Photodisintegration of the Deuteron by Meson Reabsorption

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A calculation is made of the photodisintegration of the deuteron which is caused by a meson being photoproduced on one of the nucleons of the deuteron and then subsequently being reabsorbed by the two nucleons. The measured photomeson production cross sections in hydrogen are separated into S-wave and P-wave parts so that the production of mesons on the neutron can be computed. The probability of meson reabsorption after production is taken as 0.11; this value results from Austern's calculation of the effects of P-state mesons. The effect of virtual production and reabsorption of S-state mesons even below the meson threshold is shown to be very important. Calculated values of the total cross section agree rather well with the experimentally measured cross sections.

THE total cross section and the angular distribution of the photodisintegration of the deuteron have been measured from threshold to an energy of about 500 Mev.[1] Up to about 30 Mev, the results are in accord with the theory[2] which neglects mesonic effects except insofar as they determine the wave function of the deuteron. However, at higher energies the measurements show cross sections which are much larger than predicted by this theory, and in the vicinity of 300 Mev a maximum is evident which obviously has some correspondence with the peak in photomeson production that occurs at the same energy. Austern[3] has applied the nucleon isobar (3/2, 3/2) as an intermediate state in the disintegration process and is able to show qualitative agreement near 300 Mev. Zachariasen[4] is also able to reproduce the qualitative features near 300 Mev by applying the Chew meson theory. Neither treatment gives even qualitative agreement in the energy region between 50–200 Mev, presumably because of the neglect of processes corresponding to production of mesons in S states.

The application of Fermi's phase space argument[5] gave a reasonable prediction of the high-energy behavior of deuteron photodisintegration. In this picture mesons are photoproduced on the separate nucleons. These mesons will be subsequently reabsorbed if the two nucleons are within a distance of about $\hbar/\mu c$. The available phase space is then much greater for emission of only two nucleons than for emission of two nucleons and one meson; hence photodisintegration is the most probable result of meson reabsorption. The present note is simply a more careful restatement of that phase space argument.

The cross section for photodisintegration on the above picture will be given by

$$\sigma_d=\sigma(\pi)_{np}P\rho_{np}/\rho_\pi, \qquad (1)$$

where $\sigma(\pi)_{np}$ is the total cross section for production of mesons of any kind on the neutron and proton of the deuteron, if one assumes that production on each nucleon is independent of the presence of the other nucleon. P is the probability of reabsorption of the meson and is given roughly by the fraction of time that the two nucleons find themselves within a distance of $\hbar/\mu c$. Austern's[3] isobaric-state calculation gives 0.11 for the probability of meson reabsorption and this corresponds to the two nucleons having to be within a distance of $0.7\hbar/\mu c$ for meson reabsorption to occur (Hulthén wave function assumed). The density of final states of the two nucleons is ρ_{np}, and ρ_π is the density of final states of the meson in photoproduction on a single nucleon.

The meson cross section $\sigma(\pi)_{np}$ in (1) is determined from measurements of photoproduction of π^+ and π^0 mesons in hydrogen.[6] The production has been separated into S and P states as follows:

$$\sigma(P)_{np}=3\sigma(\pi^0)_p, \qquad (2)$$

$$\sigma(S)_{np}=2.4[\sigma(\pi^+)_p-\tfrac{1}{2}\sigma(\pi^0)], \qquad (3)$$

and

$$\sigma(\pi)_{np}=\sigma(S)_{np}+\sigma(P)_{np}, \qquad (4)$$

where $\sigma(\pi^0)_p$ and $\sigma(\pi^+)_p$ are the measured total cross sections for photoproduction of π^0 and π^+ mesons in hydrogen. The relation (2) assumes that all the production of π^0 mesons in H is through the (3/2, 3/2) state and hence that the production of charged mesons through this state is one-half of the production of π^0's. The relation (3) assumes that all the photoproduction is in either S or P states and that the S-state production can be obtained by simply subtracting the P-state production which is given by $\frac{1}{2}\sigma(\pi^0)_p$. The results of this analysis are quite in accord with the analysis of the angular distributions. The factor 2.4 in (3) comes from assuming that the extra current due to the recoiling proton in π^- production on the neutron gives an enhancement of the cross section of 1.4 over the production of π^+ on the proton. The cross sections $\sigma(P)_{np}$ and $\sigma(S)_{np}$ are plotted in Fig. 1 as dotted curves.

