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COHERENT PHOTOPRODUCTION OF THE η° MESON FROM DEUTERIUM*

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ABSTRACT

The isoscalar part of the η° photoproduction amplitude near threshold has been determined by differential cross section measurements of the coherent process $\gamma + D \rightarrow \eta^\circ + D$ from near threshold to 150 MeV above threshold. By comparison of the results with earlier measurements of $\gamma + p \rightarrow \eta^\circ + p$ and a recent measurement of $\gamma + D \rightarrow \eta^\circ + (p,n)$ it is possible to argue that the isovector part of the η° photoproduction amplitude near threshold is much smaller than the isoscalar part and is consistent with zero.

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Eta photoproduction near threshold is dominated by the S wave $J = 1/2$, $I = 1/2$, mass 1550 MeV odd parity baryon resonance. A determination of the isotopic spin character of the electromagnetic transition moments from the nuclear ground state is desirable for detailed tests of various theoretical approaches such as photoproduction sum rules, and various symmetry and quark schemes. Toward this end, studies of the reactions $\gamma + D \rightarrow \eta^\circ + D$, $\gamma + D \rightarrow \eta^\circ + (p,n)$, and $\gamma + p \rightarrow \eta^\circ + p$ can be used to make a determination of the relative isovector and isoscalar couplings. Specifically, since both the deuteron and the eta meson are isoscalar particles, only the isoscalar part of the $\langle \eta^\circ N | j | N \rangle$ matrix element can contribute to the coherent production from the deuteron. This letter describes a measurement of the differential cross section for the reaction $\gamma + D \rightarrow \eta^\circ + D$ near 90° in the C.M. system from threshold to approximately 150 MeV above threshold in approximately 20 MeV steps. These measurements were made using counter techniques at the Stanford University 1.1 GeV linear electron accelerator.

Observation of η° production in the reaction $\gamma + D \rightarrow \eta^\circ + D$ has been accomplished by detecting the recoil deuteron. Since this process has a two-body final state, a measurement of the deuteron momentum and angle is sufficient to uniquely determine the incident photon energy. The electron beam is brought out into the experimental end station and passes through three secondary emission monitors, a beam position monitor, and a fast torid. The electron beam itself consists of pulses occurring at 23.0 Mc/sec, each less than 1 nsec in width during an overall machine pulse width of 1μ sec. This "chopped" beam is prepared by passing the electron beam between a set of plates near the accelerator gun to which an 11.5 Mc/sec rf voltage is applied. Immediately after the deflection plates, a collimator is positioned on the accelerator axis thus producing the "chopped" beam. This time structure in the beam is then used for a time of flight time marker in order to measure the time of flight distribution of particles traversing a magnetic spectrometer.

The electron beam passes through a 0.03 radiation length foil and is then deflected by a sweeping magnet. After collimation, the photon beam then passes through a liquid deuterium target. The beam position is monitored once more after the deuterium target, and then the photon beam energy is measured in a secondary emission quantameter.

The spectrometer used to detect the recoil deuterons is a 44 in. radius, 90° bend, $n = 0$ type magnet which is capable of 0.1% momentum resolution up to 700 MeV/c. The detecting counters consist of seven 1% momentum defining counters and two focal plane defining counters.

Deuterons are identified by range, energy loss, and time of flight requirements. Under most experimental conditions the proton flux was some 100 times more intense than the deuteron flux. Under normal experimental conditions, the time of flight requirement is set for deuterons and the resultant deuteron signal has less than a 1% proton contamination.

