Parallel momentum distribution of the $^{28}\text{Si}$ fragments from $^{29}\text{P}$

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Distribution of the parallel momentum of $^{28}\text{Si}$ fragments from the breakup of 30.7 MeV/nucleon $^{29}\text{P}$ has been measured on C targets. The distribution has the full width at half maximum with the value of $110.5\pm 23.5\text{MeV}/c$ which is consistent quantitatively with Galuber model calculation assuming by a valence proton in $^{29}\text{P}$. The density distribution is also predicted by Skyrme-Hartree-Fock calculation. Results show that there might exist the proton-skin structure in $^{29}\text{P}$.

Studies have been performed for many years for exotic nuclei with the increasing availability of radioactive nuclear beam around the world. The exotic structures of nuclei refer to the weakly bound systems that display the very diffuse surface of nearly pure nucleonic matter at densities far below that of normal nuclear matter. The nucleus $^{11}\text{Li}$ is the first observed case as a neutron halo nucleus [1], and other nuclei that are considered to have neutron halo are $^{9}\text{He}$ [2], $^{14}\text{Be}$ [2-4] and etc. Such kind of halo nucleus provide good venue to investigate the weakly bound quantum system, which was not easily accessible before. Nuclear interactions in a low-density nuclear matter and loosely bound three-body interactions are among the current themes of interest related to these nuclei. In addition to the neutron halo, several experiments suggest the existence of proton halo nuclei. However, it is not yet fully established. More attentions are needed on the proton halo structure. Recently, the nuclei including $^{8}\text{B}$ [1], $^{12}\text{N}$ [5] and $^{23}\text{Al}$ [6], which have the very low one-proton separated energy, are considered to have single proton halo structure. Compared with the neutron halo, proton halo is difficult to be formed because of the Coulomb repulsion interaction, but it is still an experimental observable phenomenon.

The methods which are used to study the halo structure have been explored and extended in recent years. For the size of the nuclei, the methods of the total reaction cross section and the one nucleon knocked-out cross section are widely used [7-10]. From which, the sensitive probes to the abnormal structure of the nuclei, namely the radius and the density distribution can be deduced. However, to some nuclei, which have the larger cross section compared with the neighbored isotopes, may be not the candidates of the halo ones. This attributes to the extended density distribution of the core of the nucleus, which would induce the larger cross section [11,12]. Therefore, it is necessary to find a suitable approach to explore the internal structure of the nuclei. The momentum distribution of the nucleus fragment could accord with such requirement. In a highly simplified picture, the longitudinal momentum distribution of fragment from the breakup of a loosely bound projectile directly reflects the internal momentum distribution of the valence nucleon and hence the square of the Fourier transform of its wave function. In the previous works, it was shown that the width of the momentum distribution can be understood in terms of the Fermi motion or a temperature corresponding to the nuclear binding energy [12,13], and the momentum distribution of the valence-nucleon in a beam nucleus can be deduced from the observed momentum distribution of the fragment by taken the evaporation correction [12,13]. Thus, halo formation in such loosely bound nuclei can be investigated by measuring the momentum distribution of the fragment from a breakup reaction. The wide spatial dispersion of a halo nucleon translates into a narrow momentum distribution. Many practical works have been done in the measurements of the momentum distribution widely both theoretically and experimentally [12,13]. It has been reliable while searching for the exotic structure of the nuclei. Very recently, the momentum correlation function among the nucleons of the neutron-rich nuclei has also been investigated and it seems to be sensitive to the binding energy per nucleon and single neutron separation energy [12,13].

In the previous works, the study of the proton-halo
structure mainly focuses on the light proton-rich nuclei, whose mass numbers are not more than 25. It is interesting to investigate the characters of the nuclei with whose mass numbers are not more than 25. It is in-
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For the candidates of proton halo nuclei, from the core due to its small separation energy will arising nuclei among its isotopes. The proton most far away separation energy is smaller than that of the neighbor-halo nuclei which have been discovered, the one proton which is obtained from the one-Gaussian fit.

