Momentum distributions of backward-emitted protons in 1-GeV proton-nucleus interactions

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The spectra of protons emitted at an angle of 156° from various target nuclei ranging from deuterium to lead have been measured. For light nuclei, the proton spectrum changes slope in the momentum interval 350–450 MeV/*c*. The results obtained for the deuteron are compared with the predictions of various models.

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Inelastic nuclear reactions which produce particles in a kinematic region forbidden in scattering by the free nucleon have recently attracted considerable interest. According to the customary cascade mechanism for inelastic reactions, the production of particles in this kinematically forbidden region may result from the rescattering of nucleons and the production and subsequent absorption of π mesons in nuclei.[1] Some other mechanisms which are now being discussed extensively link the production of particles in the kinematically forbidden region with a high-angular-momentum component of the nuclear wave function[2] or short-range few-nucleon correlations in the nuclei.[3] It has not been possible to draw conclusions regarding the validity of the various models on the basis of the experimental data available. In an effort to obtain the systematic and more accurate experimental information necessary we have measured the spectra of protons produced in the kinematically forbidden region by 1-GeV protons for a wide range of target nuclei, from deuterium to lead.

The experiments were carried out in the proton beam of the synchrocyclotron of the Leningrad Institute of Nuclear Physics. A magnetic spectrometer was combined with time-of-flight measurements to record the spectra and to identify the particles. The targets were D, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, Be, C, Al, ^{58}Ni, Ag, and Pb nuclei. The measurements were taken at an angle of 156° from the direction of the proton beam. The experimental results are shown in Fig. 1. The absolute errors in the cross sections

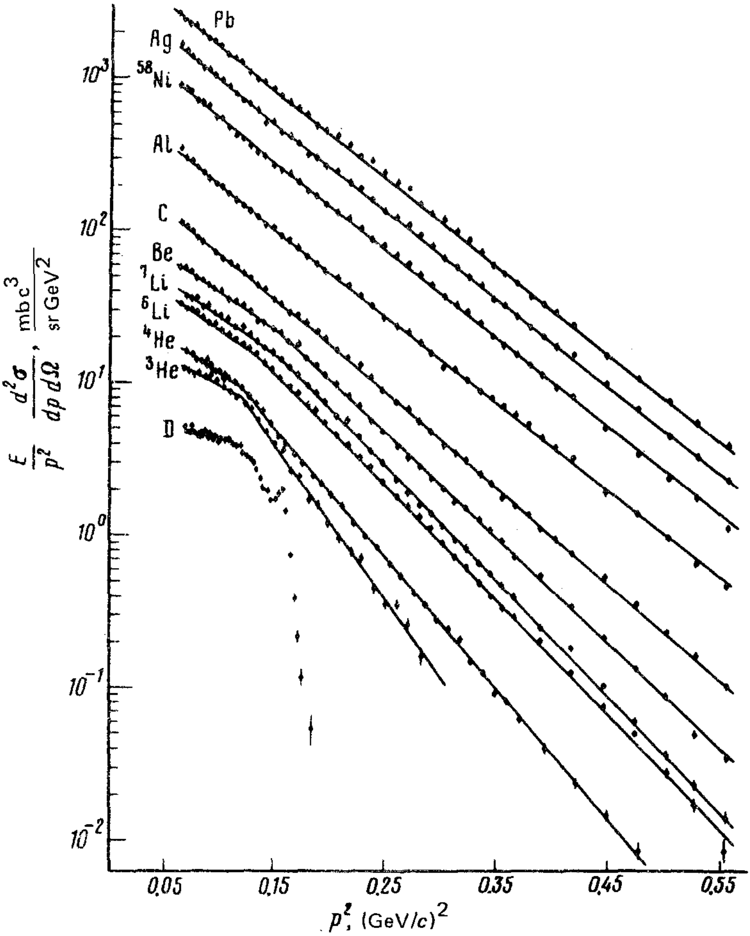

FIG. 1. Invariant cross sections vs the square momentum of protons emitted at an angle $\theta = 156°$ from various nuclei bombarded by 1-GeV protons. Solid curves—exponential approximation of the cross section.

determined with the solid targets and the gaseous targets (D, ^{3}He, and ^{4}He) are 20% and 25%, respectively. The experimental procedure is described in detail in Ref. 4.

It can be seen from Fig. 1 that the invariant cross section is an exponential function of the square momentum of the protons in the case of the heavy targets:

$$\frac{E}{p^2}\frac{d^2\sigma}{dp\,d\Omega} = C\exp(-Bp^2)\ , \tag{1}$$

where B is the slope parameter of the spectra. The values of the criterion χ^2/N_f, where N_f is the number of degrees of freedom, lie in the range 1.4–1.7 for most of the heavy and intermediate-weight nuclei for this parametrization of the cross sections. For nuclei lighter than carbon, however, the spectral shape may be significantly different from this simple exponential function. The slope of the proton spectrum is observed to

