The Production of Neutral Mesons by Photons*

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A NUMBER of recent experiments at Berkeley have given independent and strong support for the hypothesis that there exists a neutral meson which is strongly coupled to nucleons. Of particular interest are the experiments of Steinberger, Panofsky, and Steller[1] which seem to indicate that neutral mesons can be produced by photons with a cross section which is not less than that for charged mesons.

Photo-meson production is among the simplest of phenomena involving mesons; and it might therefore be hoped that some of its general features can be understood on the basis of our admittedly very incomplete theoretical knowledge of the properties of mesons. In particular, we are interested in seeing whether a photo-production cross section for neutral mesons as large as that for charged mesons can be understood theoretically.

For the photo-production of charged mesons Brueckner[2] found that of the four types of meson fields only the pseudoscalar theory gave satisfactory agreement with experiment. For such a theory as the scalar theory with charged meson currents extending about the nucleon over a region of the order of the meson Compton wave-length, the angular (dipole) distribution of the ejected photo-mesons arising from the coupling of the electromagnetic field to the meson currents is incompatible with the observed,[3] flat angular distribution for charged mesons. Such a coupling of the charged meson field to the electromagnetic field would also lead one to expect the ratio of cross sections for neutral to charged mesons to be of the order of $(\mu/M)^2$ (where μ is the meson mass and M is the nucleon mass), since for neutral meson production the electromagnetic field coupling is to the nucleon. This is in contradiction to the observed largeness of the neutral meson cross section.

Assuming that neutral meson production takes place through the interaction of the electromagnetic field with the magnetic moment of the nucleon, both classical and lowest order perturbation calculations for scalar mesons and pseudoscalar mesons with pseudovector coupling lead to a ratio of the neutral to charged meson cross section (near threshold) of the order of $(\mu/M)^2$, in agreement with the above qualitative arguments.

Such semiclassical arguments are not necessarily applicable in the case of the pseudoscalar field, however, where relativistic quantum-mechanical effects are likely to be important. Here the matrix element for neutral meson production for a γ-ray striking a proton is proportional to

$$(F|H|I)\simeq\boldsymbol{\mu}\cdot\xi(\rho)\left\{\left[\frac{1}{(P_{I\mu}\rho_\mu)}-\frac{1}{(P_{F\mu}\rho_\mu)}\right]M_{\rho 0}\right\}. \qquad (1)$$

Here μ is the Dirac magnetic moment of the proton, $(P_{I\mu})$ and $(P_{F\mu})$ are its four-momenta in the initial and final states, respectively, (ρ_μ) is the four-momentum of the incident photons, and ξ is the electric field strength. Equation (1) differs from that for charged meson emission by the factor in brackets, which is non-vanishing only because of retardation effects and is of order (μ/M) near threshold. This is because the magnetic moment is relatively undisturbed by the process of neutral meson emission, causing phase cancellation between initial and final states. Thus, again the ratio of neutral to charged meson cross sections is of order $(\mu/M)^2$. Similar results are obtained for vector and pseudovector theories. (The experimental evidence is against the neutral mesons having spin one, because of their apparent annihilation into two photons.[4])

It is seen, therefore, that neither classical considerations nor lowest order perturbation theory provide a clue to the largeness of the cross section for neutral photo-mesons. We note, however, that the factor in the brackets in Eq. (1) is small only when the nucleon recoil is small. Due to the very close binding of the meson field to the nucleon for pseudoscalar theory, high energy virtual recoils are expected and it might be thought that these will remove the near cancellation of the two terms in the brackets. To investigate this possibility, we have calculated the first-order radiative corrections to Eq. (1). The corresponding radiative corrections for charged meson production have been calculated by Brueckner.[2] Combining lowest order and first-order radiative corrections for both charged and neutral meson production and choosing the coupling constant as $g^2/4\pi\simeq 10$ (a reasonable value obtained from other considerations), we obtain about equal cross sections for the two processes, in reasonable agreement with experiment. With this choice of coupling constant, the radiative corrections to charged meson production are not qualitatively important, while for neutral meson production the lowest order terms are small.

Since the validity of large radiative corrections is open to considerable doubt, we feel justified in concluding only that the large observed cross section for neutral meson production is not necessarily incompatible with conclusions that can be drawn from pseudoscalar meson theory.

We would like to express our appreciation to Dr. Steinberger and his co-workers for dicussion of their experiments.

