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DISTORTION EFFECTS FOR (^{3}He, t) REACTION AT INTERMEDIATE ENERGIES

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ABSTRACT

Distortion effects for inelastic scattering of heavy ions from nuclei at intermediate energies are discussed in terms of Glauber multiple scattering theory. Effective impact parameter is introduced for one-step inelastic collisions. The absorption appears to be smaller for inelastic scattering compared to pure elastic collisions.

In recent years much of interest has been brought to slightly inelastic nucleus-nucleus collisions. A bright example of it is the (^{3}He, *t*) reaction where various reaction channels have been observed. Namely, the excitation of Gamow—Teller transitions, nucleon knockout and Δ-production have comparable cross-sections [1—4].

The parameters of delta-peak observed in the reaction on nuclei differ from those observed in the reaction on a proton. The peak is shifted around 40 MeV down and is broadened up to 150 MeV. The possible explanation of the shift is usually based on medium effects [5, 6]. These effects become significant at densities about $0.5n_0$ where n_0 is average nuclear density [7]. From the other hand, calculations of the cross-section based on nuclear response function and convolution model for distortion factor give extreme peripherality of the process and can explain neither observed shift no magnitude of the cross-section [8].

The origin of this failure lies in using unappropriate distortion factor. Indeed, the distortion factor

$$\exp\left[-\frac{\chi(\vec{r})}{2}\right]=\exp\left[-\frac{3\sigma_{NN}}{2}\int d^2r'\,\tilde{\rho}_A(\vec{r}-\vec{r}\,')\,\tilde{\rho}_{\mathrm{He}}(\vec{r}\,')\right] \qquad (1)$$

appeares in description of elastic nucleus-nucleus collisions [9]. It depends on impact parameter which is for elastic scattering the distance between centers of mass of the colliding nuclei. Therefore, it tells nothing about the position of the nucleon in a projectile undergoing charge exchange. The magnitude of inelastic cross-section depends, however, on target density at the position of this very nucleon and not the position of the center of mass of a projectile. Since the target density varies rapidly at the surface the difference of the positions must be important for the cross-section magnitude.

In this Letter the distortion factor for (^{3}He, t) reaction with excitation of $1p-1h$ or $\Delta-h$ states in target nucleus is obtained. To describe the distortion Glauber approach for accounting rescattering will be used.

Let $T_{c.e.}(\vec{s}-\vec{r})$ be T-matrix amplitude for charge exchange reaction in nucleon-nucleon collisions. It can be either elastic charge exchange or inelastic with Δ-production. To obtain the nucleus-nucleus amplitude we shall follow the way used in [9] for elastic nucleus-nucleus collision.

First, we introduce the profile function $\gamma_{\alpha j}(\vec{s}_\alpha-\vec{r}_j)$ for elastic nucleon-nucleon scattering between nucleons α and j.

$$\gamma_{\alpha j}(\vec{s}_\alpha-\vec{r}_j)=\frac{1}{2\pi i p}\int d^2q \exp[-i\vec{q}(\vec{s}_\alpha-\vec{r}_j)]\, f^{el}_{\alpha i}(\vec{q}\,). \qquad (2)$$

In the following the simplest case will be assumed for profile function $\gamma_{\alpha j}(\vec{s}_\alpha-\vec{r}_j)$. Namely, it will be taken spin and isospin independent. Moreover, the same $\gamma(\vec{s}-\vec{r}\,)$ will be used for delta-nucleon elastic scattering as well. With these approximations the amplitude of charge-exchange reaction between nuclei B and A can be written as

$$T_{BA}=\int d^3R\, e^{i\vec{q}\vec{R}} \sum_{j=1}^{A} \sum_{\alpha=1}^{B} T_{c.e.}(\vec{R}+\vec{s}_\alpha-\vec{r}_j) \prod_{\substack{\beta=1\\(\alpha\neq\beta)}}^{B} \prod_{\substack{k=1\\ \wedge(k\neq j)}}^{A} [1-\gamma(\vec{R}+\vec{s}_\beta-\vec{r}_k)]. \qquad (3)$$

The structure of the amplitude (3) is obvious, every rescattering gives the factor $1-\gamma(\vec{R}+\vec{s}-\vec{r}\,)$ and one must exclude rescattering between inelastically scattered nucleons to avoid double counting.

