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Formation of Neutral π-mesons in (n-p) Collisions at Effective Neutron Energies of 590 mev

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THe kinematic calculation of the processes of formation of π^0-mesons in collisions of neutrons with free protons:

$$n + p \rightarrow \pi^0 + d, \qquad (1)$$

$$n + p \rightarrow \pi^0 + n + p, \qquad (2)$$

which are accompanied by the decay of these mesons into two γ-quanta shows that the probability of emission of the γ-quanta at 90° (in the laboratory system) from the beam of neutrons, depends very slightly on the angular distribution of π^0-mesons in the center of mass system of the colliding nucleons as well as on the velocity of the center of mass. This fact makes it possible in principle to determine the sum of the total cross sections for forming π^0-mesons in reactions (1) and (2) by measuring the number of γ-quanta coming out of the target at an angle of 90°.

The arrangement of the apparatus, used in the experiment, is shown in Fig. 1. Neutrons of high energy were generated by bombarding the internal beryllium target of the synchrocyclotron with protons of energy 680 mev. The intensity of the beam of neutrons of energy above 400 mev in the region of the apparatus was $\sim$ 1-2 $\times 10^4$ neutrons/cm^{2}sec. The energy distribution of neutrons in the beam was investigated in a special experiment by Fliagin[1] and is shown in Fig. 2.

Gamma-quanta from the decay of π^0-mesons, generated in the target, were detected in the telescope of two scintillators and one Cerenkov counter labeled in the Figure by the numbers 1, 2 and 3, respectively. The conversion of the

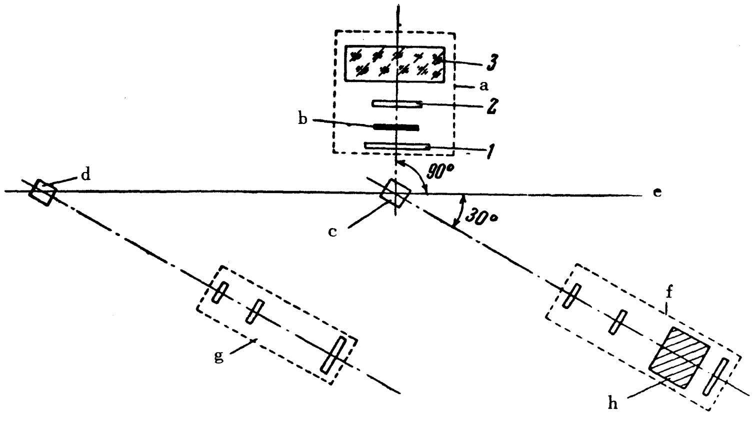

FIG. 1. Scematic Arrangement of the Apparatus
a - telescope-detector of γ-quanta, b - converter, c - target, d - scatterer, e - neutron beam, f - telescope-detector of protons, g - telescope-monitor, h - Tungsten filter

γ-quanta was carried out in a lead plate (converter) of 3 mm thickness, located behind the first counter. This counter serves to prevent the possibility of the detector registering fast charged particles flying from the target, and is connected in anti-coincidence with the counters 2 and 3. The Cerenkov radiation of the conversion electrons in a 3-meter counter, which is a block of plexiglas, was recorded simultaneously on a pair of photo multipliers. All of the relative measurements were carried out with the aid of this detector.

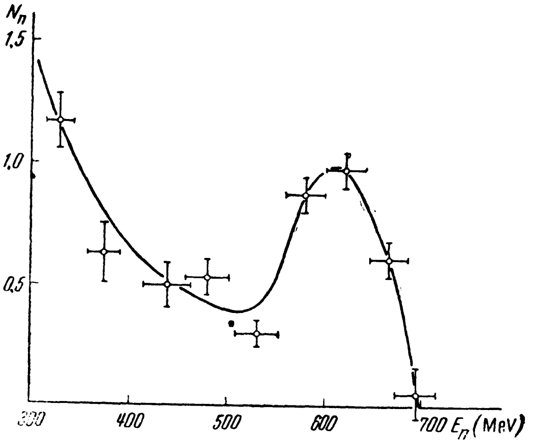

FIG. 2. Energy distribution of Neutrons

The effect of the generation of π^0-mesons in collisions of neutrons with free protons was determined as a difference between the effects of targets of polyethylene and graphite, consisting of an equal number of carbon atoms. By means of this study, carried out with these targets, we have the ratio of the cross sections for emission at angles of 90° (in the laboratory system) of γ-quanta from the decay of π^0-mesons from hydrogen and carbon. This ratio was shown to be equal to

