Mechanism of backward emission of fast protons in hadron-nuclear interactions at medium and high energies

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The backward emission of fast protons in the hadron-nuclear interactions is described by a simple model without taking into account the anomalously large momenta or nucleon densities in the ground state of the target-nucleus. The universal excitation function of few-nucleon groups in nuclei is described.

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At high energies (T_0) of incident hadrons the target nucleus emits fast protons at angles $>90°$. The inclusive spectra of such protons with an energy $\geqslant 30$ MeV have the form

$$E/(p_p^2\,\sigma_t)\,d\sigma/(d\Omega\,dp_p) = A_0\exp(-A_1 p_p^2), \tag{1}$$

(E and p_p are the energy and momentum of the backward-emitted fast proton, σ_t is the total cross section of the hadron-nuclear interaction), A_0 and A_1 depend weakly on the type and energy of the incident hadrons h and the slope parameter A_1 also depends weakly on the mass number A of the target nucleus (see Refs. 1 and 2). An analogous emission of proton was also observed at intermediate energies.[3,4] It is important that as T_0 increases $A_1 \to A_1^{as} \approx 10$–$15$ (GeV/c)$^{-2}$. A number of different hypotheses have been advanced to explain the observed regularities (see, for example, Ref. 5). Most of them attempt to explain the anomalously high intranuclear momenta,[6] densities,[7] or specific mechanisms[8] characteristic of only high energies (for example, quark-parton mechanisms, fireballs). The ability of many models to reproduce the properties of inclusive backward emission of fast protons has prompted us to assume that these models have a redundance in describing the inclusive data. A question arises whether these data can be described at medium and high energies from a single viewpoint without resorting to the special hypotheses on high-momentum nuclear structure.

In view of this, we examined an inclusive emission of protons from the reaction $h + A \rightarrow p(\theta_p > 90^\circ, T_p > 30 \text{ MeV}) + \ldots$ under the following assumptions.

1) The hadron interacts with a group of several nucleons $[kN]$ from a target nucleus. As a result, h scatters forward principally at small angles, which increases the invariant mass of the group M^{inv} ("excitation of the few-nucleon group"):

$$h + [kN] \rightarrow h' + [kN]^*. \tag{2}$$

The protons are back scattered as a result of the decay

$$[kN]^* \rightarrow p + N_1 + N_2 + \ldots + N_{k-1}\,. \tag{3}$$

In the calculations we assumed that (3) occurs statistically.

2) The relative probability that M^{inv} will increase by a specific amount ΔM^{inv} does not depend on the type and energy of h. This probability ("excitation function") is an intrinsic property of the few-nucleon group (FNG), which effectively participates in the process (2) and depends weakly on k and A at $\Delta M^{inv} \geqslant 100$ MeV. For specific calculations we selected the excitation function of the FNG in the form

$$W_k(\Delta M^{inv}) = \exp(-\Delta M^{inv}/M_{ex})/(1 - \exp(-E_k^{\max}/M_{ex}))\,, \tag{4}$$

where M_{ex} is the characteristic parameter of the excitation probability and $E_k^{\max}$ is the maximum kinematically attainable excitation energy in the process (2). If we assume that excitation of the group in question is accomplished via exitation of its nucleons (i.e., primarily via excitation of the Δ (1232) resonance or pion production), then the parameter M_{ex} should be equal to the pion mass.

3) The process (2) has a quasi-diffraction nature, i.e., the scattering of h approaches a diffraction scattering with increasing T_0. (The 4-momentum transfer to the hadron at a fixed $\Delta \Phi M^{inv}$ approaches with increasing T_0 the corresponding value for the elastic $h + [kN]$ scattering.) Therefore, the scattering probability at an angle θ^* in the c.m.s. $(h + [kN])$ at a momentum p_k^* is assumed to be in the form which describes the main maximum of the diffraction scattering on a black sphere of radius $a = 1.81\, k^{1/3} R_{c2}$:

$$W_k(\theta^*) = \exp(-(\theta^* p_k^* k^{1/3} R_{c2})^2)\,, \tag{5}$$

(R_{c2} is the free parameter of the model).

