Production of fast hypernuclei as a result of collisions of relativistic ions with nuclei

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The cross sections for production of relativistic hypernuclei in high-energy, heavy-ion beams as a result of their collision with target nuclei was calculated. The obtained cross sections show that direct experimental observation and study of the main properties of hypernuclei are possible by using the existing high-speed streamer chambers.

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Indirect photoemulsion methods have been used until now to investigate the properties of hypernuclei by analyzing the decay products of slow hypernuclei.[1] The production of relativistic heavy-ion beams makes it possible for the first time to directly observe the relativistic hypernuclei produced in the collision of incident ions with nuclei. The existing high-speed streamer chambers for recording of fast nuclei can be used here as detectors.[2] This technique makes it possible to directly investigate the main properties of hypernuclei and the mechanisms for their production.

In this paper, we calculate the cross sections for production of hypernuclei in the reaction

$$_ZA + B(\text{target}) \rightarrow {}_\Lambda A + \dots , \tag{1}$$

as a function of the ion energy and of the possible transition modes. A detailed analysis of other reactions will be given in another paper.

The reactions such as (1) are peripheral in nature (Ref. 3), i.e., the collision involves one or several nucleons in each colliding relativistic nucleus. As a result, the velocity of the secondary ${}_\Lambda A$ nucleus differs slightly from that of the beam nuclei and the process itself can be represented in the form of a diagram in Fig. 1. We assume that the hyperons are produced as a results of a single collision of an ion nucleon with a nucleon of the target nucleus, which is captured in one of the ion levels. Since the characteristic momentum transfer in the reactions (1) $q \sim 0.2$–0.4 GeV/c is much smaller than the initial momentum, we can use the impact parameter in the theoretical analysis.[4] Thus, the cross section of the process, after summing over the nonrecorded final states of the target nucleus, can be written as follows:

$$\sigma = \int d\mathbf{b}\, \sigma(\mathbf{b}) = \int d\mathbf{b}\, dq_{\parallel} < \psi_T^{\circ} \Big| \Big| < \psi_p^f \,|\, \Gamma(\mathbf{b}, \mathbf{s}_p, \mathbf{s}_T, q_{\parallel}) \,|\, \psi_p^{\circ} > \Big|^2 \Big| \psi_T^{\circ} > , \tag{2}$$

where $\mathbf{S}_p$ and $\mathbf{S}_T$ are projections of the radius vectors of the ion and the nucleus in the plane of variation of the impact parameter **b**, Γ is the profile function of the system,

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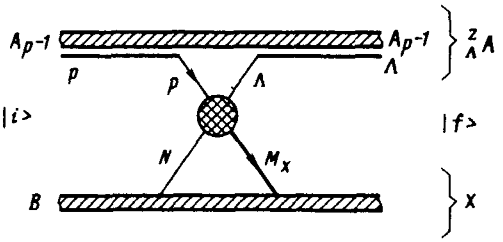

FIG. 1.

$\psi^{0,f}_{p,T}$ are the wave functions of the initial and final state of the ion and the target nucleus. The ψ^j_p functions can be written in the form of superposition of the core functions and single-particle functions of particles before and after the collision ψ^i_p (proton) and ϕ^j_Λ (Λ particle), respectively.

Going over from the profile function of the system Γ to the profile functions of individual particles and using the technique of the Glauber formalism, we determine:

$$\sigma(\mathrm{b}) = \int d\mathrm{b}\; C_{if}(\mathrm{b})\; P_m^{A_T-1}(\mathrm{b}). \tag{3}$$

The quantity $P_m(\mathbf{b})$ is

$$P_m(\mathrm{b}) = \int \rho_T(\mathrm{s}) \exp[\sigma_{NN}^{tot} \rho_m(\mathrm{b}-\mathrm{s})]\, d\mathrm{s}, \tag{4}$$

where $\sigma_{NN}^{\mathrm{tot}}$ is the total cross section of the nucleon-nucleon interaction, $\rho_T(\mathbf{s})$ is the single-particle density of the target nucleus, and $\rho_m(\mathbf{s})$ is the core density. $P_m(\mathbf{b})$ characterizes the probability that the nuclear core will not change its state during the collision. $P_m(\mathbf{b})$ decreases significantly with decreasing $\mathbf{b}$. The quantity $C_{if}(\mathbf{b})$ is given by