The procedure used for the cross section measurements is similar to that used by R. Prepost, D. Lundquist, and D. Quinn to measure the cross section for $\gamma + p \rightarrow \eta^\circ + p$. 1). For a fixed spectrometer momentum and angle setting, the deuteron yield is measured as a function of primary electron energy. As the electron energy increases (i.e., the bremsstrahlung end point energy) the counter yields will increase when the threshold energy for a new process is reached. In particular, if the process has a two-body final state, the counter yields will rise at the threshold energy and trace out a bremsstrahlung curve for fixed photon energy and variable end point energy. This yield reaches an approximately constant value some 30 MeV above the threshold for the reaction. On the other hand, if the reaction has a three body final state such as $\gamma + D \rightarrow \pi^+ + \pi^- + D$, then a measurement of the deuteron momentum and angle is not sufficient to identify the photon energy, and the yield continues to rise above the threshold with a contribution from all photon energies from the laboratory threshold energy to the bremsstrahlung end point energy. Our procedure has been to trace out the deuteron yield as a function of energy from the threshold for $\gamma + D \rightarrow \pi^\circ + D$ to approximately 150 MeV above the threshold for $\gamma + D \rightarrow \eta^\circ + D$. Figure 1 shows two examples of such yield curves which show a signal due to $\gamma + D \rightarrow \eta^\circ + D$. The process $\gamma + D \rightarrow \gamma + D$ is too small to be seen against the much larger signal from $\gamma + D \rightarrow \pi^\circ + D$. The energy interval steps are approximately 10 MeV and vary somewhat for the various experimental points. As the yield curves are continued beyond π° threshold, the next kinematically allowed process is $\gamma + D \rightarrow 2\pi + D$. The yield then continues to rise as the bremsstrahlung end point energy is increased and this is the major background for η° production. The curves clearly show the expected increase in deuteron yield corresponding to η° production. The arrows indicate the expected threshold energy at the center of the momentum acceptance. The yields show the expected behavior, which is a leveling off of the yield due to η° production some 30-40 MeV above the threshold energy.

In order to determine the η° differential cross sections from the measured yields, the height of the deuteron step must be determined and this makes it necessary to extrapolate the two pion yields from below the η° threshold where they are measured directly, to above the η° threshold where the yields are the sum of an η° signal and a two-pion yield. There is also, of course, a constant contribution from π° production. We have found that both a phase space polynomial and a linear function are a good representation for the energy dependence of the data in the vicinity of the η° threshold.

The actual interval which is fit is the region 100 MeV below the η° threshold and a 100 MeV interval which starts 50 MeV above the η° threshold. In Fig. 1, the solid line is drawn in as a representation to the actual least squares curve. In this manner we obtain a least squares solution for the height of the η° step.

The inserts in Fig. 1 show the deuteron yields in the vicinity of the η° threshold with the background processes subtracted. These background processes include single π° production, two-pion production, and a small (10%) empty target background. If the background has been subtracted properly, the remaining yield will have the shape of a bremsstrahlung curve for fixed photon energy. The main feature of this curve is that the yield must plateau some 30-40 MeV above threshold. The Fig. 1 yields have this feature as do our other experimental points.

The eta yields are converted into a differential cross section by normalizing to the deuteron yield where only deuterons accompanied by a π° are produced thus providing a normalization under the same laboratory momentum transfer and angle conditions. These data are available from the experiment of Friedman and Kendall2.) in the appropriate energy range but at somewhat lower momentum transfers. We have corrected these data to our momentum transfer conditions by using the measured slope of the $\gamma + D \rightarrow \pi^\circ + D$ cross section as a function of momentum transfer. This slope is just the slope of the deuteron form factor and is quite well known.

We have measured such yield curves for 6 photon energies, which in the laboratory frame are: 668 MeV, 690 MeV, 708 MeV, 715 MeV, 722 MeV, and 776 MeV. The threshold energy for η° production is 629 MeV. All points were taken near $\theta^*_{\eta^\circ} = 90°$ in the C.M. system. The recoil momentum ranges from 564 MeV/c to 663 MeV/c. The results for the C.M. differential cross section $\left.\frac{d\sigma}{d\Omega^*}\right|_{\eta^\circ D}$ are plotted in Fig. 2a as a function of C.M. momentum. All points have been normalized to a laboratory recoil momentum of $q = 590$ MeV/c The errors include both statistical and normalization uncertainties. The features of interest are the large cross section near threshold and the fall off with increasing C.M. momentum. This is very similar to the gross features seen in the cross section measurements for $\gamma + p \rightarrow \eta^\circ + p$.

