Big deformation in ^{17}C*

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Abstract: Reaction and interaction cross sections of ^{17}C on a carbon target have been re-analyzed using the modified Glauber model. The analysis with a deformed Woods-Saxon density/potential suggests a big deformation structure for ^{17}C. The existence of a tail in the density distribution supports the possibility of it being a one-neutron halo structure. Under a deformed core plus a single-particle assumption, analysis shows a dominant *d*-wave of the valence neutron in ^{17}C.

Key words: cross section, Glauber model, density distribution, halo, deformation

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1 Introduction

^{17}C, with small one-neutron separation energy $S_{\rm n}$=0.729±0.018 MeV and large two-neutron separation energy $S_{\rm 2n}$=4.979±0.018 MeV [1], is an interesting candidate for a one-neutron halo nucleus; since without the Coulomb barrier, the valence neutron separation energy could mostly confirm a neutron-halo structure. ^{17}C is a typical *psd*-shell nucleus, the valence neutron radial wave function exhibits configuration mixing of the *s* and *d*-wave. If the valence neutron has a *d*-dominant configuration, the radial extension of the wave function will not be significant [2].

Early experimental studies suggested there was not a possible halo structure for ^{17}C. The momentum distribution of the fragment ^{16}C from ^{17}C was found to be relatively broad [3–5]. The interaction cross section ($\sigma_{\rm I}$) at 965 MeV/A did not show a significant enhancement to its neighbors [6]; these indicated that there was no halo-structure for ^{17}C. However, subsequent experimental studies gave a conflicting result. The measurement of the reaction cross section ($\sigma_{\rm R}$) by C. Wu et al. [7] for ^{17}C on ^{12}C at 79 MeV/A suggested that ^{17}C was a one-neutron halo nucleus. Finally, they showed us the necessity of a long tail structure for ^{17}C by using the Glauber-type analysis.

This confliction reminds us whether there is a big deformation for ^{17}C, since the deformation can also greatly contribute to $\sigma_{\rm R}$ and $\sigma_{\rm I}$ [8]. Besides, Shen Yao-song et al. [9] claimed the deformation for ^{17}C by the calculation of the deformed-Skyrme-Hartree-Fock model. These works motivated us to re-analyze the experimental data of ^{17}C. In this article, we will use the modified Glauber model to reanalyze the experimental data and finally extract the density distribution of ^{17}C. With the result, we can address the confliction.

2 Formalism of the modified Glauber model

The optical limit Glauber model, given by Glauber R J [10], is a useful tool to connect $\sigma_{\rm R}$ (and $\sigma_{\rm I}$) with a nucleon density distribution, though the model underestimates the $\sigma_{\rm R}$ at low energies because the multiple scattering effect and Fermi-motion are not taken into account. Therefore, we adopted the modified optical limit Glauber model (MOL), an improvement proposed by Abu-Ibrahim and Suzuki [11], and Takechi M et al. [12]. With this improved Glauber model, we reanalyzed the experimental $\sigma_{\rm R}$ and $\sigma_{\rm I}$ and deduced the nucleon density distribution of ^{17}C through a χ^2-fitting procedure.

The MOL used in this analysis was described in detail in Ref. [12], and formulated as follows. The $\sigma_{\rm R}$ is given by

$$\sigma_{\rm R}=2\pi\int {\rm d}bb[1-T(b)]C(E), \tag{1}$$

where $C(E)$ denotes the influence of the Coulomb force [13]. $T(b)$ denotes the transmission probability at an impact parameter b. In the MOL, $T(b)$ is expressed as

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$$T(b)^{\mathrm{MOL}} = \exp\left\{-\int \mathrm{d}s\rho_Z^{\mathrm{P}}(s)\left(1-\exp\left[\left[\int \mathrm{d}t\rho_Z^{\mathrm{T}}(t)\sigma_{\mathrm{NN}} \times \Gamma(b+s-t)\right]\right)\right\}\exp\left\{-\int \mathrm{d}t\rho_Z^{\mathrm{T}}(t) \times \left(1-\exp\left[\left[\int \mathrm{d}s\rho_Z^{\mathrm{P}}(s)\sigma_{\mathrm{NN}}\Gamma(b+t-s)\right]\right]\right)\right\}, \quad (2)$$

where ρ_Z^{P} and ρ_Z^{T} are the z-integrated densities of the projectile and the target nuclei, respectively, σ_{NN} is the nucleon-nucleon total cross section at kinetic energy, Γ is the nucleon-nucleon profile function, and s, t are the nucleon coordinates of the projectile and the target in the plane perpendicular to the beam axis. In the MOL, σ_{NN} is corrected by the effective σ_{NN}, which is described as:

$$\sigma_{\mathrm{NN}}^{\mathrm{eff}} = \int_{-\infty}^{\infty} \mathrm{d}P_{\mathrm{rel}}\sigma_{\mathrm{NN}}D(P_{\mathrm{rel}}), \quad (3)$$

where $D(P_{\mathrm{rel}})$ is expressed with the relative momentum between nucleons in the projectile and the target as

$$D(P_{\mathrm{rel}}) = \frac{1}{\sqrt{2\pi(\langle P_{\mathrm{p}}^2\rangle + \langle P_{\mathrm{T}}^2\rangle)}} \times \exp\left[-\frac{(P_{\mathrm{rel}}-P_{\mathrm{proj}})^2}{\sqrt[2]{\langle P_{\mathrm{p}}^2\rangle + \langle P_{\mathrm{T}}^2\rangle}}\right]. \quad (4)$$

In this equation, P_{proj} denotes the momentum of a nucleon with the same velocity as the projectile, $\langle P_{\mathrm{p}}^2\rangle$ a mean square momentum of a nucleon in the projectile and $\langle P_{\mathrm{T}}^2\rangle$ that in the target. For stable nuclei, we employed the averaged experimental value of 90 MeV/c as $\sqrt{\langle P_{\mathrm{T}}^2\rangle}$. For ^{17}C, the ρ^{n} in Eq. (2) was divided into a core and one valence nucleon part. For the core part, we used the experimental value of momentum width from the data for ^{16}C (=73 MeV/c), and for the valence part, the data for ^{17}C (=61 MeV/c) [3].

3 Nuclear density distribution of ^{17}C

Like Wu C et al. [7], the density function of ^{17}C was divided into a core (^{16}C) and a valence neutron part, a spherical harmonic oscillator (HO) type function was used as the core shape and the Yukawa function and single particle model (SPM) density were used as the valence neutron shape.

The HO type function

$$\rho_{\mathrm{c}}^{\mathrm{i}}(r) = \rho_{\mathrm{c0}}^{\mathrm{i}}(r) \times \left(1+\frac{c-2}{3}\left(\frac{r}{b}\right)^2\right), \quad (5)$$

where i denotes the proton or neutron and c is the number of protons or neutrons in the core. The b is the core width parameter and ρ_{c0} is the normalization factor. The same width was used for the proton- and neutron-core densities.

The Yukawa function

For protons

$$\rho^{\mathrm{p}}(r) = \rho_{\mathrm{c}}^{\mathrm{p}}(r). \quad (6)$$

For neutrons

$$\rho^{\mathrm{n}}(r) = \begin{cases} X \times \rho_{\mathrm{c}}^{\mathrm{n}}(r) & r \leqslant r_{\mathrm{c}} \\ Y \times \dfrac{\exp(-\lambda r)}{r^2} & r > r_{\mathrm{c}} \end{cases}, \quad (7)$$

where r_{c} is the intersection point of the core and the tail part, λ the tail slope and X and Y are the amplitude (or the normalization factors) of the core and the tail part, respectively. Free parameters in this HO+Yukawa function are the core width b, the tail slope λ and the relative tail amplitude Y/X. In the χ^2-fitting process, we assume that b (=1.778 fm) is the same as that of ^{16}C [14], thus the normalization factor X is fixed.

Single particle model

In SPM, the wave function of the valence neutron was calculated by solving the Schrödinger equation numerically, assuming the Woods-Saxon (WS) potential, the Coulomb barrier and the centrifugal barrier. The nuclear part of the assumed potential is written as

$$V = \left(-V_0 + V_1(l\cdot s)\frac{r_{l\cdot s}^2}{r}\frac{d}{\mathrm{d}r}\right)\left[1+\exp\left(\frac{r-R_{\mathrm{c}}}{a}\right)\right]^{-1}, \quad (8)$$

where a(=0.70 fm) and R_{c} ($=r_0A^{1/3}$, r_0=1.22 fm) are the diffuseness parameter and radius of the WS potential [15]. The depth of this potential was adjusted to reproduce the experimental binding energy of the valence neutron. ^{17}C is a typical psd-shell nucleus, the valence neutron radial wave function exhibits configuration mixing of the s and d-waves. We assumed that the neutron density of ^{17}C consisted of a ^{16}C core plus a neutron with a mixing of the s-wave and the d-wave. In this case, S_n is a free parameter and is assumed to be in the range from 0.729 MeV to 0.729+1.766 MeV (1.776 MeV is the excitation energy). We searched for the minimum χ^2-fit between the low- and high energy data by varying the ratio of the s- and d-wave. A proportion of 73±24% for the d-wave was found when the χ^2 reached the minimum.