$$\left(\frac{d\sigma_\gamma}{d\Omega}\right)^{\mathrm{H}}_{90^\circ} \Big/ \left(\frac{d\sigma_\gamma}{d\Omega}\right)^{\mathrm{C}}_{90} = 0.215 \pm 0.014. \qquad (3)$$

The absoulute value of the yield of emitted γ-quanta was determined in experiments in which (simultaneously with the measurement of the flux of γ-quanta) we determined the recoil proton flux produced by elastic ($n-p$) scattering whose cross section for neutrons of mean energy 590 mev had been determined in our laboratory[2]. For this purpose, the telescope which detected γ-quanta, the Cerenkov counter, was replaced by a scintillator. In this manner we eliminated the need of determining the effect of the Cerenkov counter in an auxiliary experiment. The converter in this experiment has a thickness of 1 mm. The telescope which registered the proton recoils was located at an angle of 30° relative to the direction of the neutron beam (see Fig. 1) and acted on the target in common with the γ-detector. In order to use the data of experiments on ($n-p$) scattering in our work, a tungsten filter wasplaced in front of the last counter of the telescope-detector of protons. This filter guaranteed an energy threshold for the particle counter the same as the threshold of the detector used in reference 2.

The absolute cross section for the emission of γ-quanta at 90° (in the laboratory system) from the neutron beam for a hydrogen target under the conditions of our experiment is expressed by the following formula:

$$\left(\frac{d\sigma_\gamma}{d\Omega}\right)^{\mathrm{H}}_{90^\circ} = \left(\frac{N_\gamma}{N_p}\right)^{\mathrm{H}} \frac{\Delta\Omega_p \cdot K_p}{\Delta\Omega_\gamma K_\gamma} \left(\frac{d\sigma_{np}}{d\Omega}\right)_{30^\circ}, \qquad (4)$$

where the symbols γ and p stand for the detector of γ-quanta and protons respectively; N = the counting rate of the detector; $\Delta\Omega$ the solid angle intercepted by the detector; k the efficiency of the detector; $(d\sigma_{np}/d\Omega)_{30}$ the elastic (n-p) scattering for an angle of 30°, equal, according to reference 2 to $(3.1 \pm 0.2) \times 10^{-27}\,\mathrm{cm}^2$/steradian.

For determining the values of N_γ^H and N_p^H, we measured simultaneously in both detectors the effect of the carbon target, while the effect of the hydrogen was determined with the help of the known value of Eq. (3). A similar analysis was performed for the proton detector (for 30°).

The coefficient K_p takes into account the absorption of recoil protons by the filter. This coefficient was determined directly from the experiment With this in view, we placed a system of two telescopes in the proton beam emerging from the synchrocyclotron; these registered elastic (p-p) events. One of these telescopes was used as described here as the proton detector. The coefficient K_p was determined as the ratio of the counting rates with and withoutthe filter* and was given experimentally as equal to 0.5.

The efficiency for detecting γ-quanta K_γ is equal to the product of the conversion probability p with the coefficient η, which takes into account the loss of electrons owing to scattering in the converter. The probability p is easily calculated on the basis of the known experimental and theoretical work on the total cross section for absorption of γ-rays in lead. The coefficient η was determined by calculating by the method given by Moliere[3]. For a converter of 1 mm thickness and average energy of γ-quanta ~ 100 mev, η is found to be equal to ~ 1%**.

