Possible Proton Halo and Skin in Light Proton-Rich Nucleus

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Measurements of reaction cross section (σ_R) for some proton-rich nuclei ($N = 8$, 10, 12 isotones) on carbon target at intermediate energies have been performed on RIBLL of HIRFL by a transmission method. The experimental σ_R values for ^{23}Al and ^{27}P are abnormally large compared with its neighboring nuclei and that of ^{17}F has an enhancement compared with neighboring isotopes. The calculation of relativistic density-dependent Hartree (RDDH) approach shows there is proton-halo structure in ^{23}Al and ^{27}P and there is a proton-skin in ^{17}F. The significance of these measurements was discussed.

§1. Introduction

Since the pioneering work at LBL,[1)] the radioactive ion beam physics has become one of frontiers in nuclear physics. The structure of exotic neutron-rich or proton-rich nuclei has been studied through measurements of σ_R, fragment momentum distribution of fragmentation reaction, etc. The neutron skin or halo in nuclei ^{6}He, ^{8}He, ^{11}Li, ^{11}Be, ^{14}Be, ^{19}C, etc.,[1)–5)] has been reported by these experimental methods. Meanwhile, the study of exotic nuclear structure extends from neutron-rich region to proton-rich region. But it is a little difficult to form a proton halo or skin because of the Coulomb barriers. The momentum distribution and σ_R for ^{8}B indicate a proton halo in it,[6),7)] whereas other σ_R measurements at relativistic energies around GeV/u are not in favor of this conclusion.[8)] For the proton halo candidate ^{17}F, no anomalous increase is shown in the experimental σ_R[9)] though a very clear signature of the proton halo in the first excited state of ^{17}F has been demonstrated in the capture cross section measurement of reaction ^{16}O(p,γ) ^{20}F.[10)] So far, the heaviest well-established halo nucleus is ^{19}C.[4),5)] However, the proton halo in ^{26,27,28}P and ^{27,28,29}S has been proposed within the framework of shell-model and relativistic mean-field (RMF) calculations.[11),12)] The experimental search for heavy halo nuclei plays a significant role for the investigation of nuclear structure. Recently the measurement of the momentum distribution shows a proton halo character in the ground states of ^{26,27,28}P.[13)] Motivated by a search for proton halo or

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skin nuclei, we report here the experimental measurement of the σ_R for ($N = 8$, 10, 12 isotones) close to the proton drip-line in this paper.

§2. Experiment method and results

The σ_R is measured by a transmission method with a Si detector telescope. The experiment was performed at the Radioactive Ion Beam Line in Lanzhou (RIBLL) using beams of 69MeV/u ^{36}Ar which were delivered by the Heavy Ion Research Facility in Lanzhou (HIRFL). The isotopes were produced in a production target of Ni (92.3 mg/cm^2) and separated by means of magnetic rigidity (B_ρ) and energy degrader in the doubly achromatic secondary beam line as described in Ref. 7). The optical settings for selecting proton-rich isotones were used. The selected isotopes were further identified by the time of flight (TOF) that was measured by two scintillator detectors installed at the first and second achromatic focal planes with a flight path of 16.8 m and energy loss (ΔE) in a transmission Si surface barrier detector before incidence on a reaction target of C (109.7 mg/cm^2). Behind the reaction target a telescope was installed, which consisted of five transmission Si surface barrier detectors and gave the ΔE and total energy of the reaction products. The thickness of the six Si detectors were 150, 150, 150, 700, 700 and 2000 μm respectively and the energy resolutions were not greater than 1.8 %. In order to derive the experimental σ_R, the energy-deposition spectrum after the reaction target is used. The detailed description is given in Refs. 14) and 15). The energy for the obtained σ_R corresponds to the incident ion's energy in the middle of the carbon target. The errors of σ_R refer to the statistical error plus the estimated ± 4 % systematic error.

For consistent comparison, all the obtained σ_R are converted to the same energy 30 MeV/u using the parameterized formula.[16)] The radius parameter in this formula is fitted to the original σ_R and then the corresponding σ_R at 30 MeV/u is calculated with the fitted parameter. For neutron-rich nuclei, the isospin dependences of σ_R for nuclei with the same atomic number are often used. However, the isospin dependences of σ_R for nuclei with the same neutron number should be better to search for proton halo nuclei. The σ_R of ^{17}F, ^{23}Al and ^{27}P are abnormally larger than their neighboring nuclei and these suggest that there may exist skin or halo structure. Usually σ_R increases smoothly with A for an isotope series because σ_R is proportion to the square of the matter rms radius. This contrary trend is an indication of the appearance of proton skin or halo in these proton-rich nuclei.

