Possible Experimental Evidence of a Moderate Proton Halo in ^{29}S *

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The total reaction cross sections (TRCSs) of ^{29}S+^{28}Si have been measured at intermediate energies. An obvious enhancement in TRCS of ^{29}S is observed as compared with its neighbouring nuclei. The TRCSs of ^{29}S+^{28}Si are calculated with the modified Glauber theory in the optical limit and few-body approaches. The different factor d as a possible measure of halo appearance is deduced from the experimental and theoretical data. It is well accepted that ^{27}P is a proton halo nucleus. Although not as anomalous as ^{27}P, the different factor d of ^{29}S is obviously larger than that of its neighbouring isotones of $N = 13$. This result indicates that a moderate proton halo may exist in ^{29}S nucleus. We calculate the total reaction cross sections for ^{29}S with the modified Glauber theory as a function of incident energy and compare the results with those for ^{27}Si which is a core nucleus of ^{29}S. The measured TRCSs of ^{27}Si+^{28}Si can be described to be satisfactory by the modified Glauber theory of the optical limit approach. Although a diffused nuclear density distribution is used, the theories still inadequately predict the experimental TRCSs of ^{29}S+^{28}Si, which further indicates the possibility of proton halo in ^{29}S.

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The existence of proton halo in some proton-rich nuclei far from the stability line was predicted by the relativistic mean-field model and nuclear shell model.[1,2] To date, the proton halos in ^{8}B,[3−7] and ^{26,27}P,[8−10] as well as possibly in ^{28}P[8] and ^{23}Al,[11] have been confirmed experimentally. Except in the nuclear ground state, the proton halo structure has also been observed in the first excited state of ^{17}F.[12,13] The neutron-deficient sulfur isotopes are the most possible two-proton halo candidates because the last two protons in these nuclei occupy the $2s_{1/2}$ state. The existence of proton halos in ^{26}P and ^{27}S was first predicted by Ren *et al.*[1] By further investigation, Brown and Hansen indicated[2] that ^{26,27}P and ^{27,29}S are good candidates for halo nuclei. The properties of proton-rich nuclei in the $2s1d$ shell were also investigated in the framework of relativistic mean-field model by Chen *et al.*[14] Their results show that there are one-proton halos in ^{26,27,28}P and two-proton halos in ^{27,28,29}S. Although predicted by several theoretical groups, the proton halo structures in the sulfur isotopes have not yet been observed experimentally. By means of the present experimental conditions, we have measured the total reaction cross sections σ_R of ^{29}S+^{28}Si in the intermediate energies. Large increase of σ_R for ^{29}S as compared to that of the adjacent isotones was observed. In this Letter, we present our experimental results and discuss the possible relevant mechanisms responsible for the large increase of σ_R observed in the ^{29}S+^{28}Si reaction.

The experiment was performed at the HILF-RIBLL of Institute of Modern Physics, Lanzhou. Secondary beams of ^{29}S and the corresponding isotones were produced by the projectile fragmentation of an ^{36}Ar primary beam on a Be production target at 69 A MeV. The Be production target was 98.8 mg/cm^2 in thickness. The isotopes of the secondary beams were separated and selected by the magnetic rigidity of the Radioactive Ion Beam Line which served as a double-achromatic magnetic spectrometer in the present experiment. An Al energy degrader was used to improve the momentum resolution and purity of the secondary beams. The time of flight (TOF) of the projectiles was determined by two scintillators placed at the first and second achromatic focal planes of RIBLL 16.8 m away. The resolution of TOF was 4 ns. The position information was given by two parallel-plate-avalanche counters (PPACs) placed in the front of and behind the second scintillator. Finally, a telescope consisting of seven transmission Si surface barrier detectors was installed after the second PPAC. The thicknesses of these detectors were 150 μm for the first one and 300 μm for the others. The TOF information along with the energy deposition (ΔE_i) in the Si detectors was used to identify those projectiles of interest which underwent reactions. Apart from ΔE detection, some of these Si detectors also served as the reaction target. Hence, the use of multiple Si detectors permits

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simultaneous measurement of reaction cross sections σ_R for several different energies.

Our data analysis procedure is similar to that used by Warner *et al.*[15,16] and Liu *et al.*[10] A tight gate on PPACs, TOF and ΔE_i was set for each detector to identify projectiles which have not yet reacted in preceding detectors. The probability η_1 for a reaction to occur beyond the first Si detector was determined by the ratio of the reaction events to the total events in the spectrum of the total energy deposited in the telescope by ^{29}S projectiles, which was gated on PPACs, TOF and ΔE_1. Likewise, the probability η_{i+1} for a reaction to take place beyond the $(i+1)$-th detector was found from a total energy spectrum gated on PPACs, TOF and the $(i+1)$th ΔE and all the preceding Si detectors. From the difference $\eta_i - \eta_{i+1}$, the average σ_R corresponding to the reactions taking place in the ith Si detector was determined by

$$\sigma_R = \frac{A}{N_A t} \ln\left[\frac{1-\eta_{i+1}}{1-\eta_i}\right], \qquad (1)$$

where A is the mass number of the target, N_A is the Avogadro constant, and t is the target thickness in units of g/cm^2.