The next step is calculation of matrix elements of the amplitude (3) between nuclear states. It will be done for (^{3}He, t) reaction on Carbon. At this step it is important what kind of final states is excited in target nucleus. We shall restrict ourselves by $1p-1h$ or $\Delta-h$ states that can be excited by one inelastic step. In this case the matrix element between target states can be factorized

$$T_{\mathrm{He}-A}=\int d^3R\, e^{i\vec{q}\vec{R}} \langle f|\sum_{j=1}^{A} T_{c.e.}(\vec{R}+\vec{s}_1-\vec{r}_j)\,|0\rangle \times$$

$$\times\langle 0|\prod_{\substack{\beta=1\\(\beta\neq 1)}}^{3} \prod_{\substack{k=1\\ \wedge(k\neq j)}}^{A} [1-\gamma(\vec{R}+\vec{s}_\beta-\vec{r}_k)]\,|0\rangle. \qquad (4)$$

This approximation is expected to be good in the regions of nucleon or delta quasi-free peaks. In other regions of triton spectrum the multistep excitation should be taken into account.

To calculate the diagonal matrix element of rescatterings in (4) usual approximation for target wave function as a product of single-particle densities will be used. For diagonal matrix element one obtains

$$\langle 0|\prod_{\substack{\beta=1\\(\beta=1)}}^{3} \prod_{\substack{k=1\\ \wedge(k\neq j)}}^{A} [1-\gamma(\vec{R}+\vec{s}_\beta-\vec{r}_k)]\,|0\rangle=\Big\{1-\frac{1}{A}\int d^2r\tilde{\rho}(\vec{r}\,)\,[\gamma(\vec{R}+\vec{s}_2-\vec{r}\,)+$$

$$+\gamma(\vec{R}+\vec{s}_3-\vec{r}\,)-\gamma(\vec{R}+\vec{s}_2-\vec{r}\,)\,\gamma(\vec{R}+\vec{s}_3-\vec{r}\,)]\Big\}\times$$

$$\times\Big\{1-\frac{1}{A}\int d^2r\tilde{\rho}(\vec{r}\,)\Big[\sum_{\alpha=1}^{3}\gamma(\vec{R}+\vec{s}_\alpha-\vec{r}\,)-\sum_{\alpha>\beta=1}^{3}\gamma(\vec{R}+\vec{s}_\alpha-\vec{r}\,)\,\gamma(\vec{R}+\vec{s}_\beta-\vec{r}\,)+$$

$$+\gamma(\vec{R}+\vec{s}_1-\vec{r}\,)\,\gamma(\vec{R}+\vec{s}_2-\vec{r}\,)\,\gamma(\vec{R}+\vec{s}_3-\vec{r}\,)\Big]\Big\}^{A-1} \qquad (5)$$

where $\tilde{\rho}(\vec{r}\,)=\int_{-\infty}^{\infty} dz\,\rho(\vec{r},z)$ is the thickness function.

The profile function $\gamma(\vec{r}\,)$ is narrow peaked compared to sizes of both target nucleus A and ^{3}He or t. It can be used to obtain optical limit that gives clear physics of the process. First, integration over r in (5) can be performed explicitly,

$$\int\gamma(\vec{R}+\vec{s}-\vec{r}\,)\,\tilde{\rho}(\vec{r}\,)\,d^2r\approx\bar{\gamma}\tilde{\rho}(\vec{R}+\vec{s}) \qquad (6)$$

where $\bar{\gamma}=\int\gamma(\vec{r}\,)\,d^2r$. Second, the terms in (5) containing product of γ's with different s_α can be omitted because in integration over all $\vec{s}$ with wave functions of ^{3}He and t these terms will have small factor $(r_0/R_{\mathrm{He}})^2$, where r_0 is the width of $\gamma(\vec{r}\,)$. Omitting these terms and taking limit $A\gg 1$ one obtains

$$\langle 0| \prod_{\substack{\beta=1\\ (\beta\neq 1)}}^{3} \prod_{\substack{k=1\\ \wedge (k\neq i)}}^{A} [1-\gamma[\vec{R}+\vec{s}_\beta-\vec{r}_k)]\,|0\rangle \approx$$

$$\approx \exp\left[-\bar{\gamma}\frac{A-1}{A}\tilde{\rho}(\vec{R}+\vec{s}_1)-\bar{\gamma}\tilde{\rho}(\vec{R}+\vec{s}_2)-\bar{\gamma}\tilde{\rho}(\vec{R}+\vec{s}_3)\right]. \tag{7}$$

Now the matrix element of the reaction amplitude is

$$T_{\mathrm{He}-A}-\int d^3R\,d^3s_1 d^3s_2\, e^{i\vec{q}\vec{R}} \sum_{i=1}^{A} \langle f|\, T_{c.e.}(\vec{R}+\vec{s}_1-\vec{r}_i)\,|0\rangle \times$$

$$\times \exp\left[-\bar{\gamma}\frac{A-1}{A}\tilde{\rho}(\vec{R}+\vec{s}_1)-\bar{\gamma}\tilde{\rho}(\vec{R}+\vec{s}_2)-\bar{\gamma}\tilde{\rho}(\vec{R}+\vec{s}_3)\right]\times$$

$$\times \Psi_{\mathrm{He}}(\vec{s}_1,\vec{s}_2,\vec{s}_3)\,\Psi_t^*(\vec{s}_1,\vec{s}_2,\vec{s}_3)\,. \tag{8}$$

where $\Psi(\vec{s}_1, \vec{s}_2, \vec{s}_3)$ is the internal wave function of ^{3}He or t depending on internal coordinates $\vec{s}_\alpha$ $(\vec{s}_3=-\vec{s}_1-\vec{s}_2)$.