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Neutron Spectrum for Protons on Be⁹*

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WITH the observation of two energy groups of neutrons in the Li(p, n) spectrum,[1,2] it has become of considerable interest to find a more satisfactory source of monoenergetic neutrons. Since the inelastically scattered protons from Be^9 indicate only one level at 2.4 Mev in the range[3] up to 5.0 Mev, one can expect from mirror nuclei arguments that B^9 also has only one level at about 2.4 Mev in the same range. Thus, it seemed likely that the $Be^9(p, n)B^9$ reaction would produce monochromatic neutrons in the region below 2.5-Mev neutron energy. Additional interest in this reaction arises from the suggestion by Guth and Mullin[4] that a level may occur in Be^9 at about 1.6 Mev, a level which did not show up clearly in the proton scattering work of Davis and Hafner. Again from mirror nuclei arguments, it would be expected that a level in B^9 would also occur in the neighborhood of 1.5 Mev, if this postulate were correct.

The measurement of the neutron spectrum was accomplished by the photographic plate technique in essentially the same way

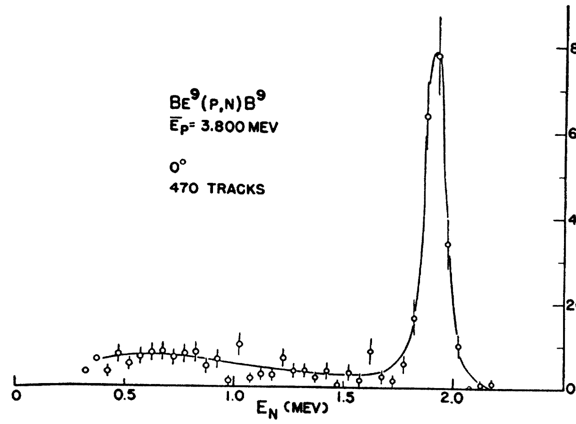

FIG. 1. Number of neutrons per 50 kev interval *versus* neutron energy for $\bar{E}_p = 3.800$ Mev at 0°

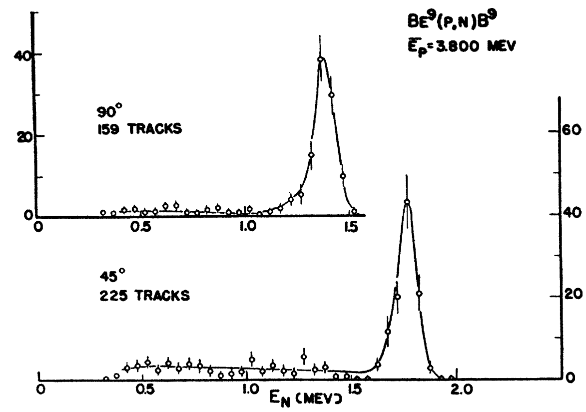

FIG. 2. Number of neutrons per 50 kev interval *versus* neutron energy for $\bar{E}_p = 3.800$ Mev at 45° and 90°.

as was described earlier.[1] In this case, the targets were approximately 30 kev thick foils of beryllium mounted on a tantalum backing. Eastman NTA 100 micron emulsions were mounted 4 inches away at angles of 0, 45, and 90 degrees. The first exposure was made with a bombarding energy of 3.817 Mev. The data plotted in 50 kev intervals and corrected for variation of $n-p$ scattering cross section is shown in Fig. 1 and Fig. 2. Because of the large uncertainty in the determination of the angle of recoil for tracks from low energy particles, 0.4 Mev was arbitrarily set as the lower limit of measurements. Applying the criteria for acceptance of tracks becomes increasingly difficult below 1.0 Mev, so that the actual uncertainty in the region between 0.4 and 1.0 Mev is somewhat greater than the indicated statistical uncertainty.

The data show clearly the group from the transition to the ground state of B^9. Below this there occurs a continuous energy distribution of neutrons. Comparison with the earlier Li(p, n) data[1] under similar conditions indicates that this continuous distribution does not result from background neutrons and scattering. The low intensity of the continuum in the region between 0.4 and 1.0 Mev on the 90° plate also excludes the possibility of the intensity in this region on the 0 and 45 degree plates from being due to an isotropic background in the room. To check the results of the first experiment a somewhat different target arrangement was

