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INTEGRAL CROSS SECTIONS OF THE HYPERTRITON INTERACTION WITH NUCLEI AT HIGH ENERGIES

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The diffraction approximation is used to perform both the exact numerical and general theoretical analyses of various integral cross sections of the nuclear and Coulomb interactions of incident hypertritons with absorbing nuclei at high energies. The sensitivity of the cross sections to the value of the binding energy of hypertriton with respect to its dissociation into a Λ-hyperon and a deuteron is shown.

Интегральные сечения взаимодействия гипертритонов с ядрами при высоких энергиях

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С использованием дифракционного приближения проведены как точный численный, так и общий теоретический анализы различных интегральных сечений ядерного и кулоновского взаимодействий падающих гипертритонов с поглощающими ядрами при высоких энергиях. Показана чувствительность сечений к величине энергии связи гипертритона относительно его развала на Λ-гиперон и дейтрон.

An increasing interest has recently been shown in the investigation of the interaction of hypertritons with nuclei in connection with the opening possibility of obtaining the beams of ${}^{3}_{\Lambda}H$ hypernuclei with good characteristics (in particular, at the accelerating complex: Synchrophasotron-Nuclotron of JINR, Dubna [1—4]). Such investigations can give more detailed information about the structure of hypertriton. In particular, they can specify the numerical value of its binding energy with respect to the dissociation into a Λ-hyperon and a deuteron ($\varepsilon = 0.13 \pm 0.05$ MeV [5]), which is known so far with a large error, give new information about the interaction of ${}^{3}_{\Lambda}H$ with various nuclei, improve our knowledge of the forces between lambda-hyperon and nucleons and of the strong interactions, on the whole.

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In this paper the theoretical investigation of incident hypertritons with various nuclei at medium and high energies is carried out using the diffraction approximation which is well applicable to the indicated energies. Particular attention is given to the highly actual search of such processes and conditions when it is possible to extract the value of ε with a sufficient accuracy.

The use of the mathematical apparatus of the diffraction interaction of incident composite two-cluster particles with nuclei at medium and high energies (one can consider the hypertritons (${}^{3}_{\Lambda}H \to \Lambda + d$) as such particles), makes it possible not only to reproduce many dependences obtained by other, more labour-consuming methods, but also to deduce a series of new relationships and often in an explicit form.

Figure 1 shows the dependence on the ${}^{3}_{\Lambda}H$ binding energy ε (calculated on the basis of the exact formulas of the diffraction nuclear model [6—9]) of the integral cross sections of the complete absorption σ_a of the ${}^{3}_{\Lambda}H$ hypernucleus, incomplete absorption or stripping σ_s, when only one of the clusters initially forming a part of the incident ${}^{3}_{\Lambda}H$ is absorbed by the nuclear target, elastic scattering σ_{el}, diffraction two-fragment dissociation σ_d^N and total cross

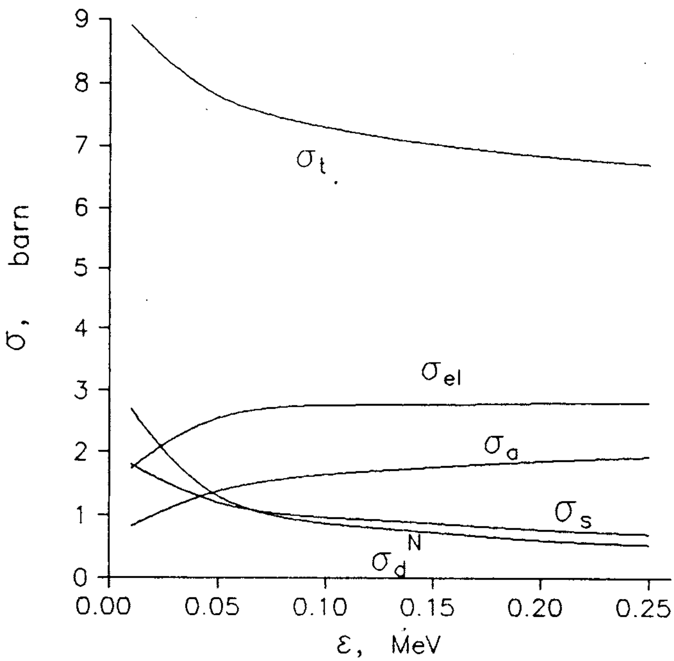

Fig.1. Integral cross sections of various processes of the diffraction nuclear interaction of ${}^{3}_{\Lambda}H$ hypernuclei with ${}^{238}_{92}U$ nuclei depending on the hypertrition binding energy ε

section $\sigma_t = 2\sigma_s + \sigma_a + \sigma_{el} + \sigma_d^N$ for the black nuclear targets of uranium $^{238}_{92}U$. (Here and then the cross sections are given in barns).

