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DESCRIPTION OF THE PROTON-TRITON RECHARGE PROCESS WITH FORMATION OF INTERMEDIATE ISOBAR IN DIFFRACTION APPROACH

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Using the general formalism of the quantum theory of resonance scattering and its diffraction approximation, the charge exchange amplitudes for the p(t, ^{3}He) processes with the generation of intermediate Δ-resonances in the incident particle and the nucleus-target are constructed. The energy distributions of escaping ^{3}He nuclei are calculated.

1. Introduction

During last years, study of the charge exchange processes in the collisions of three-nucleon nuclei with energy of a few GeV and protons or complex nuclei is of high interest. Both theoretical and experimental investigation of these processes may gain an insight into the strong interaction and the nuclear structure of few-nucleon systems [1 - 11]. At such energies, there is a high probability of the intermediate baryon isobar excitation in the nucleus-target or in the incident nucleus. This isobar decays then within $\tau \sim 10^{-23}$ s (the corresponding width $\Gamma \approx 115$ MeV) into nucleons and (more probably) pions. In particular, the reaction (^{3}He, t) on nucleons and nuclei of ^{2}H and ^{12}C was studied in work [12], and it was shown that the isobars are excited mainly in the target nucleus (see also [4, 6]). That is, the so-called DET mechanism [8] is dominant here.

In this work, we investigate the process p(t, ^{3}He) at the incident triton energy of several GeV. The resonance process p(t, ^{3}He) with charge exchange was already studied theoretically using the diffraction approximation in our work [13], where we presented the calculations of cross-sections, in which we took into account the excitation of □-isobars in the protons of the target only. However, in reactions (t, ^{3}He), isobar resonances can be excited with a reasonable probability in the incident triton also [6, 8], and this possibility is taken into account in the present paper (DEP mechanism).

Here we propose more consistent approach (somewhat different from that in [13]) to the construction of the process amplitudes within the diffractive approximation.

We will study the process of collision of the incident triton and fixed proton with production in a single act of collision of a ^{3}He nucleus and one intermediate Δ-resonance, what is shown on Feynman diagrams in Fig. l, *a* and *b* (with the excitation of the isobar in the proton-target – the DET mechanism) and in Fig. l, *c* and *d* (with the excitation of the isobar in the incident nucleus – the DEP mechanism). In this figure, the nucleons are shown by straight solid lines, pions (including virtual) by dashed lines, and Δ-resonances (isobars) by the narrow rectangles.

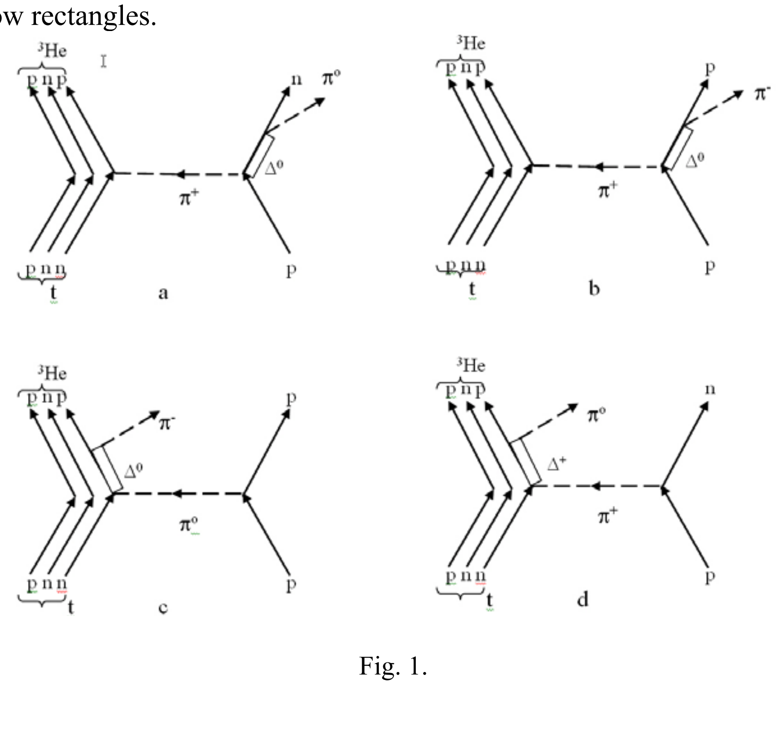

Fig. 1.

