A Possible Halo-Like Neutron 2*p* States of ^{13}C *

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Abstract Assuming a single-particle $2p$ structure of ^{13}C, we study proton-^{13}C elastic scattering at the incident energy of 1 GeV in the Glauber multiple scattering theory. A good agreement between theoretical prediction and corresponding experimental data is obtained. The result evidently indicates a possible halo-like neutron skin of ^{13}C.

Key words nuclear structure, high energy scattering, Glauber theory

The recent discovery of neutron halo[1,2] is one of the most interesting events in nuclear physics. Many experimental and theoretical work have been devoted to the investigation of the neutron-rich nuclei ^{6}He, ^{8}He, ^{11}Li, ^{11,12,14}Be, ^{14}B, and ^{14}C[3] and the proton-rich nuclei ^{8}B[4], ^{11}C, ^{12}N[5], ^{17}F and ^{17}Ne[6—9] to establish the existence of the proton halo or skin in these nuclei.

Theoretically, we consider in this short note if the neutron-halo-like single-particle $2p$ state with the occupation number less than 1 exists in the ground state of the ^{13}C nucleus. The reason is that the analysis of the charge and magnetic form factors of elastic electron scattering on ^{13}C, magnetic moments of ^{13}C and ^{13}N, and also log *ft* for β-decay of ^{13}N into ^{13}C clearly indicates a necessity to take into account the $2p$ shell in the ground state of nuclei ^{13}C and ^{13}N[10,11].

The previous researches in Refs. [12,13] confirmed that the neutron $2p$ state in ^{13}C is the single-particle halo-like state with a large root-mean-square radius $\langle r^2_{2p_{1/2}}\rangle^{1/2} = 11.02$fm, in comparison with $\langle r^2_{1p_{1/2}}\rangle^{1/2} = 3.40$fm. Those papers analyzed the magnetic form factor of elastic electron scattering on ^{13}C, and the experimental elastic magnetic form factor was found to be reproducible when the $2p$ shell was taken into account. For confirmation of the existence of the $2p$ state in the structure of ^{13}C, we investigate the elastic scattering of protons with an intermediate energy on nuclei, using the Glauber theory of diffractive multiple scattering[14].

According to Glauber Multiple scattering theory, the amplitude of an elastic proton scattering off nucleus can be written in eikonal form as

$$F_{fi}(q) = \frac{ik}{2\pi}H_{cm}(q)\cdot \int d^2 b e^{iqb}\langle\psi_f \mid 1 - \prod_{j=1}^{A}[1-\Gamma_j] \mid \psi_i\rangle, \quad (1)$$

where $\psi_{i(f)}$ are the wave functions of the initial (final) state, $H_{cm}(q)$ denotes correction factor of center-of-mass and the $\Gamma_j(\boldsymbol{b}-\boldsymbol{s}_j)$ stands for the single-particle profile function,

$$\Gamma_j(\boldsymbol{b}-\boldsymbol{s}_j) = \frac{1}{2\pi ik}\int d^2\boldsymbol{q} e^{-i\boldsymbol{q}(\boldsymbol{b}-\boldsymbol{s}_j)} f_j(q), \quad (2)$$

with $f_j(q)$ being the hadron-hadron scattering amplitude. The k in Eq.(1) is the wave vector of the projectile proton, $\boldsymbol{b}$ the impact parameter, $\boldsymbol{q}$ the momentum transfer. Since the effect of a nucleon correlations is negligibly small, so that the amplitude in Eq. (1) can be represented as

$$F_{fi}(q) = \frac{ik}{2\pi}H_{cm}(q)\int d^2\boldsymbol{b} e^{iqb}[\delta_{fi} - \langle\psi_{neu} \mid \Gamma_{pn}(\boldsymbol{b}-\boldsymbol{s}_n) \mid \psi_{neu}\rangle \cdot F(^{12}C)], \quad (3)$$

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$$F(^{12}C) = \langle \psi(^{12}C) \mid \prod_{i=1}^{A-1} [1 - \Gamma_i(\boldsymbol{b} - \boldsymbol{s}_i)] \mid \psi(^{12}C) \rangle, \tag{4}$$

where $\langle \psi_{neu} \mid \Gamma_{pn}(\boldsymbol{b} - \boldsymbol{s}_n) \mid \psi_{neu} \rangle$ represents incident proton scattering off the target neutron in target ^{13}C, while $\langle \psi(^{12}C) \mid \prod_{i=1}^{A-1} [1 - \Gamma_i(\boldsymbol{b} - \boldsymbol{s}_i)] \mid \psi(^{12}C) \rangle$ denotes the proton elastic scattering off the ^{12}C core.

