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π^- -D Neutral Reactions*

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The neutral reactions $\pi^- + D \to n + n$, $n + n + \gamma$, $n + n + \pi^0$ are analized for a π^- kinetic energy of 224 ± 12 MeV, obtained in a 22 cm diameter and 15 cm long cylindrical bubble chamber containing deuterium, under a magnetic field of 24.3 ± 0.2 kgauss. The total measured cross section for the three reactions was $\sigma_T = 50.0 \pm 3.7$ mb. Applying the principles of detailed balance and charge invariance to the $p + p \to \pi^+ + D$ reaction, the value $\sigma_{nn} = 18.6 \pm 1.6$ mb was obtained. With this result and estimating $\sigma_{nn\gamma} = 1 \pm 1$ mb, it resulted $\sigma_{nn\pi^0} = 30.4 \pm 4.2$ mb.

As reações neutras $\pi^- + D \to n + n$, $n + n + \gamma$, $n + n + \pi^0$ são analisadas para uma energia cinética incidente de 224 ± 12 MeV, obtidas em uma câmara de bolha cilíndrica, de 22 cm de diâmetro e 15 cm de comprimento, contendo deutério sob um campo magnético de 24.3 ± 0.2 kgauss. A seção de choque total medida para as três reações foi $\sigma_T = 50.0 \pm 3.7$ mb. Usando-se os princípios do balanço detalhado e de invariância de carga para a reação $p + p \to \pi^+ + D$, obteve-se $\sigma_{nn} = 18.6 \pm 1.6$ mb. Desse resultado, e da estimativa $\sigma_{nn\gamma} = 1 \pm 1$ mb, resultou $\sigma_{nn\pi^0} = 30.4 \pm 4.2$ mb.

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1. INTRODUCTION

The reactions

$$\pi^- + D \to \pi^- + D \quad : \text{elastic}, \qquad (1)$$
$$\to \pi^- + p + n \quad : \text{inelastic}, \qquad (2)$$
$$\to \pi^0 + n + n \quad : \text{charge exchange}, \qquad (3)$$
$$\to n + n \quad : \text{absorption}, \qquad (4)$$
$$\to n + n + \gamma \quad : \text{radiative absorption}, \qquad (5)$$

have been analyzed theoretically and experimentally, mainly the elastic and the inelastic ones, due to their implications either in the study of the 3-body problem or to the reactions involving neutrons. A special attention is given to the above reactions for the π^- kinetic energy near the (3/2, 3/2) resonance, when some of the impulse approximation (IA) hipotheses, Refs. 1-5, have to be modified to allow for higher order approximations, Refs. 6-10.

This paper analyzes the three neutral reactions (3), (4) and (5) for a 224 MeV π^- kinetic energy, and it completes the work of one of us, in which the elastic and inelastic scattering at the same energy[11] was studied.

Special care was taken in determining the incident π^- energy, since the final products are not visible in the chamber and, therefore, kinematical checks cannot be used. Events with an error in the π^- energy larger than 5% were rejected, although they were taken into account in evaluating the error in the cross section.

2. EXPERIMENTAL AND SCANNING PROCEDURES

The film we analyzed was obtained from the Enrico Fermi Institute of the University of Chicago (EFI-UC) where the experiment was carried out. The pion beam was produced by the collision of a 450 MeV proton beam from the EFI-UC Syncrocyclotron with a berillium target. The bubble chamber was a 15 cm deep and 22 cm diameter steel cylinder containing deuterium with a density 0.26 g cm^{-3} under a pressure of 8 atm, placed in a 24.3 ± 0.2 kgauss magnetic field.

The pictures were examined and measured at the University of Brasília, using a table with two encoders for the x and y coordinate measurements, one meter in the table corresponding to 5000 encoder units. The results from the measurements were registered in a paper tape through a digitrneter.

Two sets of 20,000 pictures each were examined twice by two scanners, using projections with a magnification of *2.2* relative to the actual track dimension in the chamber. The number of possible events found by the two scanners were N_1 = 4479 and N_2 = 4752, respectively, which gave the total number of 5154 for the intersection of both. The efficiency was, then, 98.7%.

