Production of Neutral Pions by Neutrons on Deuterons and Complex Nuclei*

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The γ-ray yield from the decay of neutral pions produced by 590-Mev neutrons in deuterium has been measured at an angle of 90° in the laboratory system. The total cross-sections for the production of neutral pions in (nd) and (nn) collisions, determined on the basis of these measurements, were found to be $\sigma^{\pi^0}_{nd} = (7.4 \pm 2.0) \times 10^{-27}\ \text{cm}^2$, $\sigma^{\pi^0}_{nn} = (1.7 \pm 0.5) \times 10^{-27}\ \text{cm}^2$.

The relative yield of γ-rays from the decay of neutral pions produced in various elements was also measured at this angle. The γ-ray yield can be described approximately by the function $A^{2/3}$.

1. INTRODUCTION

PROCESSES in which neutral mesons are produced in the interaction of high-energy neutrons with nucleons and complex nuclei have been investigated less thoroughly than similar processes induced by protons. This situation arises as a result of the difficulties encountered in neutron experiments. On one hand one finds relatively weak neutron flux intensities; on the other there is the small cross-section for the production of neutral pions at neutron energies on the order of 400 Mev, which are typical of the large majority of existing synchrocyclotrons.

The fact that a neutron beam with an energy of approximately 600 Mev was available at the synchrocyclotron of the Laboratory for Nuclear Problems made it possible to start a systematic investigation of the production of neutral pions by neutrons on nucleons and complex nuclei. We have already reported the results of measurements of the cross-section $\sigma^{\pi^0}_{np}$ for the production of neutral pions in $(n-p)$ collisions.[1] When the present work was finished, we had obtained more complete data on the neutron spectrum which was used in our experiments and also completed the measurements of the differential cross-sections for elastic $(n-p)$ scattering which was used in Ref. 1 to determine the absolute magnitude of the cross-section $\sigma^{\pi^0}_{np}$. The new data have made it possible to obtain a more accurate cross-section $\sigma^{\pi^0}_{np}$ at an effective proton energy of 590 Mev and yield the value

$\sigma^{\pi^0}_{np} = (5.7 \pm 1.5) \times 10^{-27}\ \text{cm}^2$.

In the present work we present the results of measurements of the total cross-sections for the production of neutral pions in collisions with neutrons and deuterons as well as data on the γ-ray yields in the decay of neutral pions produced by neutrons in nuclei of various elements. The most interesting of these experiments is the investigation of the production of neutral pions in neutron-neutron collisions since this reaction has not been observed until recently.

2. PRODUCTION OF NEUTRAL PIONS IN DEUTERIUM

Difference experiments with D_2O and H_2O targets were performed to study the production of neutral pions in deuterium. The containers for the heavy water and the ordinary water were plexiglass cylinders 40 mm in diameter, 40 mm long, with a wall thickness of 0.5 mm. As in Ref. 1, the γ-rays from the decay of neutral pions were detected with a telescope oriented at an angle of 90° with respect to the neutron beam, and consisting of scintillation counters and a Cerenkov detector. The magnitude of the total cross-section for the production of neutral pions, determined from the γ-ray yield at an angle of 90° in the laboratory system, is relatively weakly dependent on the angle distribution of the neutral pions in the center of mass system (CMS) of the colliding nucleons (provided only the odd powers of $\cos\theta$ are relativetively weak in the angle distribution, where θ is the pion angle in the CMS). Hence, in determining the cross-section $\sigma^{\pi^0}_{nd}$ for the production of neutral pions on the deuteron, and also in determining the

*The results of this work have been reported at the Moscow and Geneva conferences on high-energy particle physics in 1956.

difference $\sigma^{\pi^0}_{n(d-p)}$ in the cross-sections for the deuteron and hydrogen, we have started from this assumption; furthermore, we have neglected the difference in angle distribution for neutral pions produced in the bound nucleons in the deuteron as compared with the distribution of pions produced by collisions of free nucleons.