Suppose the odd neutron in ^{13}C can stay in $1p$ state or $2p$ state so that its single-particle wave function

$$\psi_{neu} = (\eta_{1p})^{1/2}\psi_{1p} + (\eta_{2p})^{1/2}\psi_{2p}. \tag{5}$$

Then, $\langle \psi_{neu} \mid \Gamma_{pn} \mid \psi_{neu} \rangle$ can be decomposite into

$$\langle \psi_{neu} \mid \Gamma_{pn} \mid \psi_{neu} \rangle = \eta_{1p}\langle \psi_{1p} \mid \Gamma_{pn} \mid \psi_{1p} \rangle + \eta_{2p}\langle \psi_{2p} \mid \Gamma_{pn} \mid \psi_{2p} \rangle + \eta_{12}, \tag{6}$$

$$\eta_{12} = (\eta_{1p}\eta_{2p})^{1/2}\langle \psi_{1p} \mid \Gamma_{pn} \mid \psi_{2p} \rangle + (\eta_{1p}\eta_{2p})^{1/2}\langle \psi_{2p} \mid \Gamma_{pn} \mid \psi_{1p} \rangle. \tag{7}$$

Given a wave function of single-particle ψ_{1p} and ψ_{2p}, one can evaluate the matrix element $\langle \psi_{neu} \mid \Gamma_{pn} \mid \psi_{neu} \rangle$ using Eq.(2) and Eq.(5). The matrix elements of $\langle \psi(^{12}C) \mid \prod_{i=1}^{A-1} [1 - \Gamma_i(\boldsymbol{b} - \boldsymbol{s}_i)] \mid \psi(^{12}C) \rangle$ can easily be calculated as did in Ref.[12], i.e.,

$$\langle \psi(^{12}C) \mid \prod_{i=1}^{A-1} [1 - \Gamma_i(\boldsymbol{b} - \boldsymbol{s}_i)] \mid \psi(^{12}C) \rangle = 1 - \det \mid \langle \psi_{nljm} \mid 1 - \Gamma_i \mid \psi_{nljm} \rangle \mid, \tag{8}$$

with $nljm$ being the appropriate set of single-particle quantum numbers. Eq.(8) denotes the contribution from ^{12}C core in ^{13}C target nucleus, as a distortion factor to the incident proton.

The wave function of ^{13}C is taken to be a simple product of single neutron wave function ψ_{neu} in the p subshell and the wave function of the ^{12}C core, $\psi(^{12}C)$. The normalization is

$$\langle \psi(^{13}C) \mid \psi(^{13}C) \rangle = 1, \tag{9}$$

while the polarization coefficient of ^{12}C is defined as

$$pola = \langle \psi(^{12}C) \mid \psi(^{12}C) \rangle, \tag{10}$$

which can be easily calculated in the way given in Ref. [17].

The amplitude of the proton-nucleon scattering f_j in Eq. (2) can be parameterized in the form

$$f_j(q) = \frac{ik\sigma_{pn}}{4\pi}[1 - i\rho_{pn}]\exp(-q^2\beta_{pn}^2/2), \tag{11}$$

where σ_{pn} is the total cross section of the pN interaction (N = p, n), ρ_{pn} is the ratio of the real parts of the pN amplitude to its imaginary parts, and β_{pn} is the parameter of the slope of the pN amplitude. These parameters are taken here to be

$$\sigma_{pp} = \sigma_{pn} = 4.4\text{fm}^2, \tag{12}$$

$$\rho_{pp} = \rho_{pn} = -0.25, \tag{13}$$

$$\beta_{pp}^2 = \beta_{pn}^2 = 0.3\text{fm}^2. \tag{14}$$

The wave functions of single-particle are given by the harmonic oscillator potential[13—15] with size parameter b_{1p} = 2.289fm and b_{2p} = 2.753fm, η_{1p} = 1.034 and η_{2p} = 0.133. Agreement with the experimental data is excellent, as is shown in Fig.1.