3. EVENT SELECTION AND CORRECTIONS

Initially, 5154 events were considered as zero prong events, i.e., with the final point apparently stopping inside the chamber and which could be a $\pi^- -D$ reaction going into neutrals. 1673 events were rejected after the analysis was completed since they had the final point outside the confidence (or fiducial) volume, with their limits placed at 0.5 cm from the bubble chamber walls. These events were remeasured for about 4000 frames and the results were entirely consistent with the previous ones. 663 among the remainders had to be remeasured also, some twice, either for technical reasons or for having an energy error larger than 5%. 103 among these persisted with a large error in the energy and 155 could not be analyzed at all, for having tracks superimposed to others, or for being too short or for being in a region too bright for observations. The total nurnber of events resulted to be, then, 3326. For the energy distribution it was included, besides these 3326 events, those that could not be measured, which were (155/5154) × 3326 = 100, and those not obtained due to the scanning inefficiency, which were 0.013 × 3326 = 43. The inclusion of these events in the distribution was made proportionally, by supposing they have the same kind of distribution as the final set. Thus, the total number of events considered for the cross section calculation was 3469.

4. SPATIAL RECONSTRUCTION

The procedure to measure each view consisted in measuring the projections of two fiducial marks graved in the internal surface of the frontal bubble chamber glass and the projections of four points along the track, the first one being the interaction point, or vertex.

To determine the track spatial coordinates from the plane coordinates of the four points measured in each view, we used the method described in Ref. 12.

5. CALCULATION OF KINEMATICAL QUANTITIES

The known expression for the radius of curvature r of the π^- meson (kinetic energy T and mass m) in the presence of a magnetic field B (kgauss).

$$r = \frac{p \cos\alpha}{0.3B} \text{ (cm)} ,$$

where $p = \{T(T + 2m)\}^{1/2}$(MeV) and a is the angle between the π^- direction and a plane perpendicular to the magnetic field $\vec{B}$, must be corrected to take into account the π^- energy loss along its path in deuterium.

To determine the energy loss rate $-\frac{1}{\rho}\frac{dT}{ds}$ along the track, we used the table given by M. Rich and R. Madey[13]. Here, s is the length of the track in cm and ρ the deuterium density in g cm^{-3}. Eight points were adjusted in the interval between 100 and 300 MeV by an equation of the type $\frac{dT}{ds} = -k\, T^{-n}$, by the least squares method. Once the constants k and n are determined the equation is integrated to give

$$T = \left\{T_s^{1.174} - 0.869\, s\rho\right\}^{0.852} ,$$

where T_s is the π^- kinetic energy at a **distance** s from the vertex. Using a computer to **simulate** the experiment under the same conditions, we found that the radius of curvature which adjusted best to the curve passing through the four points projected on a plane normal to the magnetic field was the radius **of curvature** of the track **in** its **medium** point. Knowing this radius one can calculate the momentum **in** that plane, $(p_s)_{xy}$, in the **medium** point of the track.

The momentum in the direction of the magnetic induction, in the **medium** point, is calculated through $p_s = (p_s)_{xy}$ tg $\bar{\alpha}$ where $\bar{\alpha}$ is an average value of α given by

$$\bar{\alpha} = \tan^{-1}\left\{\frac{Z_1 - Z_4}{s_p}\right\} ,$$

s_p being the length of the track in the plane, and Z_1 and Z_4 the z-**-coordinates** of the vertex and initial points, respectively. This is **not** entirely correct, since there is also an energy loss related to the **motion** along the magnetic field. This loss was not computed, however, because the length of the projection of the track in this direction is only about 1% of the total track length, according to the results obtained after the spatial reconstruction. The correspondent error, however, was taken into account in the final calculations.

Once p_s **is determined,** one can obtain T_s and, then, the kinetic energy at the vertex, T, for each event.