The angular distribution data from one-proton removal of $^{29}\text{P}$ on Be target at 30.7 MeV/nucleon. The solid line is the fit with single Gaussian distribution.

FIG. 3: The angular distribution data from one-proton removal in $^{29}\text{P}$ on Be target at 30.7 MeV/nucleon. The solid line is the fit with single Gaussian distribution.

which is obtained from the one-Gaussian fit.

As we know, the lower nucleon separation energy favors to form the exotic structure. For the light proton halo nuclei which have been discovered, the one proton separation energy is smaller than that of the neighboring nuclei among its isotopes. The proton most far away from the core due to its small separation energy will appear in the more extended region which is defined halo. For the candidates of proton halo nuclei, $^8\text{B}$, $^{14}\text{Ne}$, $^{17}\text{Ne}$ and $^{23}\text{Al}$ all have the smaller one proton separation energies. For proton-rich nuclei, it is possible to form the proton halo structure just similar with the neutron halo existing in the neutron-rich nuclei. For $^P$-isotope, the number of proton is 15. $^{26-29}\text{P}$ have the more number of protons than that of neutrons. Considering the small one proton separation energy, one could imagine the possibility of the proton halo structure existing in the proton-rich nuclei of $^P$-isotope. For $^{26,27}\text{P}$ nuclei, the experiment results have achieved to indicate their halo structure [26, 27, 28, 29]. But for $^{28}\text{P}$, it is not sure for the existence of the exotic structure [28]. Compared with the separation energy of $^{28}\text{P}$, it is more difficult to form the halo structure for $^{29}\text{P}$. But it is still interesting to investigate its structure for the normal or proton-skin character.

We attempt to obtain the theoretical results using the Glauber model, which can give the reasonable results of the fragment momentum distribution. The Glauber model is a microscopic reaction theory based on the eikonal approximation and on the bare nucleon-nucleon interaction. It is now a standard tool to calculate the reaction of a weakly bound nucleus. The observed interaction cross sections can be related to the wave functions of these nuclei through this model and also one can obtain information on the structure of these exotic isotopes. The accurate nuclear wave functions play the very important role in the reaction simulation. Varga et al developed the Monte Carlo integration in Glauber model and some good results have been obtained [28]. Abu-Ibrahim et al. developed this model and some reasonable results have been achieved compared with the experiment [29]. We took his code in our calculation. More elaborated treatment beyond the optical-limit approximation is worked out for the valence-nucleon part by using the Monte Carlo quadrature with the Metropolis algorithm. This is suitable for reactions involving those nuclei which have spatially extended and low density distribution as in a halo nucleus.

In the model, the density of the projectile is treated as two parts: the core and the valence nucleon density distributions. The core density is assumed to be given by a combination of Gaussians:

$$\rho(r) = \sum c_i e^{-\alpha_i r^2}$$

Also, the density $\rho$ is normalized to the mass number of a nucleus, $\int d\rho(r)=A$. The valence-nucleon density distribution will be generated through the model with the typical parameters including the separated energy, the angular momentum value and so on. The density of the target is treated similar with that of the core of the projectile. Thus, the valence-nucleon character will be included in the Glauber calculation and the results show that such consideration is reliable. More details about Glauber model could be found in Ref. [28].

Using such a model, we calculated the reaction of the 30.7MeV/nucleon $^{29}\text{P}$ on $^{12}\text{C}$ target. The parallel momentum distribution of the $^{28}\text{Si}$ fragment after one-proton removal from $^{29}\text{P}$ has been obtained. The calculated FWHM is 91 MeV/c and the result is the dashed line shown in Fig. 2. In our calculation, the valence proton density distribution of $^{29}\text{P}$ is decided by the separation energy, the angular momentum value and the node of the density distribution of the valence proton. The core of the projectile and the target density distributions are fitted with five gauss function according to the calculated results with Skyrme-Hartree-Fock(SHF) method. Thus, the parallel momentum distribution of $^{29}\text{P}$ fragmentation is self-consistent in experiment and theory.