Our work is inspired by the prospects of obtaining the high-energy beams of tritons with energies of several GeV (up to 18 GeV) at the synchrophasotron-nucleotron accelerator in Dubna. This will allow one to study the process p(t, ^{3}He) experimentally [7 - 10].

2. DET mechanism

Let us consider firstly the simpler process $t + p \to {}^3He + \Delta^0$ with the excitation of Δ^0-resonance in the proton-target (DET mechanism). In this case, the ^{3}He nucleus is produced immediately in the reaction p(t, ^{3}He) as a result of the charge exchange between one of the neutrons of the incident triton and the fixed proton (see Fig. l, *a* and *b*).

In order to write the amplitude of this process with the formation of one intermediate Δ-resonance, we start from the general expression in the center-of-mass system (c.m.s.) for the resonance amplitude in quantum scattering theory [15, 16]

$$f^r(\theta') = \frac{i}{2k}(2l_r + 1)\cdot e^{2i\delta_{l_r}} \frac{i\Gamma}{E - E_r + \frac{i}{2}\Gamma} P_{l_r}(\cos\theta'), \tag{1}$$

where θ' is the escape angle of the bound three-baryon system in the c.m.s. Here,

$$E \equiv \sqrt{s} = \left[\left(M_t + M_p\right)^2 + 2M_p T_t\right]^{1/2} \tag{2}$$

is the total energy of the whole four-baryon system in the c.m.s. and

$$E_r = M_{He} + M_\Delta \tag{3}$$

is the resonance energy that determines the quasi-discrete level of the whole system with width Γ, T_t is the relativistic kinetic energy of the incident triton in the laboratory system, M_t is the triton mass, and M_p, M_Δ, and M_{He} are the masses of proton, Δ-resonance, and ^{3}He nucleus, respectively.

In order to obtain the amplitude in the diffraction approximation ($l_r >> 1$, $\theta' << 1$), we replace the resonance value of the relative orbital moment $l = l_r$ of the triton-proton system in (1) by $k\rho_r$, where *k* is the relative momentum ($\hbar = c = 1$) and $\rho = \rho_r$ is the corresponding impact parameter. The Legendre polynomial $P_{l_r}(\cos\theta')$ is replaced by the Bessel function $J_0(k\rho_r\theta')$, and the factor $\exp(2i\delta_{l_r})$, which contains the phase of the three-baryon bound system scattering off the proton-target $\delta_l = \delta_{l_r}$, is replaced by the corresponding value of the scattering matrix $\Omega_t(\rho_r) = 1 - \omega_t(\rho_r)$. Here, $\omega_t(\rho_r)$ is the triton-proton profile function which is chosen in the same form as that in [13]

$$\omega_t(\rho_r) = \omega_t^0(\rho_r) + (\vec{\tau}_t\vec{\tau}_p)\omega_t^1(\rho_r), \tag{4}$$

where $\vec{\tau}_t$ and $\vec{\tau}_p$ are the isospin operators of the triton and the proton-target, respectively. The function $\omega_t^1(\rho_r)$ in (4) is assumed, as in [13], to be proportional to the function $\omega_t^0(\rho_r)$

$$\omega_t^1(\rho_r) = \xi\omega_t^0(\rho_r), \quad \xi < 1, \tag{5}$$

where the parameter ξ is already independent of ρ_r, but it may depend on energy. The resonance impact parameter ρ_r is taken to be equal to $\rho_r = r_0(3^{1/3} + 1) \approx 3$ fm at $r_0 = 1.2$ fm.

Further formulas apply to the case when only final ^{3}He nuclei are detected as it's planned in the corresponding experiments. On summing over isospin variables, the resonance diffraction amplitude $f^r(\theta'_{He})$ for each simple process *a* and *b* shown in Fig. 1 with the excitation of the Δ-resonance in the proton-target can be written as

$$f(\theta'_{He}) = \frac{\Gamma \rho_r \omega_t^0(\rho_r)}{E - E_r + \frac{i}{2}\Gamma} \cdot \frac{1+\xi}{2} \cdot J_0(k\rho_r\theta'_{He}), \tag{6}$$

where θ'_{He} is the escape angle of the ^{3}He nucleus in the c.m.s.