Figure 1 shows the results of the analysis with HO+HO, HO+Yukawa and HO+SPM type functional shapes. The minimum χ^2 is 10.2 (with the best-fit λ=0.68 fm^{-1}, Y/X =5.13) obtained by the analysis with the HO+Yukawa function. In Fig. 1, large under- and overestimations of the calculation are found with the analysis at low and high energy, which means that these kinds of density distributions are not sufficient to describe the density distribution of ^{17}C. However, it also shows us that the results of the analysis with HO+Yukawa and HO+SPM are a little better than those of HO + HO, especially in the low energies, which means that a tail structure is necessary to describe the density distribution of ^{17}C, since the σ_{R} is more sensitive to the surface density part at low energies. So we try to test the deformed core plus tail to describe the density of

^{17}C. In order to keep the consistency of the core, the deformed WS (DWS) distribution was chosen to describe the density of the core. It is expressed as

$$\rho(r)=\frac{\rho_0}{1+\exp\left(\dfrac{r-R(\theta)}{a}\right)}, \tag{9}$$

where $R(\theta) = R_c(1+\beta Y_{20}(\theta))$, R_c ($=1.22A^{1/3}$ fm), a ($=0.70$ fm) and β ($=0.49$) were chosen according to the quadrupole momentum given by the Deformed Skyrme Hartree Fock Calculation of ^{17}C [9]. The equation of $\beta=\sqrt{5\pi}Q/[3ZeR_c^2(1+\pi^2a^2/R_c^2)]$ [16] is used to determine the deformation factor by assuming the nucleons in ^{17}C have the same deformation, because the Glauber model is not able to effectively deal with protons or neutrons, respectively. The WS potential in the SPM was corrected by $R(\theta)$ too. A proportion of 70±21% for the d-wave was found when χ^2 reached the minimum 6.5. The d-wave dominant was consistent with the calculation of Maddalena V et al. [17, 18] and Datta Pramanik U et al. [19]. The density distribution extracted is shown in Fig. 2. The error of the density for ^{17}C was obtained by the total χ^2+1(=7.5) method.

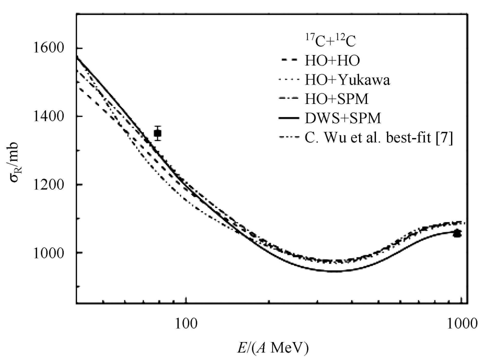

Fig. 1. The σ_R data for ^{17}C as a function of beam energy. The experimental data of the closed square were taken from Ref. [7] and the closed triangle was taken from Ref. [6].

The result of the analysis with DWS density is shown in Fig. 1. It exhibits that the analysis with DWS density is much better than that with spherical core plus tail density, which indicates the necessity of the deformation for ^{17}C. Fig. 2 shows the density distribution of ^{17}C. It shows us that ^{17}C has a tail structure, though a d-wave dominant configuration hinders the radial extension of the wave function. Although the definition of the halo structure is still ambiguous, we can conclude that ^{17}C is a mostly halo-like nucleus. The deformation may explain the broad momentum distribution of the fragment ^{16}C from ^{17}C. In order to investigate the reason for the broad momentum distribution, more experimental and theoretical work is needed.

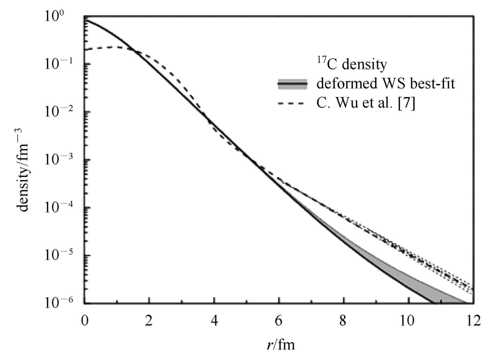

Fig. 2. Density distribution of ^{17}C deduced by modified Glauber with deformed WS core plus SPM type functional shape. The center of mass effect was taken into account.

4 Summary

We have re-analyzed the reaction and interaction cross sections of ^{17}C on a carbon target using the well tested modified Glauber model. The results of the analysis show that ^{17}C has a big deformation and a tail structure. Based on the assumption of a deformed core plus a valence neutron, it is found that the valence neutron of ^{17}C is mostly in the d-orbital.

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