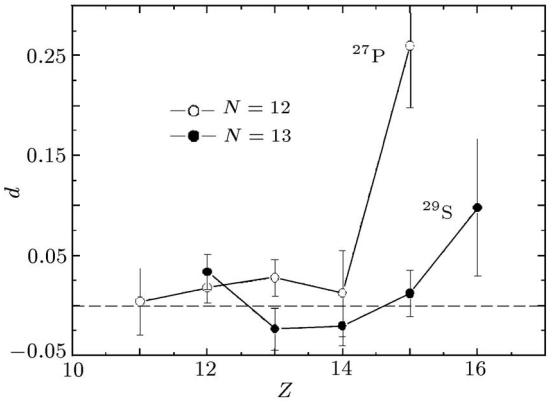

Fig. 1. Z dependence of the different factor d for $N = 12$ and 13 isotones. The symbols are connected by lines to guide the eye.

Ozawa *et al.*[17] proposed to take a difference factor d as a possible measure of halo appearance. The difference factor d is defined as[17]

$$d = \frac{\sigma_R(\text{expt}) - \sigma_R(\text{calc})}{\sigma_R(\text{calc})}, \qquad (2)$$

where σ_R (expt) represents the measured total reaction cross sections at 40 MeV/u and σ_R(calc) is the theoretical values. The theoretical total reaction cross sections are calculated with a modified Glauber theory in the optical limit (OL) approach. In this modified version of Glauber theory, the Coulomb and finite range corrections are taken into account.[18,19] It is verified[18,19] that the Glauber theory with this modified version can be extended to the low energy region. In these calculations, the nuclear density distributions are evaluated in a Woods–Saxon (WS) potential. The radius and diffuseness parameters are taken to be $r_0 = 1.17$ fm and $a = 0.65$ fm. The depth of the WS potential is adjusted by reproducing the single proton separation energy. Figure 1 shows the difference factor d as a function of Z for isotones of $N = 12$ and 13. It is worth noting that the d values abruptly increases for ^{27}P and ^{29}S as compared to their neighbouring nuclei. It is well established that ^{27}P is a proton halo nucleus.[10,20,21] Although the d value for ^{29}S does not increase as much as the case of ^{27}P, the deviation from the normal trend may also mean a halo-like structure existing in the ^{29}S nucleus.

In Fig. 2, a comparison between the experimental data and the theoretical predictions with the Glauber theory in the optical limit (OL) approach for ^{27,28}P and ^{29}S is made. In these calculations, the nuclear density distributions are, respectively, evaluated in a WS potential (open triangles) and the relativistic mean-field (RMF) theory with NL3 interactions (open diamonds and circles). The theoretical total reaction cross sections represented by open circles are evaluated with an ordinary Glauber theory. The other two (open triangles and diamonds) are calculated with the modified Glauber theory. From the figure, one may see that all the theories inadequately predict the experimental data of ^{27}P and ^{29}S.

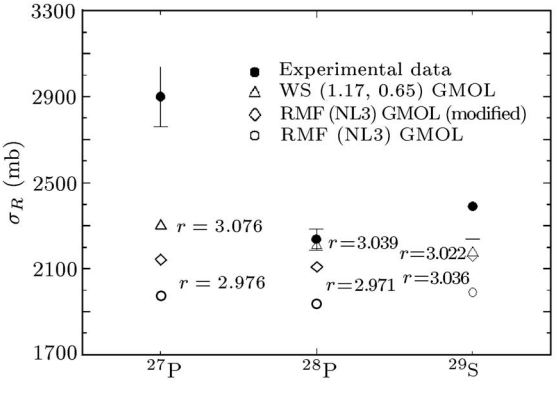

Fig. 2. Comparison of experimental total reaction cross sections for ^{27,28}P and ^{29}S with the corresponding results of the Glauber theory. The open symbols represent the predictions of different theories which are described in the text. The numbers in the figure are the root-mean-square (rms) radii of the valence proton in ^{27,28}P and ^{29}S evaluated in a WS potential (open triangles) and the relativistic mean-field (RMF) theory with NL3 interactions (open diamonds and circles).

In order to further understand the possible proton halo structure in ^{29}S, we calculated the total reaction cross sections with the modified Glauber theory as a function of incident energy and compared the results with those for ^{27}Si which is a core nucleus of ^{29}S. As seen in Fig. 3, the measured σ_R of ^{27}Si+^{28}Si can satisfactorily be described by the modified Glauber theory

of the OL approach. In the calculations, the geometry parameters of the WS potential are fixed at the values of $r_0 = 1.17\,\mathrm{fm}$ and $a = 0.65\,\mathrm{fm}$, and the depths of the WS potential are adjusted by reproducing the valence proton separation energies of ^{27,28}Si. For the reaction of ^{29}S+^{28}Si, the total reaction cross sections are calculated with the modified Glauber theory in both the OL and few-body (FB) approaches. Theoretically, halo nuclei are usually considered to have a few-body structure, which are composed of a core and valence nucleons with large diffused density distributions. In the Glauber theory of a few-body (FB) approach,[22−24] the space distributions and correlations of the core and halo nucleons are explicitly taken into account. The open up- and down-triangles in the figure represent the results calculated with the modified Glauber theory in the OL and FB approaches. Although a diffused nuclear density distribution with the WS geometry of $(r_0, a) = (1.22, 0.8)\,\mathrm{fm}$ is used, the theories still inadequately predict the experimental σ_R of ^{29}S+^{28}Si. Thus, the analysis of Glauber theory further indicates the possibility of proton halo in ^{29}S.