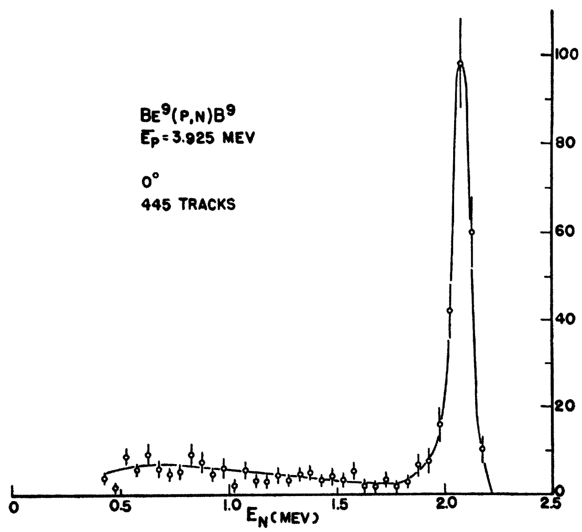

FIG. 3. Number of neutrons per 50 kev interval *versus* neutron energy for $\bar{E}_p = 3.925$ Mev at 0°.

constructed and a second exposure was made. The bombarding energy was 3.940 Mev. The 0 degree data are shown in Fig. 3.

Several possible origins of the continuum were considered. Cascade processes, in which the 2.41 Mev excited state[3] of Be^9 is formed and subsequently breaks up into either Be^8 and a neutron or into He^5 and He^4, are not able to give the observed data. The continuum could arise from the break-up of the compound nucleus either into Be^8, a proton, and a neutron, or into Be^8 and a deuteron in the singlet state. Another quite different possibility is that the continuum results from the interaction of the incident proton chiefly with the very loosely bound neutron in Be^9 without the formation of a compound state. The relatively low intensity of the continuum on the 90 degree plates might favor this possibility. Finally, one cannot rule out the possibility of the existence of a very broad level in B^9.

In regard to the use of the $Be^9(p, n)$ reaction as a neutron source, it is of interest to note that the thin target neutron yield *versus* energy curve does not show an observable yield of neutrons for proton bombarding energies between the (p, pn) threshold and the (p, n) threshold.[5] If the continuum is due to the (p, pn) reaction, one can probably expect the yield of the continuum to remain at a low value throughout a useful range of energies.

We wish to extend our sincere appreciation to Professor H. T. Richards, who suggested this problem and with whom we have had many invaluable discussions.

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Masses of Si^{30}, Co^{59}, Ni^{60}, Zr^{90}, Mo^{96} and Mo^{100}*

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THE mass spectrographic mass determinations recently reported have been extended to include Si^{30}, Ni^{60}, Zr^{90}, Mo^{96} and Mo^{100}. From the mass of Ni^{60} that of Co^{59} can be deduced, using disintegration data.

Si^{30}, Ni^{60} and Co^{59}. With an ion source consisting of a spark between two silicon electrodes, photographs were taken of the CH_3-Si^{30} doublet appearing at mass number 15. From eight photographs, the CH_3-Si^{30} packing fraction difference[1] was found to be $\Delta f = 24.53 \pm 0.05$. Assuming the packing fraction of CH_3 to be[2] 18.83 ± 0.015, that of Si^{30} is found to be -5.70 ± 0.05. This is in satisfactory agreement with the value -5.64 ± 0.02 listed by Mattauch and Flammersfeld,[3] and by Alburger and Hafner.[4]

The $Si^{30}-Ni^{60}$ packing fraction difference has been found in this laboratory[5] to be $\Delta f = 2.90 \pm 0.01$. This, when combined with the above value for Si^{30}, gives for Ni^{60}, $f = -8.60 \pm 0.05$. This is in satisfactory agreement with Shaw's[6] value of -8.69 ± 0.08, but does not agree very well with the value of -8.37 ± 0.06 obtained by Okuda *et al.*[7]

The packing fraction of Co^{59} can be computed from Ni^{60} by use of the Q-value for the $Co^{59}(d, p)Co^{60}$ reaction, recently measured by Bateson and Pollard.[8] Their Q of 5.19 Mev, together with values of 0.308 Mev and 2.40 Mev for the beta- and gamma-rays from Co^{60}, as listed by Mattauch and Flammersfeld,[3] gives a packing fraction for Co^{59} of $f = -8.43$. In this computation, Bainbridge's recommended values[2] for the masses of H^1 and H^2 were used.

Zr^{90}. With a spark between a silicon and a zirconium electrode, the $Si^{30}-Zr^{90}$ doublet was photographed at mass 30. The packing fraction difference was found from five photographs to be $\Delta f = 1.88 \pm 0.04$. This, combined with the above Si^{30} value, gives the packing fraction of Zr^{90} as $f = -7.58 \pm 0.07$.