6. ERRORS IN THE ENERGY

The errors associated to the energy come from the determination of R, S and θ and from the magnetic field $\vec{B}$. Here S is the track length, R the radius of the circle projected on a plane normal to $\vec{B}$, and θ **is** the subtended by the **arc.** The resultant error associated to the kinetic energy is given **by**

$$\Delta T = \frac{p}{(p^2+m_\pi^2)^{1/2}} \Delta p,$$

where Δp is the error in the momentum of the pion. For a detailed discussion of this expression we refer the reader to the other paper by the authors[12].

All events with a value $\frac{\Delta T}{T} \geq 0.05$ were remeasured. Some were remeasured several times and among these several were rejected for persisting with a large error in the energy. The limit of 5% for the energy error was a compromise between the precision of the measurement and a good statistics. It should be clear that errors mentioned above come from the errors associated to the measurements.

The track and the fiducial marks have a finite width in the projection on the table and so the coordinatec from a point ori the table have an intrinsic error. To determine this error we made twenty measurements for one chosen track. The maximum deviation obtained was 0.5 mm on the table, which corresponds to 0.15 mm inside the bubble chamber. The precision for the tri-dimensional reconstruction of a point was determined using the difucial marks F_A and F_B, since their fixed positions are known a *priori*. The maximum standard deviationobtained was 0.04, corresponding to the Z-coordinate evaluation.

The distortions in the projections of the films were measured using a laser beam passing through the lenses. The correction for aberration was of the order of the track measurements. Other types of errors due to nonhomogeneity of the magnetic field and turbulences inside the bubble chamber were neglected.

7. ENERGY MEAN VALUE

The histogram shown in Fig. 1 gives the number of events vs. energy. Since we have a sufficiently large number of events we considered in our analysis a small interval around the peak, that one between 198.5 and 248.5 MeV. By adjusting the correspondent Gaussian, Fig. 2, the