The function $\varphi_0(r) \sim \frac{1}{r}\exp\left(-\frac{r}{\hbar}\sqrt{\frac{2M_\Lambda M_d \varepsilon}{M_\Lambda + M_d}}\right)$ is used as a wave function $\varphi_0(r)$ of relative motion of the clusters Λ and d in the $^3_\Lambda H$ hypernucleus. While the cross sections σ_t, σ_d^N and σ_s decrease, the cross sections σ_{el} and σ_a increase with increasing ε. As can be seen from Fig.1, the integral cross sections are most sensitive to the value of ε for small values of ε. A qualitative character of the cross section dependence on ε is the same for lighter target nuclei. All these cross section increase monotonously with increasing the mass number A of nuclear target, but rather slightly depend on the energy of incident particles E. Note that the ratios σ_d^N/σ_{el} for incident hypertritons (with $\varepsilon \approx 0.13$ MeV) and deuterons differ strongly from each other for the same nuclear targets. This is also true for the ratios σ_s/σ_a and σ_{el}/σ_a, what is naturally explained, first of all, by a very small binding energy of hypertriton.

Since the most probable value of the binding energy of the $^3_\Lambda H$ hypernucleus $\varepsilon \approx 0.13$ MeV is rather small, the radius $^3_\Lambda H$ exceeds considerably the sizes of all known nuclei, i.e., we have $R^2 < 1/r^2 > \ll 1$, where $R = r_0(A_0^{1/3} + A^{1/3})$, $A_0 = 3$, $r_0 = 1.2$ fm, and $<1/r^2> = \int dr \cdot r^{-2}\varphi_0^2(r)$. The following asymptotic formulas for the integral cross sections arise from the exact formulas of nuclear diffraction in the approximation $<R^2/r^2> \ll 1$:

$$\sigma_t = 4\pi R^2\left(1 - \frac{1}{4}\left\langle\frac{R^2}{r^2}\right\rangle\right),$$

$$\sigma_s = \pi R^2\left(1 - \frac{1}{2}\left\langle\frac{R^2}{r^2}\right\rangle\right), \quad \sigma_a = \frac{\pi}{2}R^2\left\langle\frac{R^2}{r^2}\right\rangle,$$

$$\sigma_{el} = \frac{\pi}{2}R^2\left\langle\frac{R^2}{r^2}\right\rangle\left(\frac{1}{\beta_1^2} + \frac{1}{\beta_2^2}\right),$$

$$\sigma_d^N = 2\pi R^2\left[1 - \frac{1}{4}\left\langle\frac{R^2}{r^2}\right\rangle\left(1 + \frac{1}{\beta_1^2} + \frac{1}{\beta_2^2}\right)\right]. \qquad (1)$$

Here $\beta_1 = 1 - \beta_2 = M_1/(M_1 + M_2)$, where M_1 and M_2 are the masses of the first and the second clusters (Λ-hyperon and deuteron, respectively).

From formulas (1), which are the generalization of the corresponding formulas of Ref. [10] for the Gaussian deuteron wave functions, it follows that the dependence of the integral cross sections on R deviates from the simple rule R^2. The direct numerical calculations, performed according to the exact formulas of nuclear diffraction lead to the following approximate dependences of the integral cross sections on R: σ_t, σ_s, $\sigma_d^N \sim R^{1.6}$, and σ_{el}, $\sigma_a \sim R^{2.2}$.