The corresponding angular distribution $\frac{d\sigma}{d\Omega'_{He}}$ of escaping ^{3}He nuclei in the c.m.s. for each of the two processes *a* and *b* shown in Fig. 1 is determined by the squared absolute value of amplitude (6). The total double differential cross-section (with respect to the kinetic energy T_{He} and the escape angle θ_{He} of the ^{3}He nucleus) for these two processes in the laboratory system can be presented in the form (DET mechnism)

$$\frac{d^2\sigma(a+b)}{dT_{He}d\Omega_{He}} = 4\left|f^r(\theta'_{He}(\theta_{He}))\right|^2 B_{He}(\theta_{He}) \frac{\delta}{2\pi\left[\left(T_{He} - \bar{T}_{He}\right)^2 + \frac{1}{4}\delta^2\right]}, \quad \delta \sim \Gamma. \tag{7}$$

Here,

$$B_{He}(\theta_{He}) = \frac{d\Omega'_{He}}{d\Omega_{He}} = \frac{\sin\theta'_{He} d\theta'_{He}}{\sin\theta_{He}\ d\theta_{He}} \tag{8}$$

is the factor that converts the cross-section from the c.m.s. to the laboratory system [17] (θ'_{He} is the function of the escape angle θ_{He} in the laboratory system).

Since $\theta'_{He} << 1$ and $\theta_{He} << 1$ in the diffraction approximation, the smooth function $B_{He}(\theta_{He})$ in (7) can be approximated by $\bar{B}_{He} = B_{He}(\theta_n = 0)$. In this case (see [17, 18]),

$$\bar{B}_n = \frac{1}{1-V^2}(1+\frac{V}{V'_{He}})^2, \qquad V = \frac{P_t}{T_t + M_t + M_p}, \qquad V'_n = \frac{P'_{He}}{\sqrt{M_{He}^2 + \left(P'_{He}\right)^2}}, \tag{9}$$

where V is the speed of the c.m.s. (in the units of speed of light), V'_{He} and P'_{He} are the speed and the momentum of the ^{3}He nucleus in the c.m.s., P_t and T_t are the momentum and the kinetic energy of the triton in the laboratory system.

The value $\bar{T}_{He}$ in (7) is the root of the equation that follows from the conservation laws.

On the right-hand side of (7), we introduced factor 4, assuming the probabilities for the charge exchange processes for each of the two neutrons of the triton in each process *a* and *b* shown in Fig. 1 as practically identical.

3. DEP mechanism

Now we consider more complicated processes *c* and *d* (Fig. 1) of the production of a ^{3}He nucleus in the reaction p(t, ^{3}He), where an intermediate Δ-resonance is excited in the incident nucleus (DEP mechanism). Here, the ^{3}He nucleus is produced after two hadron transformations (see Fig. 1, *c* and *d*): at first, one of the neutrons of the incident triton absorbs the virtual pion emitted by the proton-target and turns into an isobar. Then a proton produced as a result of the isobar decay together with the two-nucleon remainder of the triton (one proton and one neutron) forms a ^{3}He nucleus. Thus, we should take into account that processes *c* and *d* run in two stages

$$c)\ t + p \to A_C + p \to {}^3He + \pi^- + p, \quad A_C = (pn\Delta^0), \tag{10}$$

$$d)\ t + p \to A_d + p \to {}^3He + \pi^0 + n, \quad A_d = (pn\Delta^+). \tag{11}$$

Due to the isotopic invariance of the strong interaction, the probabilities of processes *c* and *d* are almost the same. The lifetime of the three-baryon systems A_C and A_d is close to that of free isobars.

To find the analytic expressions for the differential cross-sections of processes *c* and *d*, $\frac{d^2\sigma_C}{dT_{He}d\Omega_{He}}$ and $\frac{d^2\sigma_d}{dT_{He}d\Omega_{He}}$, we assume, in accordance to the above, that each of these cross-sections is represented as a product of the total (integral) cross-section, σ_C or σ_d, of the creation of the intermediate three-baryon system, $A_C = (pn\Delta^0)$ or $A_d = (pn\Delta^+)$, and the corresponding probability of decay of the compound system, A_C or A_d, with the production of a ^{3}He nucleus, $\frac{dW_C(A_C \to {}^3He+\pi^-)}{dT_{He}d\Omega_{He}}$ or $\frac{dW_d(A_d \to {}^3He+\pi^0)}{dT_{He}d\Omega_{He}}$.