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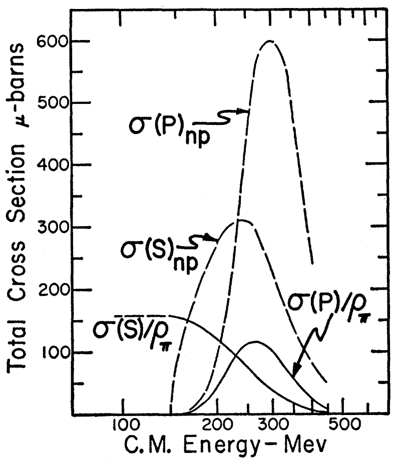

FIG. 1. The dashed curves show the total cross section for photomeson production on both nucleons of the deuteron and including mesons of plus, minus, and zero charge. The curve marked $\sigma(S)_{np}$ refers to S-wave mesons and the curve marked $\sigma(P)_{np}$ refers to P-wave mesons. The solid curves are obtained from the dashed ones by dividing by ρ_π, the density of final states of the meson-nucleon system; the scale is relative for these curves.

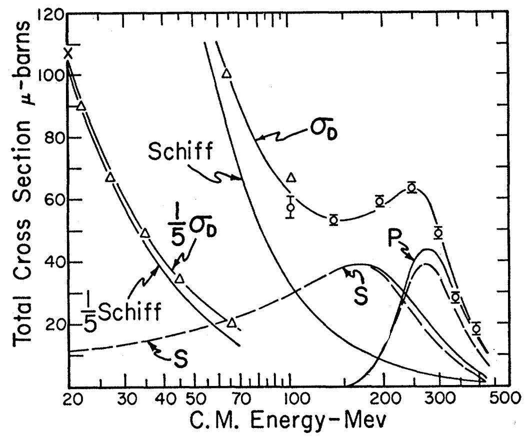

FIG. 2. The curve marked S shows the contribution to the total cross section of the disintegration of the deuteron which results from the reabsorption of S-wave mesons. The curve marked P is the same but for P-wave mesons. The curve marked "Schiff" shows the result of the calculation which neglects specific meson effects. The curve σ_D is the sum of the other curves. The triangles show the Illinois measurements and the circles show the C.I.T. measurements.

The solid curves of Fig. 1 are obtained from these curves by dividing by the density of final states, i.e., the square of meson momentum divided by the relative velocity between meson and recoiling nucleon. Hence the solid curves represent a measure of the interaction between photon and nucleon or of the matrix element for meson production. For production in the S state, we expect on the most simple interpretation a dipole interaction of the photon with a virtually emitted meson and we expect this interaction to be constant at low energies. The solid curve for the S-wave interaction is seen to approach a constant value near threshold, as Bernardini and Goldwasser[7] have already noted. We therefore extrapolate that $\sigma(S)_{np}/\rho_\pi$ will remain constant below threshold and that it gives a measure of the interaction between a photon and a virtually emitted meson. These mesons will also be available for reabsorption and eventual photodisintegration just as well as mesons which could become free.

Figure 2 shows the results of computing Eq. (1): Curve S gives the total disintegration cross section due to S-state mesons, and curve P is the cross section due to mesons produced in a P state. The curve marked "Schiff" shows the theoretical calculation of photoelectric processes which was made neglecting the direct meson effect treated here.[2] Since interference effects can be expected to cancel in the total cross sections, it should be possible to add the three curves to obtain the final result given as the curve σ_D.

In getting the final curve, a correction has been made to curves S and P which takes into consideration the probability that after the meson is absorbed it may be inelastically or elastically re-emitted. This was determined directly from the measured ratio $\sigma(n+p\rightarrow 2n+\pi)/\sigma(n+p\rightarrow n+p \text{ or } 2n+\pi)$. The dashed parts of curves S and P show the magnitude of this correction and that it becomes appreciable at high energies.

The experimental points[1] are also plotted in Fig. 2, and the excellent agreement with curve σ_D is remarkable but probably somewhat fortuitous considering the crudeness of the theory.

No quantitative comparison has been made with the measured angular distributions; however, the qualitative features of the picture are not in disagreement with the measurements. At low energies, less than 30 Mev, the distributions have the form $(1+\beta\cos\theta)\sin^2\theta$ given by theory.[2] From 30 to 200 where the effects of S-wave mesons predominate, the distributions tend to be more isotropic, which is consistent with an expected predominantly $^3P_0$ state of the nucleons which is induced by the absorption of an S-state meson. Finally, from 200–500 Mev the measurements tend toward a $2+3\sin^2\theta$ which, according to Austern,[3] would result from the absorption of P-wave mesons.

[7] G. Bernardini and E. Goldwasser, Phys. Rev. 95, 857 (1954).