In the diffraction approximation, the integral cross section of the Coulomb dissociation process of the ${}^3_\Lambda H$ hypernucleus by absorbing nuclei can be represented in the following form

$$\sigma_d^C = 8\pi n^2 R^2 \int_{x_{\min}}^{\infty} \frac{dx}{x} F(x), \quad x = qR, \tag{2}$$

$$F(x) = \left[1 - \Phi^2 \left(\frac{\beta_1 x}{R} \right) \right] \left| J_0(x) S_{2in,1}(x) - 2inJ_1(x) S_{2in-1,0}(x) \right|^2, \tag{3}$$

where $n = \frac{z \cdot Z \cdot e^2}{\hbar v}$, z and Z are the charges of the incident nucleus and nuclear target, respectively, in the units of the proton charge e, v is the relative velocity of colliding nuclei, $\Phi(\mathbf{q}) = \int d\mathbf{r} \cdot \exp(i\mathbf{qr})\varphi_0^2(r)$, $\mathbf{q}$ is the change in the projectile momentum during the scattering, and $S_{\mu,\nu}(x)$ is the Lommel function. From physical cansiderations we have found the expression for a minimum charge in the projectile momentum $q_{\min}$ and the corresponding low limit of integration in (2) (at $x_{\min} \to 0$ the integral over x in (2) diverges logarithmically):

$$x_{\min} = q_{\min} R = \frac{\varepsilon R \sqrt{1 - v^2/c^2}}{\hbar v} \max(1, 4n). \tag{4}$$

This differs slightly from the results of the previous papers [11].

The use of (4) leads to the results which agree better with the experimental data on the Coulomb dissociation of nuclei in comparison with the calculations performed in Refs. [11,12]. In the ultrarelativistic case (when $x_{\min} \to 0$), the following asymptotic formula, arising from (2) after integration in parts, will be a good approximation for the cross section σ_d^C:

$$\sigma_d^C = \frac{8\pi}{3} \beta_1^2 n^2 \langle r^2 \rangle \ln \frac{\hbar c \sqrt{1 - v^2/c^2}}{4n\varepsilon\beta_1 \langle r^2 \rangle^{1/2}}, \quad 4n > 1, \tag{5}$$

where $\langle r^2 \rangle = \int d\mathbf{r} \cdot r^2 \varphi_0^2(r)$. Cross section (5), which is approximately proportional to Z^2 and inversely proportional to ε, differs insignificantly from the corresponding formula of Ref.[13]. A more realistic dependence σ_d^C on Z can be obtained from (5), namely, for

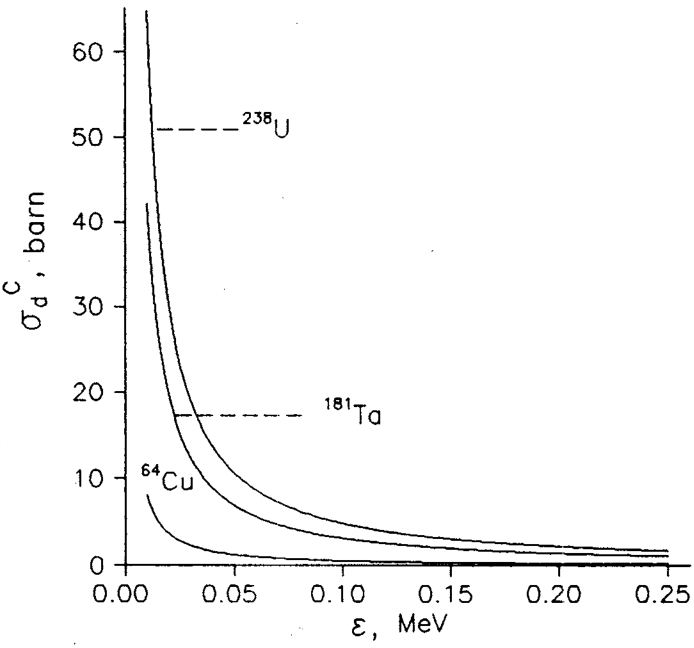

Fig.2. Theoretical dependences of the integral cross sections σ_d^C of the $^3_\Lambda H$ Coulomb dissociation on the hypertrition binding energy ε for various target nuclei at an energy *E* of 17 GeV

example, at 27 GeV and $\varepsilon = 0.13$ MeV we have $\sigma_d^C \sim Z^{1.8}$. The use of exact formulas (2) and (3) leads to the dependence $\sigma_d^C \sim Z^{1.9}$. The deviation from the simple dependence $\sigma_d^C \sim Z^2$, considered in a series of earlier papers [13—15], is explained by the fact that we use more correct expression (4) for $q_{\min}$ and take into account the finite size of the absorbing target nucleus.