Next, we discuss only process *c*, Eq. (10). The same approach is valid also for process *d,* Eq. (11).

In order to obtain the total (integral) cross-section σ_C, which is the same in both the c.m.s. and the laboratory system, we should integrate the angular distribution $\frac{d\sigma_C}{d\Omega'_C}$ (which is equal to the squared absolute value of the amplitude that can be formally obtained from (6) by the substitution of θ'_{He} by θ'_C) of the intermediate three-baryon unstable systems $A_C = (pn\Delta^0)$ which are created in reaction *c*, in the c.m.s. over all angles of escape

$$\sigma_C = \int d\Omega_C \frac{d\sigma_C}{d\Omega'_C} = 2\pi\int_0^{\pi} d\theta'_C \sin\theta'_C \frac{\Gamma^2\rho_r^2\left[w_t^0(\rho_r)\right]^2}{(E-E_r)^2+\frac{1}{4}\Gamma^2}\left(\frac{1+\xi}{2}\right)^2 J_0^2\left(k\rho_r\theta'_C\right). \tag{12}$$

Since the escape angle of the compound system A_C is $\theta'_C << 1$ in the c.m.s. in the diffraction approximation ($k\rho_r >> 1$), the integration over θ'_C in (12) will be, in fact, performed over a small range of angles θ'_C from zero to a certain angle $\theta_0 << 1$, where $\theta_0 = \frac{N}{k\rho_r}$, $N \sim 1$. As a result, we obtain the following approximate expression (see [21])

$$\sigma_C = 2\pi \cdot \frac{\Gamma^2\rho_r^2\left[w_t^0(\rho_r)\right]^2}{(E-E_r)^2+\frac{1}{4}\Gamma^2} \cdot \left(\frac{1+\xi}{2}\right)^2 \frac{1}{2} \cdot \left(\frac{N}{k\rho_r}\right)^2 \cdot \left[J_0^2(N)+J_1^2(N)\right], \quad N = k\rho_r\theta_0. \tag{13}$$

Let us assume that the integral cross-section σ_d for process *d* is approximately the same as the cross-section σ_C and take into account that a triton contains two neutrons. Then, for the total cross-section $\sigma = 2(\sigma_C + \sigma_d)$ of the formation of intermediate systems A_C and A_d with Δ-resonances in processes *c* and *d,* we obtain the expression

$$\sigma_C = \frac{\pi\Gamma^2\rho_r^2\left[w_t^0(\rho_r)\right]^2(1+\xi)^2}{(E-E_r)^2+\frac{1}{4}\Gamma^2} \cdot \theta_0^2 \cdot \left[J_0^2(k\rho_r\theta_0)+J_1^2(k\rho_r\theta_0)\right], \tag{14}$$

where θ_0 in (14) can be defined as the angle θ'_C, at which the integrand in (12) decreases approximately by 3 - 4 times in comparison to its maximum value under the condition $\theta_0 << 1$. (In this case, the contribution of the integration region $\theta'_C > \theta_0$ will be comparatively small).

In order to obtain the probability $\frac{dW_C(A_C \to {}^3He+\pi^-)}{dT_{He}d\Omega_{He}}$ we use the known general expression for the decay probability for an unstable particle (in our case, A_C) into several secondary particles in the arbitrary coordinate system [18, 19]. In particular, the decay probability into two particles $A_C \to {}^3He+\pi^-$ in the rest system of the proton-target, i.e. in the laboratory system, is determined by the formula

$$\frac{dW_C(A_C \to {}^3He + \pi^-)}{dT_{He} d\Omega_{He}} = C_\Delta \frac{1}{E_C} \left[\frac{(T_{He} + M_{He})^2 - M_{He}^2}{\left(\vec{P}_C - \vec{P}_{He}\right)^2 + M_{\pi^-}^2} \right]^{\frac{1}{2}} \delta(E), \tag{15}$$

$$E \equiv E_C - T_{He} - M_{He} - \sqrt{P_C^2 + P_{He}^2 - 2\vec{P}_C \vec{P}_{He} + M_{\pi^-}^2}, \tag{16}$$

where $\vec{P}_{He}$ is the momentum of the ^{3}He nucleus, and $\vec{P}_C$ and $E_C = \sqrt{P_C^2 + M_C^2}$ are, respectively, the momentum and the total energy of the unstable compound particle A_C in the laboratory system, $M_C = M_P + M_n + M_\Delta - \varepsilon_C$ is the mass of this particle and $\varepsilon_C \le 8.6$ MeV is its binding energy, and M_{π^-} is the mass of a pion. Similarly, we can write the probability $\frac{dW_d(A_d \to {}^3He + \pi^0)}{dT_{He} d\Omega_{He}}$, which can be obtained by replacing index *c* by *d* and π^- by π^0 everywhere in (15) and (16).