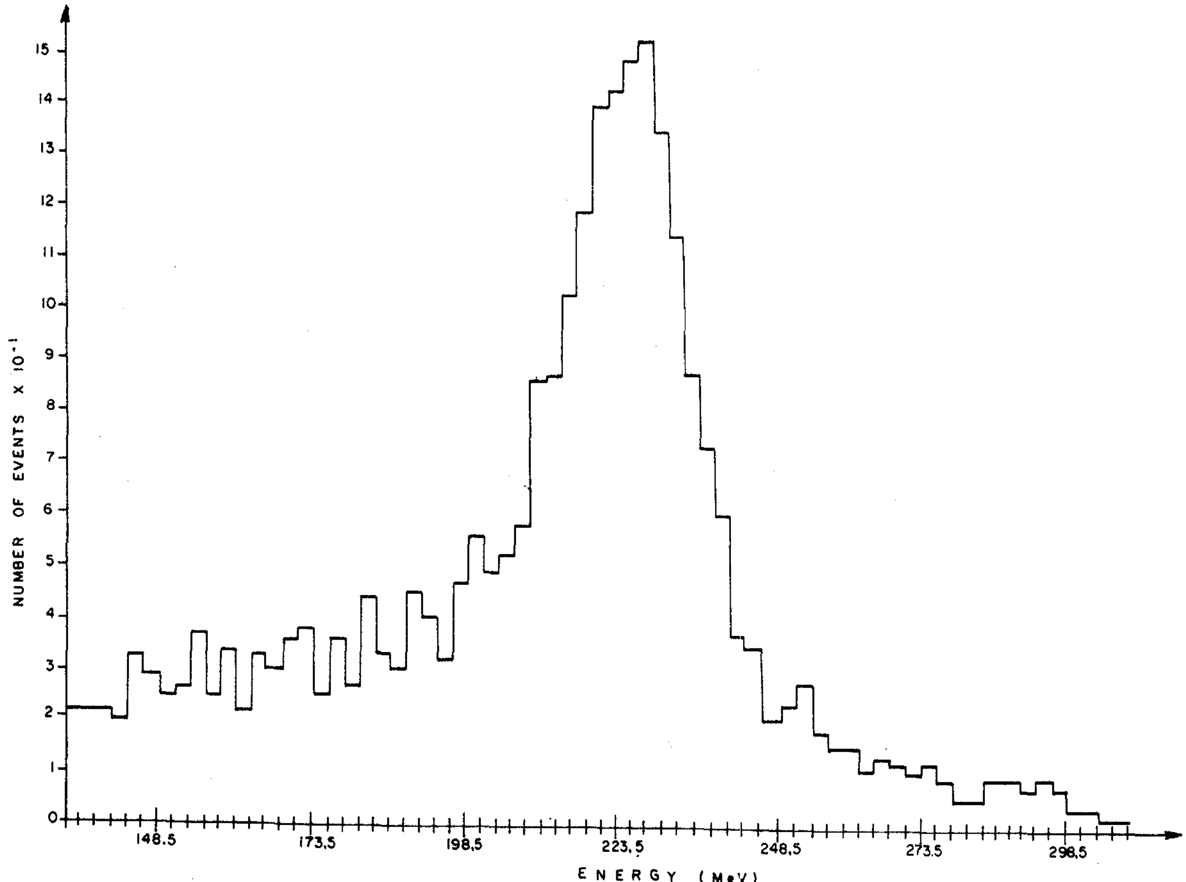

Fig. 1 - Experimental distribution of number of neutral events versus their energy.

value 224 ± 12 MeV was found for the average π^- incident kinetic energy. This value is also obtained if the distribution is made symmetric in an interval around the peak, Fig. 3, i.e., making the left branch symmetric relative to the right one, as one would expect, since several pions lose energy, due to their interaction with the matter from the equipment, before they enter the bubble chamber. These pions increase the lower energy population, resulting in an energy distribution not symmetric around the peak.

8. CROSS SECTION

To obtain the total cross section for the neutral reactions, we considered only 1163 events in the energy range 224 ± 12 MeV, assuming that the total incoming π^- flux had the same energy distribution as the π^- interacting with the deuterium in reactions (3), (4) and (5).

The total number of incident particles counted in all frames used in the scanning was 125,385, among which 42,030 are distribtited over the energy range considered above. With these data and the average length of 14.54 cm found for the tracks, the following value for the cross section was obtained:

$$\sigma_T = 50.0 \pm 3.7 \text{ mb.}$$

The error was calculated by taking into account the rejected tracks and the statistical errors.

9. PARTIAL CROSS SECTIONS

By applying the principles of detailed balance and charge invariance to the reaction $p + p \rightarrow \pi^+ + D$, the cross section for the reaction $\pi^- + D \rightarrow n + n$ was calculated. The kinetic energy for the incident proton in the former reactions has to be 760 MeV in the Lab. System, in order to apply the detailed balance principle to calculate the cross section for $\pi^- + D \rightarrow n + n$, at a π^- kinetic energy of 224 MeV. We did not find any reference to experiments at that energy. Using

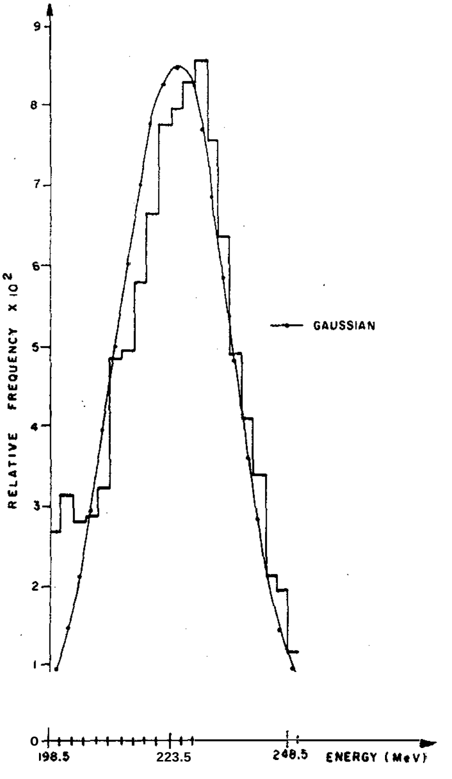

Fig. 2 — Adjusted Gaussian to the normalized distribution of number of events versus energy.