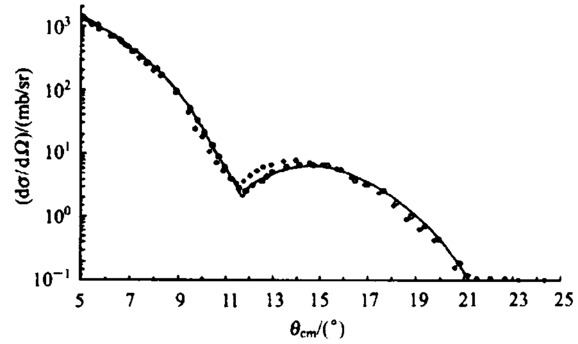

Fig.1. The differential cross sections of protons with the energy of 1 GeV, elastically scattered on nucleus ^{12}C (soild curve). Open circles: the experimental data of p-^{12}C scattering, the diamonds: the experimental differential cross sections of p-^{13}C scattering at the same energy. Experimental results were taken from Ref.16.

Substituting Eq.(7) into Eq.(2), we arrive at

$$\Gamma_j(\boldsymbol{b} - \boldsymbol{s}_j) = \frac{1}{2\pi ik}\int d^2\boldsymbol{q}\, e^{-i\boldsymbol{q}(\boldsymbol{b}-\boldsymbol{s}_j)} f_j(q)$$

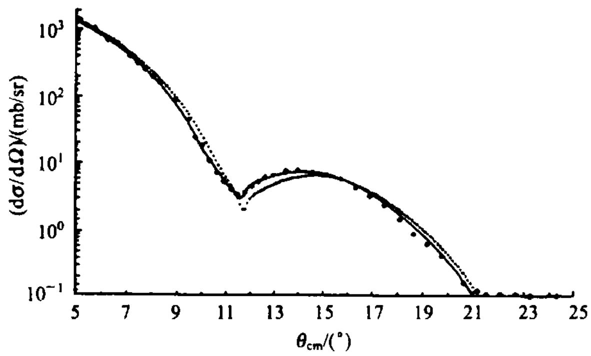

Fig.2. The differential cross sections of protons with the energy of 1 GeV, elastically scattered on ^{13}C nucleus, η_{2p} = 0.133, η_{1p} = 1.034, b_{1p} = 2.389 fm and b_{2p} = 2.753 fm (solid curve). Diamonds: the experimental data of p-^{13}C scattering. Dotted curve: the results of the calculations of p-^{12}C scattering.

$$= \frac{\sigma_{pn}(1 - i\rho_{pn})}{4\pi\beta_{pn}^2} e^{-(\boldsymbol{b}-\boldsymbol{s}_j)^2/2\beta_{pn}^2}. \qquad (16)$$

The calculated results are shown in Fig.1 and Fig.2. The Fig.1 shows the theoretical predictions of differential cross sections of proton with the energy of 1 GeV, elastically scattered off the nuclear target ^{12}C and comparison with corresponding data[16]. This calculation is purely for verifying our model's validity. Fig.2 is plot for theoretical predictions of the differential cross sections of proton with energy of 1 GeV, elastically scattered off the ^{13}C nucleon with $\eta_{2p} = 0.133$, $\eta_{1p} = 1.034$, $b_{2p} = 2.753$fm, $b_{1p} = 2.389$fm.

In conclusion, our analysis on p-^{13}C elastic scattering in Glauber theory shows that when one takes into account the $2p$ shell in the ^{13}C nucleus, a good description of experimental data is achieved. The excellent fit may imply that ^{13}C has neutron halo, namely, a neutron-halo-like structure. Based on the present investigations, we propose a possible existence of a halo-like proton $2p$ state in the ^{13}N nucleus. This work is now under study.

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^{13}C的一个可能的类晕的中子2p态*

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摘要 假设^{13}C是单粒子的2p态的结构,用Glauber多重散射理论研究了入射能量为1GeV的质子在^{13}C上的弹性散射,得到了与实验符合得很好的理论结果.这说明^{13}C可能存在着一个类晕的中子皮.

关键词 核结构 高能散射 Glauber理论

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