The quantity C_Δ encountered in (15) is proportional to the squared absolute value of the invariant amplitude (divided by $32\pi^2$) of the two-particle decay of the unstable compound particle A_C into ^{3}He and π^-. If the spins of the particles are not taken into account, this value is practically constant, and we assume that it is constant. Thus, the angular and energy distributions of the produced ^{3}He nuclei (in particular, the positions of maxima) will be determined mainly by the kinematics of the process and the conservation laws. In fact, we use the so-called statistical hypothesis (the phase volume model) which is frequently used in the study of relativistic processes [18]. Within this approximation, the formation of a secondary particle occurs independently of other secondary particles and of the states of the original particles (as in the Bohr's model). In order to calculate the constant C_Δ, we need to know the binding constants of the interaction of pions with Δ-isobars and nucleons. In principle, these constants can be determined from experimental data. We found C_Δ by comparison of the height of one of the two maxima (at higher energy of the ^{3}He nucleus) of cross-section (20) with the height of a similar maximum in the energy distribution for the reaction n(^{3}He, t) which was studied in [12] (see below).

In what follows, we assume that the escape angle of a ^{3}He nucleus $\theta_{He} = 0$ (as is planned in experiments). Since the cross-sections of processes *c* and *d* are calculated only approximately, we calculate probability (15) and the corresponding cross-section $\frac{d^2\sigma_C}{dT_{He} d\Omega_{He}}$ for the most probable angle, which is also zero, of the ^{3}He escape from the compound system A_C. Thus, in (15) and (16), we have $\vec{P}_C \vec{P}_{He} = P_C P_{He}$. From the conservation laws, we obtain the equation, from which we will determine the energy E_C

$$E_C + \left[\left(P_t - \sqrt{E_C^2 - M_C^2} \right)^2 + M_P^2 \right]^{1/2} = E_t + M_P. \tag{17}$$

Then we substitute the obtained value E_C into (15) and (16). For process *d,* we need to replace index *c* by *d* on the left-hand side of Eq. (17) and also M_P by M_n. In calculations, the energy delta-function in (15) is replaced by the final resonance factor, as was done before in (7)

$$\delta(E) \to \frac{\gamma}{2\pi\left(E^2 + \frac{1}{4}\gamma^2\right)} M_P, \qquad \gamma \sim \Gamma. \tag{18}$$

This factor is related, in fact, to the intermediate Δ-resonance (isobar).

Thus, the total differential cross-section of processes *c* and *d* (see Fig. 1, *c* and *d*) is represented by the formula [see (14) - (18)]

$$\frac{d^2\sigma(c+d)}{dT_{He}d\Omega_{He}} = \sigma \cdot \left[\frac{dW_C\left(A_C \to {}^3He + \pi^-\right)}{dT_{He}d\Omega_{He}} + \frac{dW_d\left(A_d \to {}^3He + \pi^0\right)}{dT_{He}d\Omega_{He}} \right], \tag{19}$$

which corresponds to the DEP mechanism.

4. Results of Calculations

The total differential cross-section of the reaction p(t, ^{3}He) with the escape of ^{3}He nuclei, which takes into account all partial processes *a*, *b*, *c*, and *d*, is equal to the sum of the cross-sections (7) and (19):

$$\frac{d^2\sigma(a+b+c+d)}{dT_{He}d\Omega_{He}} = \frac{d^2\sigma(a+b)}{dT_{He}d\Omega_{He}} + \frac{d^2\sigma(c+d)}{dT_{He}d\Omega_{He}}. \tag{20}$$

The calculated cross-sections (7), (19) and (20) should be compared with the corresponding experimental cross-sections. In particular, the study of cross-section (7) (related to the DET mechanism) and cross-section (19) (related to the DEP mechanism) for the charge exchange reaction p(t, ^{3}He) with the formation of an intermediate isobar separately allows us to calculate the relative contributions of the DET and DEP mechanisms as well as to evaluate the difference of these cross-sections from the corresponding partial cross-sections of the reaction p(^{3}He, t) that was already studied theoretically and experimentally.