4) The total interaction cross section (2) is determined with an accuracy to the constant factor ($\mathscr{P}$) by the geometric transverse cross section of the FNG $[kN]$ and by the combinatorial probability of determining it in the nucleus:

$$\sigma_{kA} = \mathscr{P}\pi(k^{1/3}R_c + \sqrt{\sigma_{hN}/\pi})^2 (A/k!)(R_k/R_o)^{3(k-1)}$$
$$\times \exp(-(R_k/R_o)^3), \tag{6}$$

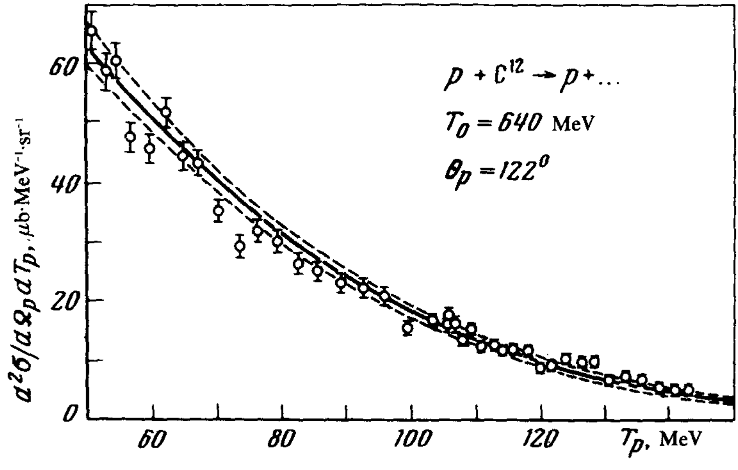

FIG. 1. Energy spectrum of protons. The calculation is represented by the curve with the corridor of errors and the experiment is represented by the points.[4]

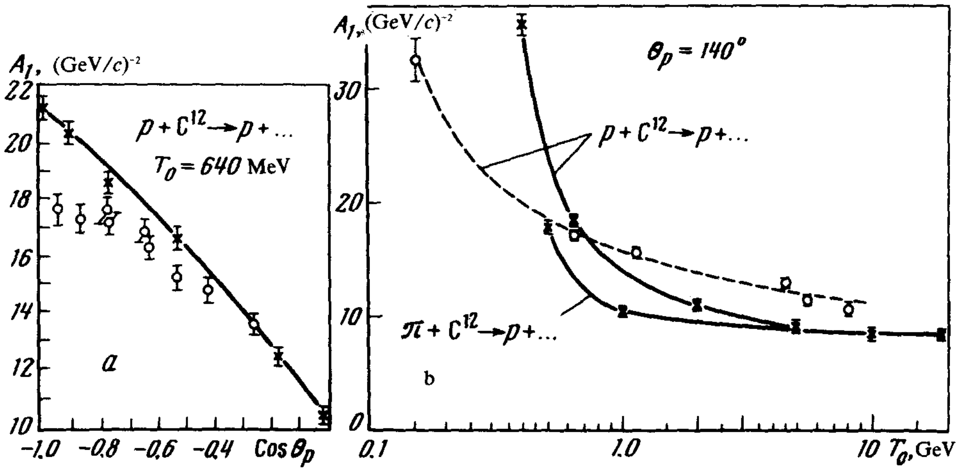

FIG. 2. The angular (a) and energy (b) dependence of A_1: x, calculation; o, experiment (the references are given in Ref. 4); 50 MeV $< T_p <$ 150 MeV.

where σ_{hN} is the total cross section of the hN interaction, $R_k = k^{1/3} R_c$, R_0 and R_c are the average internucleon spacings in the nucleus and in the FNG, respectively. If the average nucleon density in the FNG is close to the average nuclear density, then $R_c = R_0$. We assumed that the momentum distribution of the FNG in the nucleus is Gaussian with the standard $\sigma_F(k) = (\sqrt{k}/2)\, 90$ MeV/c. The secondary interactions h or p in the nucleus were not taken into account.

The proton spectra were calculated as the sum

TABLE I.