The interpretation of these results is interesting primarily in relation to the process $\gamma + p \rightarrow \eta^\circ + p$. This reaction has been studied near threshold by the Stanford1.) and Orsay3.) groups and at somewhat higher energies by the Frascati and California Institute of Technology groups.4.) The rapid rise from threshold together with the isotropic angular distribution show that the production is in an $S_{1/2}$ or $P_{1/2}$ state or a mixture of the two. Related experiments in the reaction $\pi^- + p \rightarrow \eta^\circ + n$ near threshold show a similar behavior. Theoretical considerations5.) have shown that the threshold behavior may be identified as an $I = 1/2$, $S_{1/2}$ resonance (S_{11}) with mass = 1500 - 1530 MeV.

The process $\gamma + D \rightarrow \eta^\circ + D$ may be related to $\gamma + p \rightarrow \eta^\circ + p$ and $\gamma + n \rightarrow \eta^\circ + n$ within the framework of the impulse approximation. The photoproduction amplitude may be separated into an isoscalar and isovector part viz., $T = (T^\circ + \tau_3 T^+)$ where T° and T^+ are the isoscalar and isovector parts of the single nucleon amplitude respectively, and τ_3 is the z component of the nucleon isospin operator. Only T° contributes to the process $\gamma + D \rightarrow \eta^\circ + D$, and the relevant photoproduction multipole for an $S_{1/2}$ final state is therefore the isoscalar part of the E_{0+} electric dipole amplitude. In the impulse approximation $\langle\eta^\circ D|T^\circ_D|\gamma D\rangle = \int d^3r \, e^{iq.r/2} \, \Psi_d(r) \, [T^\circ_1 + T^\circ_2]_{Av.} \, \Psi_d(r)$ where q is the laboratory recoil momentum, r is the nucleon relative coordinate, and $\Psi_d(r)$ is the deuteron wave function. The amplitude $[T^\circ_1 + T^\circ_2]_{Av.}$ represents an average over the deuteron Fermi momentum distribution for the single nucleon amplitudes. This has the effect of averaging over a range of photon energies. For an $S_{1/2}$ final state this reduces to$^{6.)}$: $|\langle\eta^\circ D|T_d|\gamma D\rangle|^2 = 8/3 \, |T^\circ|^2_{Av.} \, F^2(q^2)$ where $F^2(q^2)$ is a deuteron structure function and is generally referred to as the effective form factor. For comparison, the corresponding amplitude for production from the proton is: $|\langle\eta^\circ p|T|\gamma p\rangle|^2 = |T^\circ + T^+|^2$. Thus a measurement of $\gamma + D \rightarrow \eta^\circ + D$ determines the isoscalar amplitude if the deuteron form factor is independently known. The isovector amplitude may then be determined with the additional information provided by a measurement of incoherent production from the deuteron which is essentially just the sum of the cross sections from the free proton and neutron. The result of such an experiment has been recently reported by the Frascati group.$^{7.)}$ In terms of T° and T^+, the differential cross sections for $\gamma + D \rightarrow \eta^\circ + D$ and $\gamma + p \rightarrow \eta^\circ + p$ are:

$$d\sigma/d\Omega^*\Big|_{\eta^\circ D} \simeq 1/(4\pi)^2 \quad 8/3\ |T^\circ|^2_{Av.} \left(\frac{p^*}{k^*}\right)_{\gamma\text{-}D} F^2(q^2) \qquad 8.)$$