The amplitude (8) has clear interpretation. The particles emerge from bound ^{3}He with probabilities given by the wave function $\Psi_{\mathrm{He}}(\vec{s}_1, \vec{s}_2, \vec{s}_3)$. In neglection of excitation energies of ^{3}He and t in intermediate states every particle rescatters independently with its own factor $\exp[-\bar{\gamma}\tilde{\rho}(\vec{R}+\vec{s}_\alpha)]$. The particle undergoing charge exchange has one rescattering less than others. The probability of collecting them into bound tritium is described by wave function $\Psi_t(\vec{s}_1, \vec{s}_2, \vec{s}_3)$.

The amplitude of charge exchange depends on coordinate $\vec{s}_1$ coupling thus inelastic step with elastic rescattering. To separate them let us introduce the effective impact parameter $\vec{R}_{eff}=\vec{R}+\vec{s}_1$. This is, in fact, the distance between proton in ^{3}He undergoing charge exchange and the target. The amplitude of the reaction can be represented as

$$T_{\mathrm{He}-A}=\int d^3R_{eff}\, e^{i\vec{q}\vec{R}_{eff}} \langle f| \sum_{i=1}^{A} T_{c.e.}(\vec{R}_{eff}-\vec{r}_i)\,|0\rangle \exp\left[-\frac{1}{2}\chi_{in}(\vec{R}_{eff},\vec{q})\right], \tag{9}$$

where inelastic eiconal factor is introduced

$$\exp\left[-\frac{1}{2}\chi_{in}(\vec{R}_{eff},\vec{q})\right]=\exp\left[-\bar{\gamma}\frac{A-1}{2}\tilde{\rho}(\vec{R}_{eff})\right]\int d^3s_1 d^3s_2\, e^{-i\vec{q}\vec{s}_1}\,\Psi_t^*(\vec{s}_1,\vec{s}_2,\vec{s}_3)\times$$

$$\times\exp[-\bar{\gamma}\tilde{\rho}(\vec{R}_{eff}+\vec{s}_2-\vec{s}_1)-\bar{\gamma}\tilde{\rho}(\vec{R}_{eff}+\vec{s}_3-\vec{s}_1)]\,\Psi_{\mathrm{He}}(\vec{s}_1,\vec{s}_2,\vec{s}_3)\,. \tag{10}$$

For Gaussian wave functions of ^{3}He and t integration over longitudinal coordinates can be factorized and performed explicitly giving longitudinal formfactor of (^{3}He, t) vertex. The remaining transversal eiconal factor for 0°-degree reaction on Carbon is shown in Fig. 1. It is obviously less steep at nuclear surface compared to elastic eiconal factor in convolution model and has greater probability of penetration inside a nucleus to higher density. The smoothing arose from additinal integration over $\vec{s}_1$ in (10). This integration corresponds to averaging over different positions of the ^{3}He center of mass with the effective impact parameter being fixed.

The eiconal factor (10) has been used for calculation of absolute cross-section in Δ-region for 0° ^{12}C(^{3}He, t) reaction at 2 GeV kinetic energy of ^{3}He. At this energy the momentum transfer in delta region is rather big compared to size of ^{12}C. Thus, local density approximation for nuclear response has been used [7]. For the nuclear response function at given density the model developed in [6] has been used.

The results of calculation are shown in Fig. 2. The medium effects are definitely stronger here than in [8] giving both the shift of the peak and almost all the cross-section in Δ-region. The cross-section is proportional to

$$\tilde{\rho}(\vec{r})\exp[-\chi_{in}(\vec{r},\vec{q})]\,. \tag{11}$$

For Woods—Saxon density of Carbon this expression has its maximum at 0.4 f. behind the radius of ^{12}C. The maximum corresponds to the density $\sim 1/3n_0$, where n_0 is average nuclear density. This value is considerably bigger than that found in [8] with elastic eiconal factor. This is the reason for stronger medium effects. The results shown in Fig. 2 are not sensitive to the constant of short-range nucleon-nucleon interaction g'_N. The constants g'_Δ and $g'_{N\Delta}$ are, however, important. The constant g'_Δ influences mainly the peak position and $g'_{N\Delta}$ the strength of delta excitation in nuclei.

In summary, it was shown that the eiconal factor for inelastic one-step reactions in nucleus-nucleus collisions differs from the one for elastic nucleus-nucleus scattering. The absorption is not so strong for inelastic reaction giving possibility to reveal the influence of nuclear medium on nucleon resonances.