In view of the fact that the effect due to the neutron bound in the deuteron is small as compared with effects due to D_2O and H_2O a long observation time was required to obtain the necessary statistical accuracy.

The results of the measurements were used to determine the ratio

$$(\sigma^{\pi^0}_{nd} - \sigma^{\pi^0}_{np}) / \sigma^{\pi^0}_{np} = 0.30 \pm 0.04$$

This relation makes it possible to determine from the known cross-section $\sigma^{\pi^0}_{np}$ the difference in the cross-sections for the production of neutral pions in (nd) and (np) collisions

$$\sigma^{\pi^0}_{n(d-p)} = (1.7 \pm 0.5) \cdot 10^{-27}\ cm^2,$$

and also to determine the cross-section for the production of neutral pions in (nd) collisions

$$\sigma^{\pi^0}_{nd} = (7.4 \pm 2.0) \cdot 10^{-27}\ cm^2.$$

The difference $\sigma^{\pi^0}_{n(d-p)}$, if one neglects the binding of the nucleons in the deuteron, is the quantity of interest–the cross-section for the production of neutral pions in neutron-neutron collisions $\sigma^{\pi^0}_{nn}$.

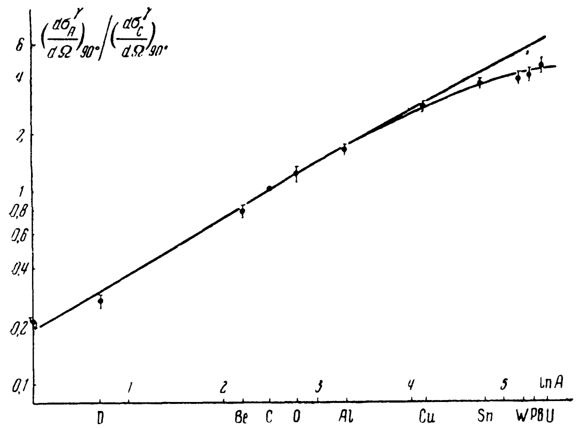
The effective energy corresponding to the cross-section which is found is determined from the neutron spectrum and the excitation function for the processes being investigated. However, as has been shown by calculation, for a given neutron spectrum this quantity is relatively insensitive to the excitation function. Thus, for example, if one replaces the excitation function $K^{3.5}$ by K^5 (where K is the maximum momentum of the neutral pions in the CMS of the colliding nucleons), the effective energy increases only by 3–5 Mev. According to Ref. 2 the excitation function for the reaction $p + n \to \pi^0 + (p + n)$ is similar to the first function while the excitation function for the reaction $p + p \to \pi^0 + p + p$ is similar to the second. This fact makes it possible to take the effective neutron energy as approximately 590 Mev, as in Ref. 1, for the measured cross sections for the production of neutral pions on deuterons as well as complex nuclei.

As is well known, in the experiments carried out by Pontecorvo and Selivanov[3] with deuterons at energies of 400 Mev, no systematic difference in the intensity of γ-rays from targets of D_2O and H_2O was observed; the authors give only an estimate of the upper limit for the cross-section for the production of neutral pions in neutron-neutron collisions: $\sigma^{\pi^0}_{nn} < 10^{-28}$ cm^2. A comparison of the data obtained by the present authors with these results indicates that there is an extremely rapid increase in the probability of production of neutral pions in $(n–n)$ collisions, similar to that which occurs in $(p–p)$ collisions. In both cases this situation can be explained by the fact that transition to higher energies means that final nucleon states characterized by high orbital moments $(l > 0)$ become important; hence the production of neutral pions in $(p–p)$ and $(n–n)$ collisions tends to be inhibited by considerations connected with conservation of total momentum and parity in the emission of a pseudoscalar neutral pion in a P-state and nucleons in an S-state.

