Resonant enhancement in the distributions of cumulative nucleons from the reaction $\pi^- d \to \pi^- pn$

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The distributions of the cumulative nucleons produced in the interaction of π^- mesons with momenta of 371, 438, and 552 MeV/c with deuterons have been measured. There is a difference between the neutron and proton distributions, which is explained in terms of a resonant enhancement in double pion scattering by the nucleons of the deuteron.

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Of particular interest in research on the interaction of intermediate-energy hadrons with nuclei is the production of cumulative nucleons, i.e., particles in a region of variables which is kinematically forbidden in the case of scattering by a free nucleon. The distributions of cumulative nucleons usually have an exponential energy dependence, which has been explained qualitatively by several models. The simplest way to test the various mechanisms in their "pure" forms is to study the production of cumulative nucleons in the interaction of hadrons with deuterons, since in this case there is no distortion of the shape of the distributions resulting from the passage of nucleons through a nucleus, and the wave function of the deuteron is known quite well.

In this letter we are reporting a study of the production of cumulative nucleons during the breakup of the deuteron by intermediate-energy π mesons.

The experiments were carried out with a 35-cm bubble chamber filled with deuterium and exposed to the π-meson beam of the synchrocylotron of the Leningrad Institute of Nuclear Physics, for three values of the momentum of the incident π^- mesons: 371, 438, and 552 MeV/c. The beam momentum spreads were 35, 35, and 25 MeV/c (FWHM), respectively. The total numbers of stereo photographs examined for the respective momenta were 2.5×10^4, 1.2×10^5, and 1.4×10^5. After measurements and identification, the total statistical bases for the reaction $\pi^- d \to \pi^- pn$ were 2000, 7200, and 13 000 events, respectively. There was an important experimental limitation here: Events with a proton track length shorter than 1.5 mm in the chamber were not detected. The procedure is described in detail elsewhere.[1]

Figure 1 shows the energy distributions of the cumulative protons and neutrons emitted into the rear hemisphere with respect to the beam direction. For all three momenta of the incident π mesons, the distributions of cumulative neutrons differ in shape from those of the cumulative protons. Above 30 MeV in the proton distri-

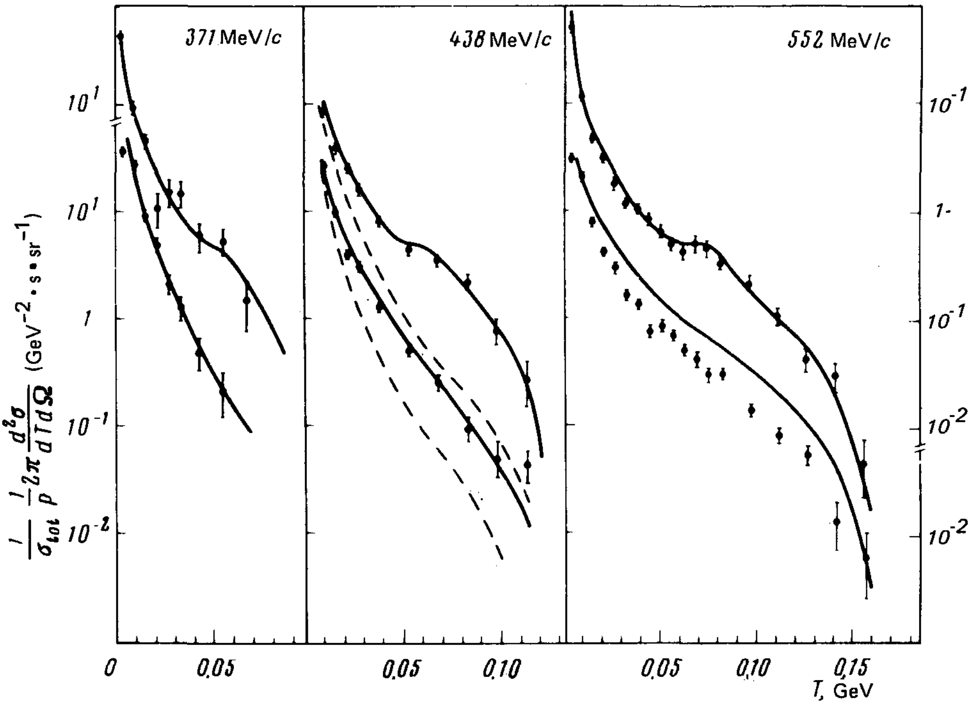

FIG. 1. Energy distributions of the nucleons emitted into the rear hemisphere. Circles–neutrons; squares–protons; curves–theoretical (see the text).

butions we see the usual exponential decay of the invariant cross section, while the neutron distributions have a broad knee at 60–80 MeV.