In order to quantitatively analyse the possibility of exotic structure in ^{17}F, ^{23}Al and ^{27}P from the measured σ_R, a difference factor (d) is used. If the d for one nucleus is evidently larger than that of its neighboring nucleus, it may appear nucleon halo or nucleon skin in this nucleus. Ozawa et al. had successfully applied the d to analyse the structure of exotic nuclei in neutron-rich nuclei. Here we also use the d to judge whether the ^{17}F, ^{23}Al and ^{27}P have an exotic structure by comparing the d of their neighboring nuclei. Figure 1 shows the (N-Z) dependences for the d (left) and σ_R (right) for $N = 8$, 10, 12 isotones. The experimental σ_R of different nuclei at different energies are converted into the same energy 30 MeV/u by using Shen's formula.[16)] We draw the (N-Z) dependence of the σ_R also in Fig. 1 (right).

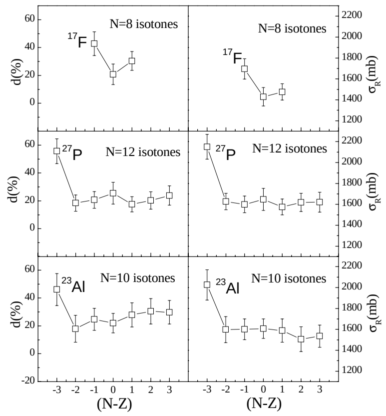

Fig. 1. The (N-Z) dependences for the d and σ_R for $N = 8$, 10, 12 isotones from the present experiment at 30 MeV/u.

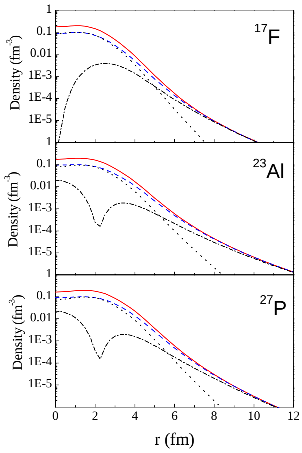

Fig. 2. Density distribution of proton, neutron, matter and the last proton in ^{17}F, ^{23}Al and ^{27}P in the RDDH model. Solid, dashed, dotted and dot-dashed curves represent the density distributions for matter, proton, neutron and the last proton, respectively.

The parameter of Glauber model obtained by fitting high energies experimental σ_R is used in calculation in order to obtain the σ_R(Gl) at 30 MeV/u. It can be seen from Fig. 1 (left) that there is a typical underestimation of 10~30 % for almost all the nuclei. For the ^{17}F, ^{23}Al and ^{27}P, they show a large d compared with neighboring nuclei. The σ_R of ^{17}F, ^{23}Al and ^{27}P have the same trend with the d. This is an evidence that ^{23}Al and ^{27}P may have proton halo structure and ^{17}F may have proton skin structure. In order to obtain more information about the nuclei of ^{17}F, ^{23}Al and ^{27}P and the possible reason for appearance of exotic structure, the RDDH model is adopted in calculation. The first excitation state of ^{17}F has a proton halo structure [17)] and the last proton occupies in $2S_{1/2}$ level, the RMS radii of proton, neutron and matter are obtained with RDDH calculation where the last proton separation energy is adjusted to the experimental value. RMS radii of the proton, neutron and halo proton are 2.86, 2.54 and 4.46 fm, respectively. It is almost consistent with Ref. 17). For ground state of ^{17}F and with the same parameter in RDDH calculation, the last proton separation energy in ^{17}F is S_p=0.525 MeV and it occupies $1d_{3/2}$ level. Because of small separation energy and an enhancement of experimental σ_R but little bit high angular momentum for level of last proton, the ^{17}F in the ground state may have a proton skin structure. The density distribution of the ground state of ^{17}F drawn in Fig. 2 shows the proton skin structure in it. It should be mentioned that normal shell model calculation shows that last proton in ^{23}Al occupies $1d_{5/2}$ level. With such occupation, we will obtain density distribution without proton halo, but it will underestimate σ_R compared with experimental σ_R. Assumption of level inversion for last proton is needed to fit the experimental σ_R. Therefore, we assume the last proton of ^{23}Al occupies the spherical levels $2S_{1/2}$ and obtains the matter density distribution of ^{23}Al. The result of density distribution is also drawn in Fig. 2 where the proton separation energy is adjusted to the experimental value S_p=0.125 MeV. At the same time, a large enhancement of experimental σ_R exists in ^{23}Al compared with the neighboring isotones. So, the ^{23}Al may show the proton halo structure. Finally, we investigate whether there have an exotic structure in ^{27}P. Normal shell model calculation shows the last proton in ^{27}P fills the spherical levels $2S_{1/2}$. The density distribution of ^{27}P is drawn in Fig. 2 where the separation energy of the last proton is adjusted to the experimental value S_p=0.9 MeV. The proton density distribution in ^{27}P is larger than neutron density distribution. With such density distribution, we can fit our experimental σ_R. So, we can see clearly that the last proton in ^{17}F, ^{23}Al and ^{27}P plays a great role in density distribution and leads to exotic structure. From above results, we can know that ^{23}Al and ^{27}P may have a proton halo structure and ^{17}F may have a proton skin structure. It should be mentioned that above theoretical calculation is a simple spherical RDDH calculation. The real situation in halo nuclei may be much more complex. For example, ^{22}Mg is large deformed and its quadrupole deformation is β_2=0.56.[18] Therefore, a detailed study is needed.