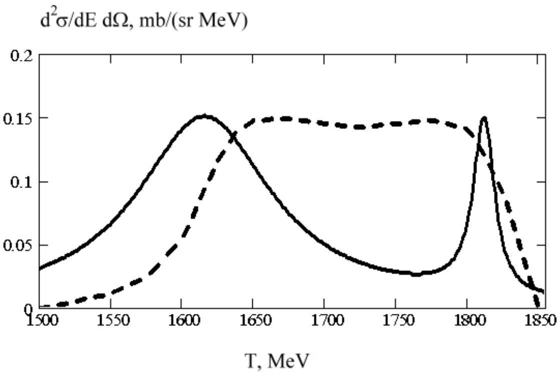

Fig. 2.

Since the studied process p(t, ^{3}He) and the process p(t,^{3} He), which was studied earlier in [8, 12], are isotopically mirrored to each other, one can expect that the general dependences of cross-sections on the kinetic energy of produced three-nucleon nuclei will be similar. This is exactly the case, as can be seen in Fig. 2, where the calculated cross-section (22) versus T_{He} at $\theta_{He} = 0$ and T_t = 2 GeV of the process p(t, ^{3}He) is represented by the solid line, and the curve, taken from work [12], which corresponds to the dependence of the similar cross-section on T_t for $\theta_t = 0$ and $T_{He} = 2$ GeV in the n(^{3}He, t) process, is represented by the dashed line. In both processes, we observe two maxima at energies of escaping three-nucleon nuclei of approximately 1650 and 1800 MeV. The left maximum (at the lower energy) is related to the DET mechanism, and the right – to the DEP mechanism. The positions of these two maxima are described by different formulas, (7) and (19), respectively. For the process p(t, ^{3}He), the contributions of the both DET and DEP mechanisms to the total cross-section (20) are of the same order, as for the reaction n(^{3}He, t), whereas the main contribution (up to 90%) for the process p(^{3}He, t) is due to the DET mechanism [8, 12].

5. Conclusions

Within the diffraction approximation, we obtained the expressions for the differential cross-section of the charge exchange process p(t, He) with the excitation of the Δ-resonances in the proton-target (DET mechanism) and in the incident triton (DEP mechanism).

The energy distribution of ^{3}He nuclei produced in the reaction p(t, ^{3}He) at zero escape angle is calculated for the incident triton energy 2 GeV. It is shown that the maximum at the lower energy is related to the DET mechanism, and the maximum at higher energy – to the DEP mechanism.

The comparison of the cross-sections and the energy distributions of the produceed three-nucleon nuclei is carried out for the mirror processes p(t, ^{3}He) and n(^{3}He, t).

Similar theoretical investigations with the use of the diffraction approximation can be carried out for other resonance charge exchange processes and for various nuclei that collide at relativistic energies as well.

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ОПИСАНИЕ ПРОЦЕССА ПЕРЕЗАРЯДКИ ПРОТОНА НА ТРИТОНЕ С ФОРМИРОВАНИЕМ ПРОМЕЖУТОЧНОЙ ИЗОБАРЫ В ДИФРАКЦИОННОМ ПРИБЛИЖЕНИИ

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С использованием общего формализма квантовой теории резонансного рассеяния и ее дифракционного приближения построены зарядообменные амплитуды процесса p(t, ^{3}He) с формированием промежуточного Δ-резонанса в налетающей частице и в ядре-мишени. Произведен расчет энергетических распределений вылетающих ядер ^{3}He.

ОПИС ПРОЦЕСУ ПЕРЕЗАРЯДКИ ПРОТОНА НА ТРИТОНІ З ФОРМУВАННЯМ ПРОМІЖНОЇ ІЗОБАРИ В ДИФРАКЦІЙНОМУ НАБЛИЖЕННІ

В. В. Давидовський, М. В. Євланов, В. К. Тартаковський

З використанням загального формалізму квантової теорії резонансного розсіяння і її дифракційного наближення побудовано зарядообмінні амплітуди процесу p(t, ^{3}He) з формуванням проміжного Δ-резонансу в налітаючій частинці та в ядрі-мішені. Проведено розрахунок енергетичних розподілів вилітаючих ядер ^{3}He.