and

$$d\sigma/d\Omega^*\Big|_{\eta^\circ p} = 1/(4\pi)^2\ |T^\circ + T^+|^2 \left(\frac{p^*}{k^*}\right)_{\gamma\text{-}p}$$

where p^* and k^* are the final state C.M. momentum and C.M. photon energy respectively. Values for the form factor $F^2(q^2)$ may be obtained from the impulse approximation analysis of the measurements of reference 2.) and may also be calculated directly from the deuteron wave function. These two methods agree well as long as one is working in a region where the meson rescattering corrections are small. The Frascati group has concluded that the η° rescattering correction is small from measurements on inelastic η° photoproduction on various nuclei.$^{7.)}$

In order to make a direct comparison of $|T^\circ|_{Av.}$ and $|T^\circ + T^+|$ we have plotted in figure 2b the quantity $\dfrac{d\sigma/d\Omega^*\big|_{\eta^\circ D}}{8/3\ F^2(q^2)} \simeq d\sigma/d\Omega^*\big|_{\eta^\circ\text{-}N(\text{isoscalar})}$

as a function of p^*, the C.M. momentum. The figure also includes as a solid line the average value of the measured cross sections for $\gamma + p \rightarrow \eta^\circ + p$ taken from references 1.), 3.) and 4.). The approximate spread in experimental precision is shown by the dashed lines. It is convenient to plot the cross sections as a function of p^* since the phase space factor is then kept the same for both reactions, and since the Fermi momentum distribution in the deuteron prevents a unique determination of the effective single nucleon photon energy.

The conclusions of interest are:

1.) Figure 2a shows that coherent η° production from the deuteron is significant and measurable near threshold and falls off rapidly as a function of energy. The points at approximately 85 MeV and 140 MeV above threshold do not show a measurable signal.

2.) Figure 2b shows that when the form factor dependence is removed from the cross sections, the resultant isoscalar cross section is comparable in size to the $\gamma + p \to \eta^\circ + p$ cross section near threshold and shows a similar resonant behavior. This allows us to conclude that $|T^\circ|^2_{Av.} \approx |T^\circ + T^+|^2$ near threshold.

3.) The recent η° production measurements from deuterium of reference 7.) are dominated by incoherent production and allow one to conclude that $\mathrm{Re}(T^\circ T^{+*}) \approx 0$. Assuming that this result is valid over our photon energy range, and combining with 2.) above, one can solve for $|T^+|$ and therefore $|T^+| \approx 0$. This shows that the production near threshold is dominated by the isoscalar amplitude and that the isovector part is consistent with zero until ∿80 MeV above threshold.

4.) If the threshold behavior of the η° deuteron production is determined by the S_{11} (1550 MeV) isobar, then the photoproduction amplitude for this isobar is predominantly an isoscalar transition. One must, however, qualify this statement and keep in mind that the effective single nucleon-photon invariant mass can not be uniquely determined due to Fermi momentum smearing.

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FIGURE CAPTIONS

Fig. 1a and 1b - Two deuteron yield curves showing a signal due to η° production. The inserts in the upper left corner show the yields in the vicinity of η° threshold with backgrounds subtracted.

Fig. 2a - The differential cross section for the process $\gamma + D \rightarrow \eta^\circ + D$ in the C.M. system versus p^*, the C.M. final state momentum. The C.M. meson angle is $\simeq 90^\circ$ and the points have all been normalized to the value of the deuteron form factor evaluated at $q = 590$ MeV/c. $F^2(590 \text{ MeV/c}) = 1.4 \times 10^{-2}$ was used.

Fig. 2b - The differential cross section for $\gamma + D \rightarrow \eta^\circ + D$ divided by $8/3\ F^2(q^2)$ versus p^*. The measured cross sections for the reaction $\gamma + p \rightarrow \eta^\circ + p$ ($\theta^* \simeq 90^\circ$) are represented by the solid line.