Figure 2 presents the dependences of the $^3_\Lambda H$ Coulomb dissociation cross section σ_d^C on the binding energy of the hypertriton ε calculated by exact formulas (2), (3) for various nuclear targets at $E = 17$ GeV. The calculations of the dependence of σ_d^C on ε by formula (5) at the same high energy give nearly the same results. It is seen that the cross section σ_d^C is highly sensitive to the value of ε in the range of small values of ε where for heavy nuclear targets the cross section σ_d^C considerably exceeds in value the integral cross sections of diffraction nuclear processes. Thus, if the binding energy of the $^3_\Lambda H$ hypernucleus ε

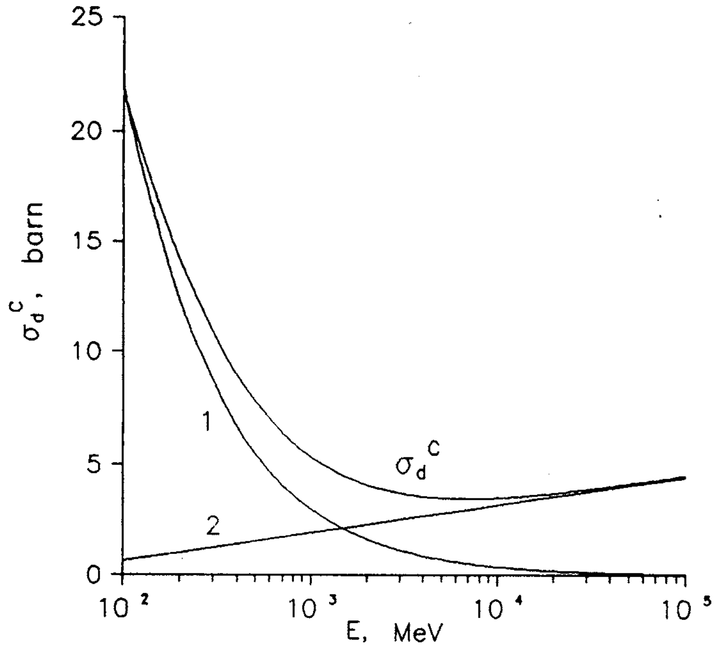

Fig.3. The dependences of the integral cross sections σ_d^C of the ${}^3_\Lambda H$ Coulomb dissociation on the incident particle energy E calculated by the exact formulas (2) and (3) for the ${}^{238}_{92}U$ target nucleus at $\varepsilon = 0.13$ MeV. Curves 1 and 2 illustrate the dependences of $\sigma_d^C \sim 1/E$ and $\sigma_d^C \sim \ln(E/M_0c^2)$, respectively

appears to be smaller than the value of $\varepsilon = 0.13$ MeV, it could be determined experimentally with a sufficient accuracy.

The Coulomb dissociation cross section of the hypertriton σ_d^C increases much faster with increasing the mass number A of target nucleus than the cross section of the diffraction nuclei dissociation σ_d^N. As a result of this, at $\varepsilon \approx 0.13$ MeV and at high energies E, the cross section σ_d^C is noticeably larger than the cross section σ_d^N for heavy nuclear targets, while we have opposite situation, namely, $\sigma_d^N > \sigma_d^C$ for medium and light nuclear targets.

While the integral cross sections of nuclear diffraction depend slightly on the incident particle energy E, the cross section σ_d^C depends on E rather greatly. At E of the order of hundreds of MeV, σ_d^C falls down rapidly with increasing E approximately under the rule

$1/E$ and has a broad minimum in the range $E \approx 6$ GeV (where $\sigma_d^C \approx 3.5$ barns), after which it increases slowly with increasing E under the rule $\sim \ln (E/M_0c^2)$ (see Fig.3). The indicated explicit dependences of the cross sections σ_d^C on E in the nonrelativistic and ultrarelativistic ranges arise from the exact and asymptotic formulas for σ_d^C listed above.

The direct numerical calculations, we performed by the exact formulas of the diffraction model taking into account the Coulomb interaction between colliding nuclei, show that not only at $\langle r^2 \rangle \ll R^2$, as it was found earlier [16—19], but also at $\langle r^2 \rangle \gg R^2$, as in the case of incident hypertritons, the diffraction and Coulomb mechanisms of the incident nucleus break-up are practically independent of each other, since in all the cases the interference term proves to be considerably smaller than the cross sections σ_d^N and σ_d^C.

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