The value of $\sigma^{\pi^0}_{nn}$ found in the present work coincides, within the error limits, with the cross section for the production of neutral pions in $(p–p)$ collisions, which is (1.8 ± 0.4) cm^2 at an energy of 590 Mev according to measurements of Prokoshkin and Tiapkin:[2] these data are not in contradiction with charge symmetry for nuclear forces. On the hand, the ratio of the cross-sections $\sigma^{\pi^0}_{n(d-p)} / \sigma^{\pi^0}_{np}$ measured by us with considerably greater accuracy than the absolute value of the corresponding cross-sections, was found to be smaller than the ratio $\sigma^{\pi^0}_{pp} / \sigma^{\pi^0}_{p(d-p)} = 0.41 \pm 0.08$ measured at a proton energy of 580 Mev. This fact apparently indicates that in assuming the equality $\sigma^{\pi^0}_{pp} = \sigma^{\pi^0}_{nn}$ the cross-section for the production of neutral pions on a deuteron is smaller than the sum of the cross-sections for the production of neutral mesons on a free proton and neuteron.

3. PRODUCTION OF NEUTRAL PIONS BY NEUTRONS IN COMPLEX NUCLEI

Using a similar method (also at 90°), measurements were made of the relative yield of γ-rays from the decay of neutral pions produced in collisions of neutrons with an effective energy of approximately 590 Mev with Be, C, AI, Cu, Sn, Pb and U nuclei. Measurements with heavy water and ordinary water made it possible to also determine the γ-ray yield in deuterium nuclei and oxygen nuclei. The amount of material in the targets was chosen to give approximately the same γ-ray yield. The absorption of γ-rays in the samples themselves was determined from the well-known experimental data on the total cross-section for the absorption of γ-rays in various materials.[4] The results of the measurements are given in the table and the figure. The abcisa axis represents, on a logarithmic scale, the atomic weight of the material. Along the ordinate



Dependence of the γ-ray field on the atomic weight of the material. The straight line corresponds to the relation $[(A-Z)\,\sigma_{nn}^{\pi^0} + Z\sigma_{np}^{\pi^0}]\,A^{1/3}$

axis is plotted the ratio of the γ-ray yield for a given material to the γ-ray yield from carbon. For purposes of comparison, the figure shows the function

$$[(A - Z)\,\sigma_{nn}^{\pi^0} + Z\sigma_{np}^{\pi^0}]\,A^{-1/3} \approx A^{2/3} \qquad (1)$$

(in relative units) which gives the production of neutral pions as a function of the atomic weight of the material under the assumption that the mesons are effectively produced only by surface nucleons of the nucleus.*

As can be seen, the experimental dependence on the atomic weight obtained for the γ-ray yield is in agreement with that calculated from Eq. (1), for elements from carbon to copper. For the light nuclei, H, D, and Be, the dependence of the γ-yield obtained as a function of atomic weight also differs only slightly from the relation given in (1). For the heavier elements Sn, W, Pb and U, the γ-ray yield increases less rapidly.

The experimental dependence of the γ-ray yield on the atomic weight indicates that the neutral pions are produced effectively mainly by surface nucleons in the nucleus. Assuming that the mesons are produced only at the surface of the nucleus and also that the γ-rays from the decay of neutral pions move in the same direction as the neutral pions and that the neutron flux falls off exponentially in passing through the thickness of the nucleus, we have made an estimate of the relative yield of γ-rays from various elements at an angle of 90° in the laboratory system. In this case the departure from the $A^{2/3}$ law can be satisfactorily explained by the relatively lower transparency of heavy nuclei to high-energy neutrons as compared with light nuclei. A similar picture of the interaction, as presented by the authors of Ref. 5, is in qualitative agreement with their experiments, in which the dependence of the γ-ray yield on atomic weight at angles of 0° and 180° was determined for the same nuclei under bombardment by 660-Mev protons. However, we have not been able to obtain complete quantitative agreement of all results using the assumptions that have been made.