In Ref. [30], the fragment angular distribution will give the almost same character with the momentum distribution. The angular distribution indicates the scattering character of the projectile. Compared with the neutron-halo nuclei [31], the angular distribution could also describe the structure in the proton-rich nuclei. Fig. 3 shows our experimental results. The peak of the angular distribution of $^{28}\text{Si}$ fragment shows the scattering angular during the reaction. From the value of the angular distribution, it is hard to say the existence of the exotic halo structure in $^{29}\text{P}$. But the proton-skin structure might exist.

In order to understand the structure of $^{29}\text{P}$ further, it is more clear to describe $^{29}\text{P}$ from the sight of nucleon orbits. For $^{29}\text{P}$, the last proton orbit is $1s_{1/2}$, and the other 14 protons and 14 neutrons form the structure that similar with that of $^{28}\text{Si}$. The single-particle energies of
models which can give the reasonable nucleus structure and density distribution. The SHF is one of the suitable models to study such nucleus through the sum of the valence-proton density and the density of neutrons in level 1d5/2 and 2s1/2 for $^{29}$P are, respectively, 11.585MeV and 2.748MeV. These indicate that $^{29}$P can be approximately considered as a $^{28}$Si core plus one proton because the valence-proton is weakly bound. One could use some models to study such nucleus through the density distribution. The SHF is one of the suitable models which can give the reasonable nucleus structure and density distribution from the wave function after normal-ization. The solid line shown in Fig.4(c) is the valence-proton $^{29}$P density distribution from the Glauber model. With the density distribution of the core, $^{28}$Si, we get $^{29}$P density distribution, which is the total one shown in Fig.4(c). Compared with the result from SHF model, the density distribution of $^{29}$P from Glauber model is suitable to embody the nuclear character and it would be reliable to get the momentum distribution.

In summary, the experimental measurement of the parallel momentum distribution of $^{28}$Si fragment from the breakup of 30.7 MeV/nucleon $^{29}$P has been reported for the first time. The parallel momentum width is 110.5±23.5 MeV/c FWHM which is consistent with the calculation of the Glauber model assuming the core plus one proton. The Skyrme-Hartree-Fock calculation also gives a proton-skin density distribution in comparison with $^{28}$Si. Taken together with the theoretical analysis of the density distribution and the nucleon orbit arrangement, it is obviously hard to form the halo structure in $^{29}$P. But the possibility of the proton-skin structure of $^{29}$P exists, and this nucleus could be understood as the transition one between the exotic and stable isotopes.

We appreciate helpful discussions with Prof. Gen-Ming Jin of Institute of Modern Physics.

21, 22. We calculated the density distributions of $^{29}$P and $^{28}$Si shown in Fig. 4. The dashed lines in (a) and (b) are the proton density distributions. From the figure one find that the density distribution of neutrons in $^{28}$Si and $^{29}$P are very similar, but the density distribution of protons in $^{29}$P extends farther than that of $^{28}$Si. It displays that the radii of proton and matter of $^{29}$P are a little larger than those of $^{28}$Si. This displays the weakly unbound status of the last proton of $^{29}$P, namely the proton-skin behavior.

In the Glauber model the valence-nucleon’s wave function can be obtained with the three input parameters which has been mentioned above. It is easy to get the density distribution from the wave function after normalization. FIG. 4: The calculated density distribution of protons and neutrons for $^{28}$Si (a) and $^{29}$P (b) with SHF model. In (c), the valence-proton density distribution is from Glauber model while the density distribution of $^{28}$Si and $^{29}$P are from SHF model; the total one is the sum of the valence-proton density and the density of $^{28}$Si.