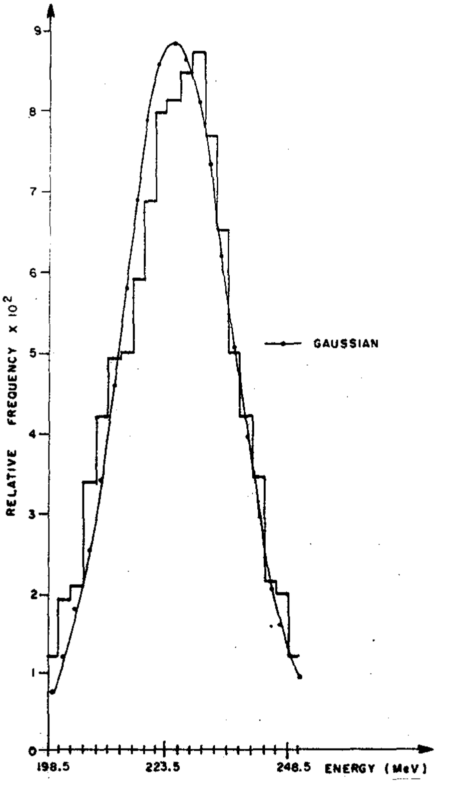

Fig. 3 — Adjusted Gaussian to the normalized and symetrized distributions of number of events against energy.

the available data, we then made a plot for the cross section vs. energy[14] for that reaction, from which it was obtained the value $\sigma(p + p \to \pi^- + D;\ 760\ MeV) = 1.70 \pm 0.15$ mb. With this value, we obtained

$$\sigma(\pi^- D \to nn;\ 224\ MeV) = 18.6 \pm 1.6\ mb.$$

Since there are no experimental data for the reaction $\pi^- + D \to n + n + \gamma$, the value for the correspondent cross section was estimated. Making use of the values for the cross sections for the reaction $\pi^- + p \to n + \gamma$, Refs. 15, 16, 17, 18, we estimated that

$$\sigma(\pi^- D \to nn\gamma) = 1 \pm 1\ mb$$

The cross section for the reaction $\pi^- + D \to n + n + \pi^0$ is obtained from the previous results, by subtracting σ_{nn} and $\sigma_{nn\gamma}$ from the total neutral cross section. The value obtained was

$$\sigma(\pi^- D \to nn\pi^0) = 30.4 \pm 4.2\ mb.$$

CONCLUSION

We analyzed the neutral reactions $\pi^- + D \to n + n + \pi^0$, and $n + n + \gamma$ for a π^- kinetic energy of 224 MeV. The resultant energy distribution for the π^- is identical to the distribution obtained in other analyses applied to the elastic and inelastic reactions for the same experiment[11], inclusive in the value of the mean energy. Our numerical program was a very simplified one and applicable to small computers.

The values obtained for the cross sections are indicated in Table 1, where it is shown, for comparison, the E. G. Pewit[18] result at 142 MeV. Note that the cross sections at 224 MeV are larger than at 142 MeV, except for the elastic reactions, which we believe are causedby the (3/2, 3/2) resonance.

FINAL PRODUCTS	a	b	a+b	c
$\pi^- D$	-	34.0 ± 1.4	34.0 ± 1.4	47.0 ± 3.2
$\pi^- p\ n$	-	115.0 ± 2.5	115.0 ± 2.5	99 ± 7
$\pi^0 n\ n$	30.4 ± 4.2	-	30.4 ± 4.2	26 ± 3
n n	18.6 ± 1.6	-	18.6 ± 1.6	9.8 ± 1.2
n n γ	1 ± 1	-	1 ± 1	1 ± 1
Total	50.0 ± 3.7		199.0 ± 10.7	183 ± 9

Table I. Values obtained for the cross sections (a - This paper; b - J. L. Acioli at 224 MeV; c - E. G. Pewitt at 142 MeV).

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