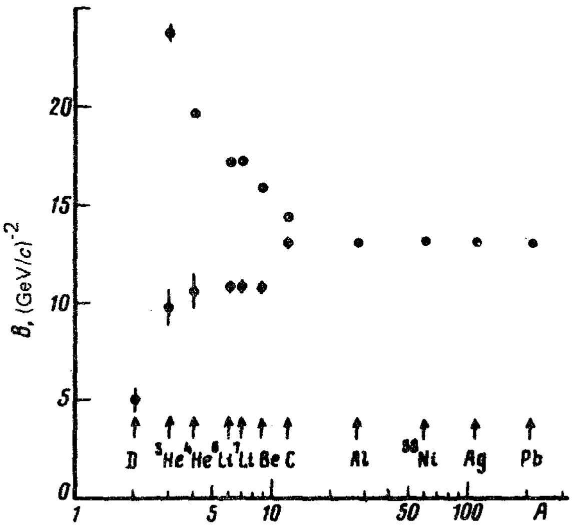

FIG. 2. Slope parameter of the proton spectrum vs the mass number of the target nucleus. ●—The slope parameter (B) for the spectra of protons from nuclei heavier than carbon; ◐—the slope parameter (B_1) in the soft part of the spectrum of protons from light nuclei; ◑—the slope parameter (B_2) in the hard part of the spectrum of protons from light nuclei.

change in the momentum interval 350–450 MeV/c. When these cross sections are parametrized by the single exponential function in (1), the value of χ^2/N_f reaches ~ 15. When the cross sections are instead parametrized by two exponential functions,

$$\frac{E}{p^2}\frac{d^2\sigma}{dp\,d\Omega} = C_1 \exp(-B_1 p^2) \qquad p < p_0\,, \tag{2}$$

$$\frac{E}{p^2}\frac{d^2\sigma}{dp\,d\Omega} = C_2 \exp(-B_2 p^2) \qquad p > p_0\,,$$

with different slope parameters B_1 and B_2 in the soft and hard parts of the spectrum, we find a rather good fit with $\chi^2/N_f = 0.7$–1.5 for most of the light nuclei. The slope parameters are shown in Fig. 2. For nuclei heavier than carbon the slope can be said very accurately to be independent of the mass number of the target nucleus. For the lighter nuclei the slope parameters become quite different for the soft and hard parts of the spectra and dependent on the mass number of the target nucleus. The particular proton momentum (p_0) at which the spectrum changes slope also depends on the mass of the target nucleus, increasing from 350 MeV/c for ^{3}He to 450 MeV/c for carbon.

A change in the slope of the proton spectrum is also observed in the case of the deuteron. In this case the shape of the spectrum is most noticeably different from the typical shape for heavy and intermediate nuclei. Indications of an irregularity at 350 MeV/c in the spectra of protons from the deuteron were also found in Ref. 5. The reaction with the deuteron is apparently the simplest process that produces protons in the kinematically forbidden region. A study of the mechanism for this reaction may be of helpful in reaching an understanding of the corresponding processes for other nu-

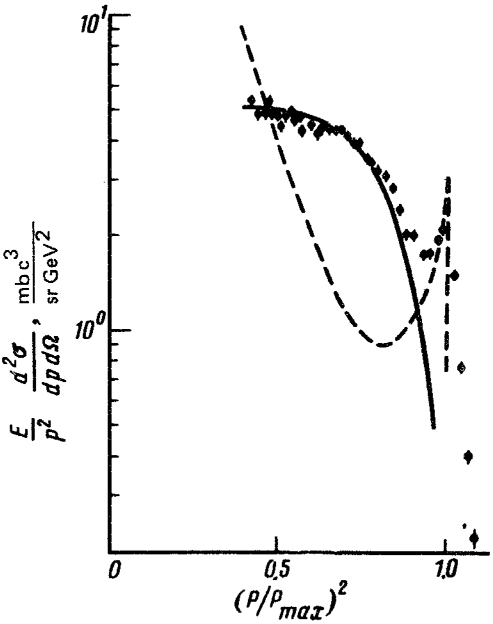

FIG. 3. Experimental and calculated invariant cross sections from the production of protons in the kinematically forbidden region in reactions involving the deuteron. Dashed curve—calculated in the model of quasifree scattering[6]; solid curve—calculated from the diagram involving a rescattering of a Δ isobar in an intermediate state.[8]

clei. Yukawa and Furui[6] have examined a simple model of quasifree proton scattering by the deuteron in which the deuteron is assigned the wave function corresponding to the Reid soft-core potential. The spectrum of protons produced at an angle of 180° for an incident-proton energy of 1 GeV, according to this model, is shown in Fig. 3. The shape of the theoretical spectrum does not agree with the experimental results. No qualitative change in the theoretical results is achieved by using the deuteron wave function corresponding to the Hamada-Johnston hard-core potential and by introducing a Glauber screening. At intermediate energies of the incident particles it is evident necessary to consider rescattering and also inelastic reaction mechanisms in addition to the single interaction, even for the lightest nuclei.

Kopeliovich and Radomanov[8] have shown that the rescattering of a Δ isobar in an intermediate state can be important in the cross section for the production of protons in the kinematically forbidden region from a deuteron in the ranges of energies and angles of interest here. Figure 3 shows the results calculated on the basis of this mechanism. Specifically, the spectrum of protons produced over the angular interval 132°–180° in interactions with 977-MeV protons was calculated. The shape of the calculated spectrum is seen to be in qualitative agreement with the experimental shape. A similar result was obtained in a calculation for the production of protons from the deuteron on the basis of a triangle diagram with the exchange of a π meson in an intermediate state.[9] According to this mechanism, the spectrum of protons in the kinematically forbidded region is similar to the energy spectrum of the π mesons produced in the $NN \rightarrow NN\pi$ reaction. At an incident-proton energy of 1 GeV, this is a resonant reaction by virtue of the formation of a Δ isobar in an intermediate state. It may also be that the irregularity in the soft part of the proton spectrum for reactions involving the other light nuclei (Fig. 1) is also due to the production of a Δ isobar in an intermediate state. For nuclei heavier than carbon, multiple rescattering of the emitted protons is probably masking the resonant effect.

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