A purely qualitative explanation for this difference between the proton and neutron distributions runs as follows[2]: After it is scattered by one of the nucleons of the deuteron, the π^- meson loses energy and changes direction, so that a scattering by the second nucleon may result in the emission of that nucleon into the rear hemisphere. The scattering amplitude in the second collision can become very large as the $\Delta(3.3)$ resonance is approached, and since the cross section for the elastic $\pi^- n$ interaction in this region is larger than the cross section for $\pi^- p$ scattering by nearly an order of magnitude, this resonant-enhancement effect should be seen more clearly in the neutron distribution. The amplitude for double scattering, which can send a neutron into the rear hemisphere, is proportional to the product of the elementary amplitudes for elastic πN scattering, $f_{\pi^- p} f_{\pi^- n}$. For protons, on the other hand, the corresponding amplitude, incorporating charge exchange of the π^- meson in an intermediate state, is proportional to[3] $(f_{\pi^- n} f_{\pi^- p} - f^{ex}_{\pi^- p} f^{ex}_{\pi^0 n})$, where f^{ex} is the amplitude of the reaction $\pi^- p \rightleftarrows \pi^0 n$. Using the familiar relation for the amplitudes at the resonant energy and the triangle rule for the πN amplitudes in the first scattering, we find that the amplitude for the emission of cumulative protons is $(1/3) f_{\pi^- p} f_{\pi^- n}$.

For an experimental test of this hypothesis, we eliminated from the statistical base those events which corresponded to proton kinetic energies in the range

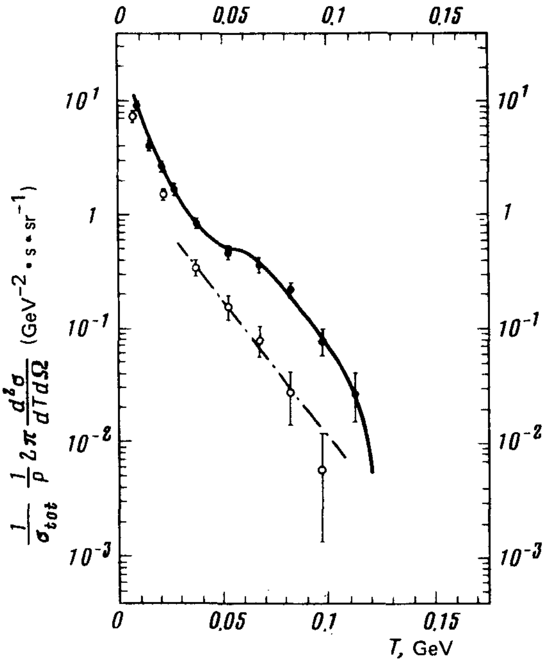

FIG. 2. Energy distributions of neutrons emitted into the rear hemisphere of a beam momentum of 438 MeV/c. Filled circles—entire statistical base; open circles—statistical base remaining after the elimination of events for which the proton energy lies in the interval $80 < T_p < 200$ MeV; solid curve—theoretical; dashed curve—distribution of cumulative protons.

$80 < T_p < 220$ MeV; this range corresponds approximately to the isobar band of the intermediate $\pi^- n$ state. Figure 2 shows the distributions of neutrons emitted into the rear hemisphere before and after the elimination of this isobar band for the momentum of 438 MeV/c; shown for comparison here is the distribution of cumulative protons. Clearly, the elimination of the events in the isobar band has eliminated the knee from the distribution of cumulative neutrons.

One of the present authors has carried out calculations[3] to finally resolve the nature of the observed effect. These calculations dealt with single and double scattering of the pion in the deuteron with allowance for the Fermi motion of the nucleons and for the final-state interaction of the nucleons. Since the π meson must change direction during the first collision in order to enter the resonant region, the theory of diffractive scattering cannot be applied here, and we are dealing with definitely non-Glauber effects in the theory of multiple scattering.[4] The amplitudes for πN scattering were taken from a CERN phase-shift analysis.[5] In the incorporation of the final-state interaction, the amplitude for pn scattering was calculated in the effective-radius approximation. The Hulthen wave function was used as the deuteron wave function. These theoretical results are shown by the solid curves in Figs. 1 and 2. The dashed curves in Fig. 1 show the results of a separate version of the calculation in which the diagrams with π rescattering were not considered.

A few conclusions can be drawn from these results. First, the multiple-scattering theory gives a correct qualitative and quantitative description of the resonant-enhancement effect. We emphasize that there were no adjustable parameters in these calculations. Second, it is clear from a comparison of the solid and dashed curves that the rescattering of the π meson is important in both the proton and neutron distributions, and the difference between these distributions is also related to the rescattering of the π meson. This situation is characteristic of those π energies at which the amplitude for the πN interaction is large with respect to the distance between the nucleons.

In summary, it can now be asserted that there is definitely a resonant enhancement in the production of cumulative nucleons during the breakup of the deuteron by intermediate-energy π mesons. The knee observed in the neutron distribution varies slightly in position, depending on the initial energy, but it remains in the region 60–100 MeV. Effects of this type may also be seen in the interaction of high-energy particles with nuclei; the resonant enhancement in the same part of the cumulative-nucleon distribution will be caused primarily by inelastically produced π mesons. It may be that the irregularities, which have been observed[6] in the distributions of cumulative nucleons produced in the ^{12}C nucleus in interactions with hadrons at 3–7 MeV/c, are of this nature.

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