The basic difficulties which arise in trying to determine K_γ, are the following: 1) The energy of π^0-mesons in the center of mass system of the colliding nucleons can take on different values, (2) the unknown form of the angular distribution of π^0-mesons in this system (both factors determine the spectrum of detected γ-quanta). However, as is demonstrated by calculation, the weighted average of K_γ over the spectrum of γ-quanta is slightly dependent on these factors and changes in the range from 0.089 to 0.098 for a mean energy of incident neutrons of 600 mev and a converter thickness of 1 mm.

The effective solid angle of the detector of γ-quanta was found by conducting a separate experiment in which we studied the dependence of the counting rate of the γ-detector on the diameter of the converter.

On the basis of our determination of the values of N, k and $\Delta\Omega$ and also the known cross section $(d\sigma_{np}/d\Omega)_{30^\circ}$ from Eq. (4) for an angle of 90°, we obtain the absolute cross section for the emission of γ-quanta from the decay of π^0-mesons by collisions of neutrons with hydrogen. This cross section equals

$$(d\sigma_\gamma/d\Omega)^{H}_{90^\circ} = (0.72 \pm 0.18)\cdot 10^{-27}\ \text{cm}^2/\textit{steradian}. \qquad (5)$$

On account of the non-monoenergetic neutron flux (see Fig. 2) the cross section found by us is averaged over the energy spectrum of the neutrons. For determining the effective energy to which we refer this cross section, we made use of data on relative yields of γ-quanta in the reaction $p + n \to \pi^0 + (n + p)$ in the proton energy range 490-650 mev obtained in the work of reference 4, data on the formation of π^0 mesons for nucleon energies 340 mev[5] and 400 mev[6] and also for the neutron spectrum shown in Fig. 2. The effective neutron energy in our experiment turned out to be equal to 590 ± 20 mev.

The absolute value of the cross section $(d\sigma_\gamma/d\Omega)^{H}_{90^\circ}$ as indicated above, enables us to get the total cross section for generating π^0-mesons in (n-p) collisions. On the assumption that the angular distribution of π^0-mesons is isotropic in the center of mass system of the colliding nucleons, we derive the value***

$$\sigma^{\pi^0}_{np} = (5.9 \pm 1.5)\cdot 10^{-27}\ \text{cm}^2. \qquad (6)$$

In the case of an angular distribution $\sim \cos^2\theta$ for π^0-mesons having a momentum (in the center of mass system) equal to half the maximum, the cross section turns out to be 5% greater and is

$$\sigma^{\pi^0}_{np} = (6.3 \pm 1.7)\cdot 10^{-27}\ \text{cm}^2. \qquad (7)$$

Comparing the cross section (6) with the cross section measured in reference 5 for protons of energy 340 mev, it is evident that the increase of the cross section for generating π^0-mesons in (n-p) collisions in the energy range 340-600 mev is proportional to $k^{3.3 \pm 0.5}$, where k is the maximum meson momentum in the center of mass of the colliding nucleons.

If we use the result of reference 7, in which was determined the cross section for formation of π^0-mesons by protons of 670 mev on neutrons bound in deuterium, and convert this to the energy 590 mev with the aid of the relation $\sigma^{\pi^0}_{pn} \sim k^{3.2}$ given in reference 7, then $\sigma^{\pi^0}_{pn}$ is found to equal $(5.3 \pm 1.2) \times 10^{-27}$ cm^2. For the same energy the cross section $\sigma^{\pi^0}_{np}$ obtained by us was somewhat larger, as was to be expected. However, the precision of the results of the two experiments is insufficient to attempt to establish, on the basis of the observed difference in the cross sections for forming π^0-mesons from nucleons that are free or bound in deuterium, a quantitative estimate of the effect of bound nucleons on the process of forming mesons.

For a neutron energy of 590 mev, the cross section for forming π^0-mesons in (n-p) collisions appears to be approximately 17% of the total cross section for the (n-p) interaction, which at this energy equals $(36 \pm 2) \times 10^{-27}$ cm^2 according to reference 8.