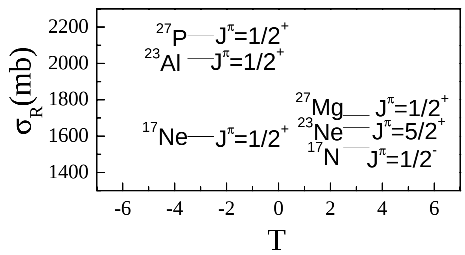

Fig. 3. The experimental σ_R for three pairs of mirror nucleus: ^{17}Ne(J$^\pi$=1/2$^+$) and ^{17}N(J$^\pi$=1/2$^-$); ^{23}Al(J$^\pi$=1/2$^+$) and ^{23}Ne (J$^\pi$=5/2$^+$); ^{27}P(J$^\pi$=1/2$^+$) and ^{27}Mg (J$^\pi$=1/2$^+$).

As we know, mirror nuclei show normally the same nuclear size for ordinary nuclei and their σ_R should be more or less same. Concerning the discussion on the proton halo ^{23}Al and ^{27}P, it is interesting to compare the experimental σ_R with that in its mirror nucleus ^{23}Ne and ^{27}Mg. By using Shen's formula,[16] the σ_R of ^{17}N, ^{27}Mg and ^{23}Ne at 30 MeV/u are extracted from the experimental σ_R of the neighboring nuclei. No enhancement of the σ_R was found for these three nuclei compared with its neighboring nuclei. The σ_R at relativistic energy has been measured for ^{27}Mg and no enhancement of σ_R was observed compared with their neighboring nuclei. The spin parity of ^{27}Mg and ^{27}P are both $1/2^+$. Therefore, they are isobaric analog states. In ^{27}Mg and ^{27}P, the last nucleon occupies the ground state of S, the contribution from the centrifugal barrier could be considered to be same. However, a difference between the separation energy of the last nucleon is quite large in this pair. S_p is only 0.9 MeV for ^{27}P while S_n is 6.443 MeV for ^{27}Mg.[19] Therefore the last neutron in ^{27}Mg is deeply bound by the core ^{26}Mg but the last proton in ^{27}P is weakly bound by the core of ^{26}Si which results in the formation of a proton halo in ^{27}P. A small difference for σ_R has been observed in ^{17}Ne and ^{17}N pair. The last neutron of ^{17}Ne should be occupied in $1P_{1/2}$ and it shows the same ground state as ^{17}N. But it is shown that these ground states are not isobaric analog states because of the intruder of $S_{1/2}$ orbital in ^{17}Ne.[9] The small enhancement of the σ_R in ^{17}Ne and no enhancement of σ_R in ^{17}N can be interpreted.

See details in Fig. 3.

For mirror nuclei, ^{23}Al and ^{23}Ne, S_p is only 0.125 MeV for ^{23}Al while S_n is 5.2 MeV for ^{23}Ne.[19] The last neutron should be occupied in $1d_{5/2}$ state for ^{23}Ne and the last proton may occupy the $2S_{1/2}$ state for ^{23}Al due to small separation energy of the last proton in ^{23}Al. Mirror-nuclei ^{23}Al$(1/2^+)$ and ^{23}Ne$(5/2^+)$ are not isobaric analog state. Proton halo structure for ^{23}Al makes the σ_R large enhancement compared with its mirror nucleus ^{23}Ne.

§3. Discussion and summary

In summary, the experimental σ_R for $N = 8$, 10, 12 isotones were measured. A stronger enhancement of the σ_R for ^{23}Al and ^{27}P was observed compared with their neighboring nuclei and an enhancement of σ_R for ^{17}F was also observed. Comparison between the σ_R at intermediate energies and the σ_R with Glauber model was made also. The abnormal increase of the d for ^{23}Al and ^{27}P compared with their neighbors supports the assumption of the proton halo structure. An enhancement of the d for ^{17}F compared with its neighbors supports the assumption of the proton skin structure. The density distribution of ^{17}F, ^{23}Al and ^{27}P by using RDDH calculation also supports the above assumption. By comparing mirror nucleus, we can find the reason about the proton halo in ^{27}P. By comparing the experimental σ_R with theoretical calculations based on the RMF and shell model, it is concluded that the last proton should occupy the $2S_{1/2}$ state in ^{23}Al. As a summary, we suggest that the ^{17}F has proton-skin structure and ^{23}Al and ^{27}P have proton-halo structure. More experimental measurements of the σ_R around this mass region at both intermediate energies and high energies are needed in order to understand their structure.

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