Parameter (x)	Accepted value	$(\Delta A_0/A_0)/(\Delta x/x)$	$(\Delta A_1/A_1)/(\Delta x/x)$
M_{ex}	0.14 GeV	−1.4	−0.7
R_0	1.1 F	2.7	−0.4
R_c	1.1 F	0.6	−0.2
R_{c2}	0.25 F	0.2	0.06
$\mathscr{P}$	2.81	1	0

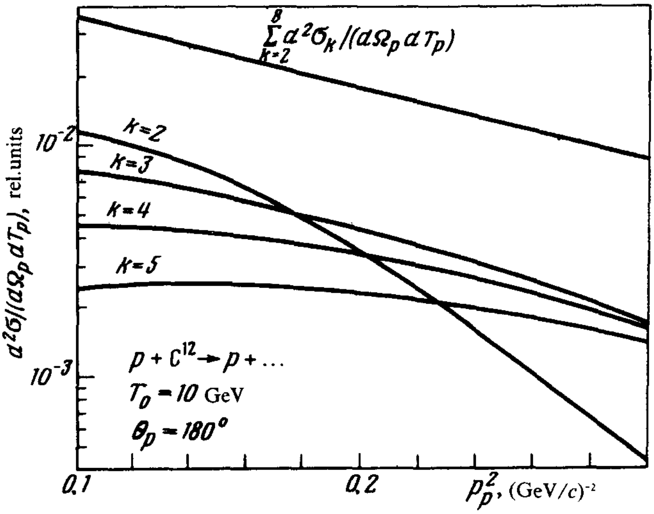

FIG. 3. The components of the calculated spectrum determined from the number k of nucleons in the few-nucleon group.

$$d^3\sigma/d\mathbf{p}_p = \sum_{k=2}^{k_{\max}} d^3\sigma/d\mathbf{p}_p,$$

where $d^3\sigma_k/d\mathbf{p}_p = (\sigma_{kA}/R_k^{FN})(d^3R_k^{FM}/d\mathbf{p}_p)$. The integral of the phase volume R_k^{FM} and its derivative were determined according to the recurrence kinematic Kopylov-Byukling-Kayati type formulas (see Ref. 9) with the introduction into the phase-volume integral of weighting functions in the form (4) and (5) and with accounting of the momentum distribution of the FNG in the target-nucleus. The integration was carried out by the Monte Carlo method.

The parameters R_{c2} and $\mathscr{P}$ were selected by comparing the calculated spectrum with the experimental spectrum[4] for the reaction $p + C^{12} \to p + \ldots$ at 640 MeV and θ_p

$= 122^\circ$. Figure 1 shows the result of such a comparison at $R_c = 0.25$ F and $\mathscr{P} = 2.8$. Having recorded these values, we obtain the calculated angular dependence A_1, which is close to the experimental, (Fig. 2a) and a scaling character of the energy dependence of this parameter (Fig. 2b). The obtained results are stable against variation of the parameters used in the calculation.

Thus, the inclusive data can be explained by using simple assumptions about the properties of the nucleus and the reaction mechanism. The results depend weakly on the specific functions (4) and (5), since the observed spectrum is a complex composition of the partial spectra of FNG with a different k (Fig. 3). The statistical character of the spectra is a consequence of the large number of possibilities for the emission of a proton with a given $\mathbf{p}_p(2 \leqslant k \leqslant k_{\max} = 6 - 8$, decay (3), Fermi motion of the center of mass of the $[kN]$ group). Specific channels (2) with the leading hadron h' can be isolated and studied in the exclusive and semi-inclusive measurements (see, for example, Ref. 10). If the scattering (2) has a quasi diffraction coherent nature, then the angular distribution of h' should have the width $\Delta\theta^k \approx (p_k^* k^{1/3} R_{c2})^{-1}$ The assumption that the excitation of FNG can be described by the same function for different nuclei and incident particles is experimentally verifiable: the distributions over ΔM^{inv} can be directly measured at least for the light nuclei in a wide range of reactions which are accompanied by excitation of the few-nucleon groups. As a consequence of such universality of the excitation function, we can expect, for example, a unique coupling between the slope parameters of the spectra of fast protons and fragments (H^2, H^3, He^3, He^4) emitted backward in the hadron-nuclear reactions or for the spectra of fast, forward-emitted pions in the deuteron-nuclear collisions and spectra of protons emitted backward as a result of disintegration of the deuteron by nucleons.

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