Element	A	$\sigma_A^\gamma/\sigma_C^\gamma$	$[(A-Z)\sigma_{nn}^{\pi^0} + Z\sigma_{np}^{\pi^0}]\,A^{-1/3}$
H	1	0.21 ± 0.015	—
D	2	0.27 ± 0.02	—
Be	9	0.78 ± 0.04	0.77
C	12	1	1
O	16	1.2 ± 0.1	1.21
Al	27	1.61 ± 0.08	1.70
Cu	63.5	2.80 ± 0.14	2.93
Sn	119	3.8 ± 0.2	4.30
W	184	4.0 ± 0.3	5.60
Pb	207	4.2 ± 0.3	6.05
U	238	4.8 ± 0.4	6.75

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[3] B. M. Pontecorvo and G. I. Selivanov, Dokl. Akad. Nauk SSSR 102, 253 (1955).

*In calculating this function we have used the values of $\sigma_{nn}^{\pi^0}$ and $\sigma_{np}^{\pi^0}$ found by us.

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Internal Conversion Electron Spectrum of Radiothorium II

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The internal conversion electron spectrum of a sample of RaTh has been investigated in the $H\rho$ range from 500 to 1380 gauss-cm. The energies and relative intensities of the conversion lines have been determined. It is shown that spectrometers can be calibrated with an accuracy of 5×10^{-4} through the use of Auger electrons.

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1. CALIBRATION OF THE SPECTROMETER

AN INVESTIGATION OF A CONVERSION spectrum has been carried out using a magnetic spectrometer with improved focusing[1] with an instrument line width of 0.25%. The aperture angle of the spectrometer in the horizontal plane is 40° and the height of the diaphragms 16 mm. The source and counter slits measure 0.3×16 mm. The magnetic field is measured by the proton-resonance method.[2] The electrons are detected in two self-quenching Geiger counters, connected in coincidence; the count at the first counter is also recorded.

The calibration of the instrument was carried out with the most accurate presently available values of $H\rho$ for the conversion lines for radiothorium. These values are given in the second column of Table 1.

The values of $H\rho$ for the A, B, F, I and J-lines were taken from the work of Siegbahn and Edvardson.[3] These values have an uncertainty of approximately 7×10^{-5}. The value of $H\rho$ for the L-line was taken from the work of Lindstrom[4] which has an uncertainty of approximately 1.2×10^{-4}. The values of $H\rho$ for the Aa and Ab-lines were calculated by using the values of $H\rho$ for the A-line given by Siegbahn. In this calculation we have used the fact that the A, Aa and Ab lines are produced by the conversion of the same 39.85-kev γ-quanta in the Tl atom in the L_I, L_{II} and L_{III}-subshells respectively. In these calculations, as in all similar calculations in this work, we have used the binding energies given by Hill[5] and the tables given by Gerholm for the conversion of $H\rho$ to energy.[6] The Hill tables are apparently the most accurate; by the author's estimate the accuracy is of order of ±10 ev for the absolute values of the binding energy and of the order ±1 ev for the differences in binding energy.

The value of $H\rho$ for the E-line was calculated starting from the fact that this line is obtained in the conversion of 115.14-kev γ-quanta in the L_I-subshell of the bismuth atom. The energy of these quanta was determined using the fact that the A-line is complex and consists of two lines, one of which is obtained in the conversion of 39.85-kev γ-quanta in the L_I-subshell of the Tl atom and the other in the conversion in the K-shell of those γ-quanta which yield the E-line. The spacing between these lines is 110 ev.[7]

Column 3 of Table 1 lists the nuclear-resonance frequencies f corresponding to the maxima of the lines, while column 4 gives the value of k, which is the ratio of $H\rho$ to the frequency f. From Table 1 and Fig. 1 it is obvious that $H\rho$ is not linear with f for $H\rho < 2600$ gauss-cm. The departure from linearity for the A-line is approximately 0.2%. This departure from linearity may be explained qualitatively by the change in the magnetic-field configuration in the low-field region. Because measurements of the magnetic field by the nuclear resonance method require the placement of the pick-up coil in