,\ 0$ ratio of the cross sections at 392-MeV proton energy. The strong isospin dependence suggests dominant tensor correlations in the neutron-proton pairs observed in the neutron pickup reaction. For details, see Ref. [2].

References

[1] D. T. Tran, H. J. Ong, G. Hagen *et al.*, Nature Comm. **9**, 1594 (2018). See also `http://resou.osaka-u.ac.jp/en/research/2018/20180423_1`.

[2] S. Terashima, L. Yu, H. J. Ong *et al.*, Phys. Rev. Lett. **121**, 242501 (2018). See also `https://resou.osaka-u.ac.jp/en/research/2018/20181227_1`.

[3] D. T. Tran, H. J. Ong, I. Tanihata *et al.*, Phys. Rev. C **94**, 064604 (2016).

[4] R. Kanungo *et al.*, Phys. Rev. Lett. **117**, 102501 (2016).

[5] A. Ozawa *et al.*, Phys. Rev. Lett. **84**, 5493 (2000); T. Otsuka *et al.*, Phys. Rev. Lett. **95**, 232502 (2005).

[6] H. J. Ong, I. Tanihata, A. Tamii *et al.*, Phys. Lett. **B725**, 277 (2013).

[7] T. Kawabata *et al.*, Nucl. Instru. Meth. A **459**, 171 (2001).

[8] M. Fujiwara *et al.*, Nucl. Instru. Meth. A **422**, 484 (1999).

[9] J. Y. Grossiord *et al.*, Phys. Rev. C **15**, 843 (1977).