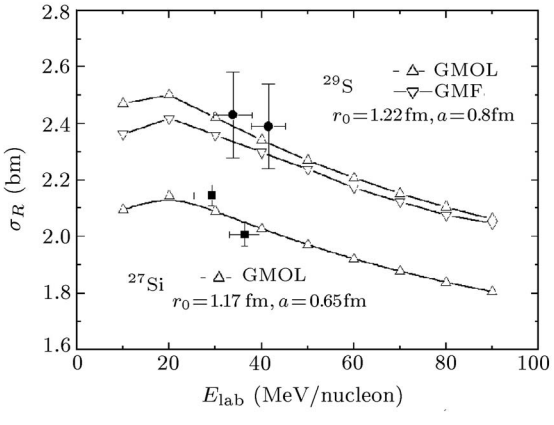

Fig. 3. Total cross sections σ_R as a function of energy for the ^{27}Si, ^{29}S + ^{28}Si reactions. The predictions of the modified Glauber model of OL and FB approaches (open symbols) are compared with the experimental data (solid symbols). The numbers in the figure represent the radius and diffuseness parameters of the WS potential.

In summary, the total reaction cross sections σ_R of ^{29}S+^{28}Si have been measured at intermediate energies. An obvious enhancement in σ_R of ^{29}S is observed as compared with its neighbouring nuclei. The total reaction cross sections of ^{29}S+^{28}Si are calculated with the modified Glauber theory in both the OL and few-body (FB) approaches. The different factor d as a possible measure of halo appearance is deduced from the experimental and theoretical data. It is well accepted that ^{27}P is a proton halo nucleus. Although not as anomalous as ^{27}P, the different factor d of ^{29}S is obviously larger than that of its neighbor isotones of $N = 13$. This result indicates that a moderate proton halo may exist in ^{29}S nucleus. We have calculated the total reaction cross sections for ^{27}Si and ^{29}S+^{28}Si with the modified Glauber theory as a function of incident energy, and compared the results of ^{29}S with those for ^{27}Si which is a core nucleus of ^{29}S. The measured σ_R of ^{27}Si+^{28}Si can be described satisfactory by the modified Glauber theory of the OL approach. Although a diffused nuclear density distribution is used, the theories still inadequately predict the experimental σ_R of ^{29}S+^{28}Si, which further indicates the possibility of proton halo in ^{29}S.

References

[1] Ren Z Z et al 1996 *Phys. Rev.* C **53** R572
[2] Brown B A and Hanson P G 1996 *Phys. Lett.* B **381** 391
[3] Minamisono T et al 1992 *Phys. Rev. Lett.* **69** 2058
[4] Pecina I et al 1995 *Phys. Rev.* C **52** 191
[5] Negoita F et al 1996 *Phys. Rev.* C **54** 1787
[6] Kelley J H et al 1996 *Phys. Rev. Lett.* **77** 5020
[7] Carstiou F et al 2001 *Phys. Rev.* C **63** 054310-1
[8] Navin A et al 1998 *Phys. Rev. Lett.* **81** 5089
[9] Zhang H Y et al 2002 *Nucl. Phys.* A **707** 303
[10] Liu Z H et al 2004 *Phys. Rev.* C **69** 034326
[11] Cai X Z et al 2002 *Phys. Rev.* C **65** 024610-1
[12] Morlock R et al 1997 *Phys. Rev. Lett.* **79** 3837
[13] Lewis R and Hayes A C 1999 *Phys. Rev.* C **59** 1211
[14] Chen B Q et al 1998 *J. Phys. G: Nucl. Part. Phys.* **24** 97
[15] Warner R E et al 1995 *Phys. Rev.* C **52** R1166
[16] Warner R E et al 1998 *Nucl. Phys.* A **635** 292
[17] Ozawa A et al 1996 *Nucl. Phys.* A **608** 63
[18] Zhao Y L, Ma Z Y, Chen B Q and Sun X Q 2001 *High Energy Phys. Nucl. Phys.* **25** 506
[19] Zhao Y L, Ma Z Y, Chen B Q 2001 *Commun. Theor. Phys.* **36** 313
[20] Navin A et al 1998 *Phys. Rev. Lett.* **81** 5089
[21] Zhang H Y et al 2002 *Nucl. Phys.* A **707** 303
[22] Ogawa Y, Yabana K and Suzuki Y 1992 *Nucl. Phys.* A **543** 723
[23] Al-Khalili J S and Tostevin J A 1996 *Phys. Rev. Lett.* **76** 3903
[24] Zhao Y L, Ma Z Y, Chen B Q and Shen W Q 2003 *Chin. Phys. Lett.* **20** 53