$$C_{if}(\mathrm{b}) \approx Z_T \rho_T(\mathrm{b}) \int \frac{d\sigma\,(pN \to \Lambda + X)}{dM_X dt} \left| F_{if}\,(\mathrm{q}\,(M_X,\, t\,))\right|^2 dM_X dt, \tag{5}$$

where $d\sigma/dM_X\, dt$ is the invariant cross section of the inclusive production of the Λ particle in the pN collisions

$$F_{if}(\mathrm{q}) = \int \phi^{*f}_\Lambda(\mathrm{r})\; \phi^i_p(\mathrm{r})\; e^{-i\mathrm{q}\mathrm{r}}\, d\mathrm{r}$$

is the form factor of the transition from the nucleon state $|i\rangle$ to the hyperon state $|f\rangle$. It follows from Eqs. (4) and (5) that the main contribution to the cross section is given by the region of large $\mathbf{b} \sim R_T + R_i$. The cross section also depends on the behavior of the form factor $F_{if}(\mathbf{q})$ at relatively large for the nuclear scale momentum transfer $\mathbf{q}$. All this requires a careful selection of the wave functions $\phi^{if}_{p,\Lambda}$, since the calculated values are highly sensitive to their behavior at the nuclear boundary.

As an example, we examined the process $^{12}C + {}^{12}C \to {}^{11}_{\Lambda}B + \cdots$, where the proton is transferred from the $S_{1/2}$ or the $P_{3/2}$ level to the $S_{1/2}$ or the $P_{3/2}$ level of the Λ hyperon.

TABLE I.

	$\sigma(A + B \rightarrow {}_{\Lambda}A' + \ldots)$, μb				
E GeV/nucleon	$S_{1/2} \rightarrow S_{1/2}$	$S_{1/2} \rightarrow P_{3/2}$	$P_{3/2} \rightarrow S_{1/2}$	$P_{3/2} \rightarrow P_{3/2}$	$\Sigma \sigma_i$
2.1	$4.0 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$2.4 \cdot 10^{-3}$	$1.2 \cdot 10^{-4}$	$2.6 \cdot 10^{-3}$
3.8	$1.2 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$	$3.2 \cdot 10^{-2}$	$2.4 \cdot 10^{-2}$	$8.0 \cdot 10^{-2}$
5	$4.0 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$	$4.0 \cdot 10^{-2}$	$6.0 \cdot 10^{-2}$	$1.8 \cdot 10^{-1}$
18	$2.5 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$	$1.6 \cdot 10^{-1}$	$1.6 \cdot 10^{-1}$	$7.1 \cdot 10^{-1}$

The single-particle wave functions were determined by solving the Schrödinger equation with the Woods-Saxon potential.

$$V_{\Lambda}(r) = -V_{0\Lambda}(r) \Big/ \left[1 - \exp\left(\frac{r - R_{\Lambda}}{d}\right)\right],$$

where $V_{0\Lambda} = 30$ MeV, $R_{\Lambda} = 1.08\,A^{1/3}\Phi$, and $d = 0.5\Phi$, whose parameters are consistent with the data of Ref. 5 and correctly reproduce the binding energy $\epsilon \approx -12$ MeV of the Λ particle in the ${}^{12}_{\Lambda}B$ nucleus: $\epsilon(s_{1/2}) = -11$ MeV, $\epsilon(P_{3/2}) = -0.4$ MeV. The results of the calculations are given in Table I.

It can be seen that 1) the cross section increases rapidly as the kinetic energy of the incident ion increases from $E_0 = 2.1$ GeV/nucleon to $E_0 = 3.8$ GeV/nucleon, but the rate of increase begins to decline with further increase of the energy, i.e., the cross section does not increase significantly with increasing initial energy at $E_0 = 5$ GeV/nucleon; 2) since in the energy region $E_0 = 3$–5 GeV/nucleon the cross sections are sufficiently large, an effective investigation of the hypernuclei can begin now by using the heavy-ion beam of the High-Energy Laboratory of the J.I.N.R.; 3) our results correlate with the calculations of Kozlov *et al.*[6] on the production of slow hypernuclei in the pA collisions. However, because of kinematic singularities the cross sections for the reactions $AB \rightarrow {}_{\Lambda}A'$ are several times larger than those for the production of slow hypernuclei in the reactions $pA \rightarrow {}_{\Lambda}A'$.

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