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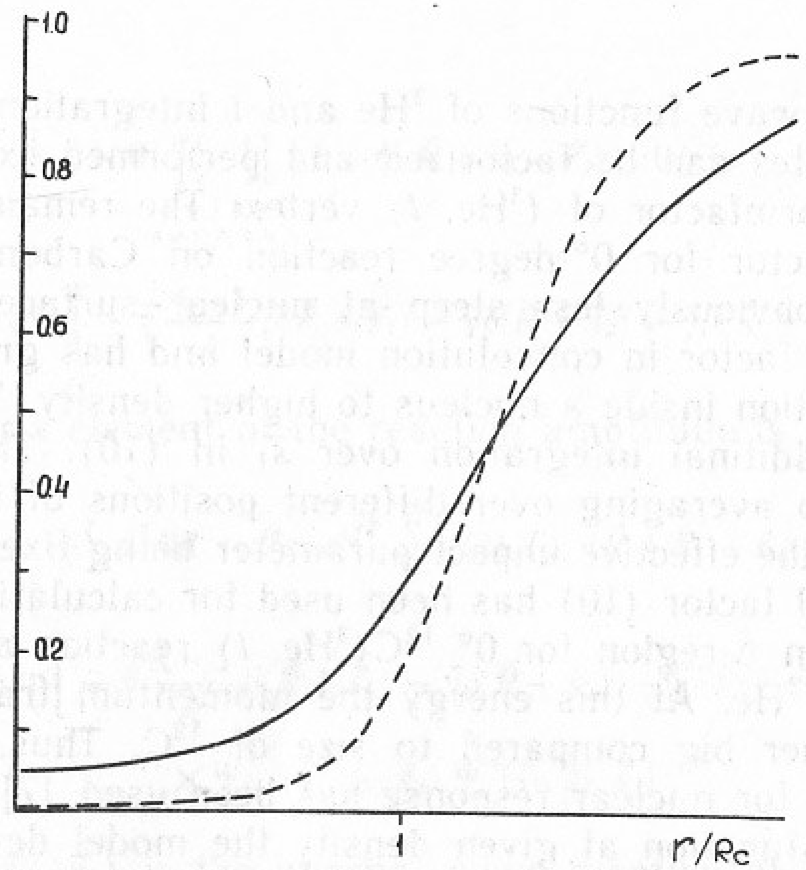

Fig. 1. Eiconal factors for ^{12}C. Full line—inelastic eiconal factor for (^3He, t) reaction. Dashed line—the eiconal factor for elastic scattering in convolution model.

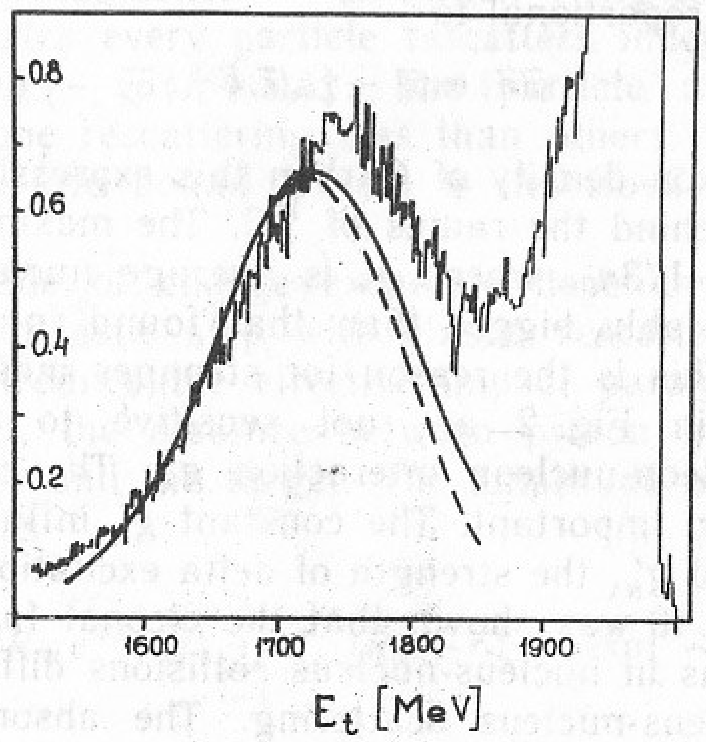

Fig. 2. The cross-section $d^2\sigma/dE_t d\Omega$ in mb/sr/MeV for $^{12}C(^3He, t)$ reaction. The lines are calculations based on [6, 7] with inelastic eiconal factor for different sets of short-range interaction constants. Full line—$g'_N=0$, $g'_\Delta=-0.1$, $g'_{N\Delta}=-0.1$, dashed line—$g'_N=g'_\Delta=0$, $g'_{N\Delta}=-0.1$.

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