In conjunction with our results and those available in the literature on the cross section for generating π^0-mesons in nucleon-nucleon collisions for $E_{\text{nucl.}} \approx 600$ mev it appears that they satisfy the relation

$$\sigma^{\pi^0}_{np} = {}^1\!/_2\sigma^{\pi^+}_{pp} + \sigma^{\pi^-}_{np} - \sigma^{\pi^0}_{pp} \qquad (8)$$

and, so, do not contradict the requirements of the charge invariance of the nuclear force. If we assume that this hypothesis is correct, then we can take advantage of the resultant equation $\sigma(pp \to \pi^+, d) = 2\sigma(np \to \pi^0, d)$. It is then possible to obtain the cross section for formation of π^0-mesons from the reaction (1). Thus, according to the experiment in reference 9, for $E_p = 586$ mev, $\sigma(pp \to \pi^+ + d)$ equals $(2.95 \pm 0.15) \times 10^{-27}$ cm^2; then for the same energy $\sigma(np \to \pi^0 + d)$ has to be equal to 1.5×10^{-27} cm^2. Under these conditions it follows that, for an energy of 590 mev, the cross section for generating π^0-mesons in reaction (2) is approximately three times greater than that in reaction (1).

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*We make use of this opportunity to express our thanks to B. S. Neganov for help rendered to us in conducting this experiment.

** The geometry of our γ-detector allows detection of all electrons of energy > 10 mev emitted in a cone of opening angle 40°.

*** On the assumption of an isotropic angular distribution of π^0-mesons Eq. (3) tells us that the cross section for formation of π^0-mesons from carbon is $\sigma_c^{\pi^0} = 27.4 \pm 6.7 \times 10^{-27}$ cm^2.

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Microwave Spectrum of the C_2H_5Cl Molecule

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We have carried out a preliminary study of the rotational spectrum of the C_2H_5Cl molecule. A short communication on the spectrum of this molecule was published by Wagner and Dailey[1], who studied the transitions $1_{11} - 2_{12}$, $1_{10} - 2_{11}$, $2_{22} - 3_{32}$ and $2_{20} - 3_{21}$ in the $C_2H_5Cl^{35}$ molecule, and the $1_{11} - 2_{21}$ and $1_{10} - 2_{11}$ transitions in the $C_2H_5Cl^{37}$ molecule. From these transitions they obtained the values of the rotational constants B and C, as well as the magnitudes of the quadrupole bonds along the principal axes of inertia.

We have studied additional transitions whose frequencies have the following values, neglecting the effects of quadrupole interactions:

Molecule	Transition	Observed Frequency (mc/sec)
$C_2H_5Cl^{35}$	$0_{00} - 1_{01}$	10 246.20 ± 0,05
$C_2H_5Cl^{35}$	$1_{01} - 2_{02}$	20 903.80 ± 0,04
$C_2H_5Cl^{37}$	$0_{00} - 1_{01}$	10 456.00 ± 0,05

The frequency of the transition line $0_{00} - 1_{01}$ coincides with the frequency calculated from the the values for B and C given in reference 1*.

The frequency of the transition $1_{01} - 2_{02}$ depends on the rotational constant A; calculation gave the value $A = 30{,}940 \pm 200$ mc/sec. The low accuracy in the determination of A is due to the fact that A enters into the value of the transition frequency $1_{01} - 2_{02}$ as a small correction of the form $(B - C)^2/A$, and the magnitudes of B and C are very similar. Note that, in general, the accuracy of determining A is always small if it is determined from transitions involving a change in the dipole moment μ_a. We propose to observe transitions involving the measurement of μ_b. Although these transitions give less intense lines, they provide a more accurate determination of A.

Using the transition $0_{00} - 1_{01}$, we have determined the dipole moment μ_a of the $C_2H_5Cl^{35}$ molecule from the Stark splitting of the line which has the hyperfine structure $F = 3/2 - 5/2$, at applied fields of 195 v/cm and 292 v/cm. The calculation of μ_a was carried out using the "weak field" formula. The value found for μ_a was 1.79 ± 0.05 D.

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* The rotational constants for $C_2H_5Cl^{37}$ given in reference 1 are incorrect, and were therefore calculated directly from the line frequencies given therein.

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