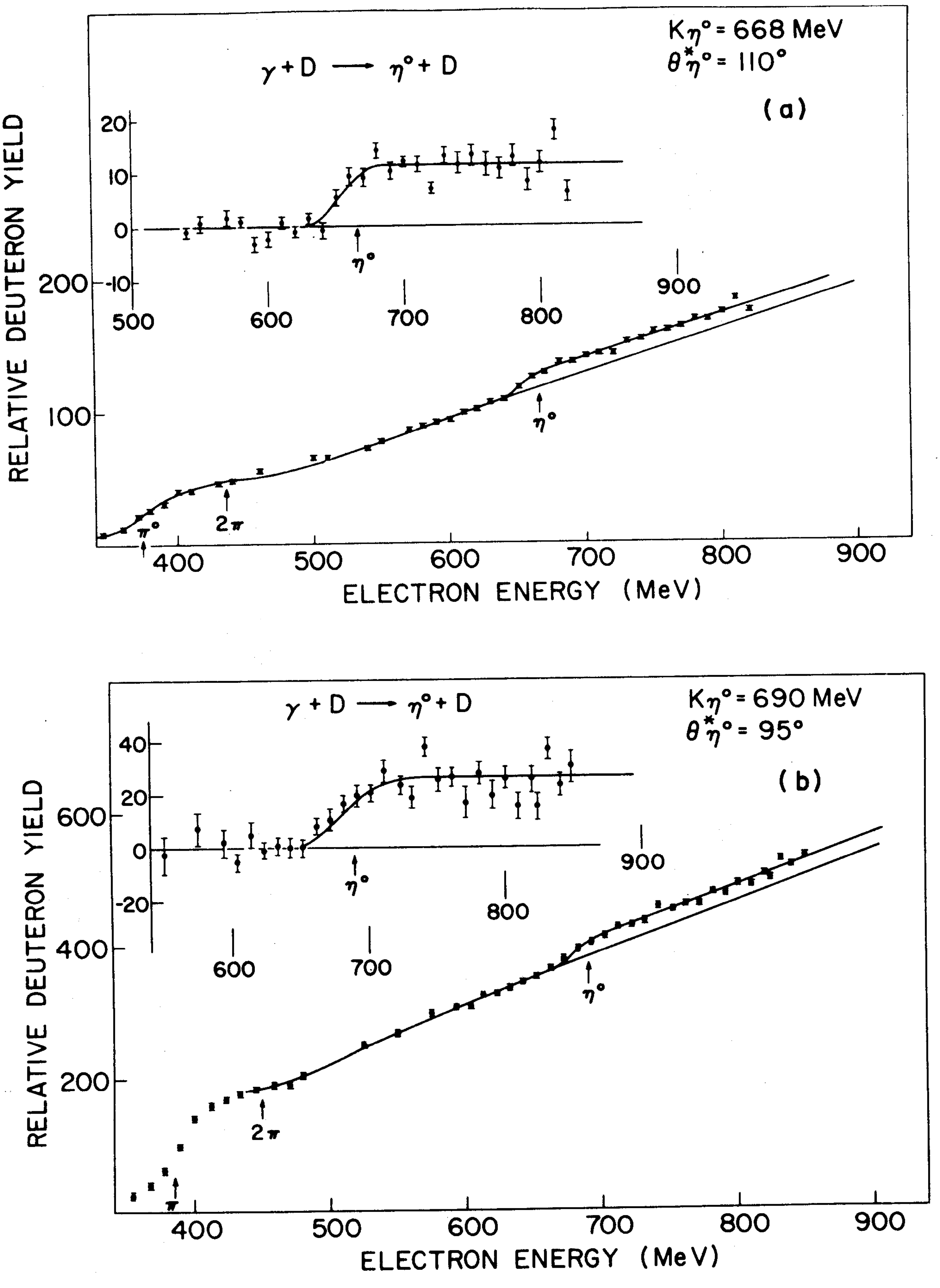
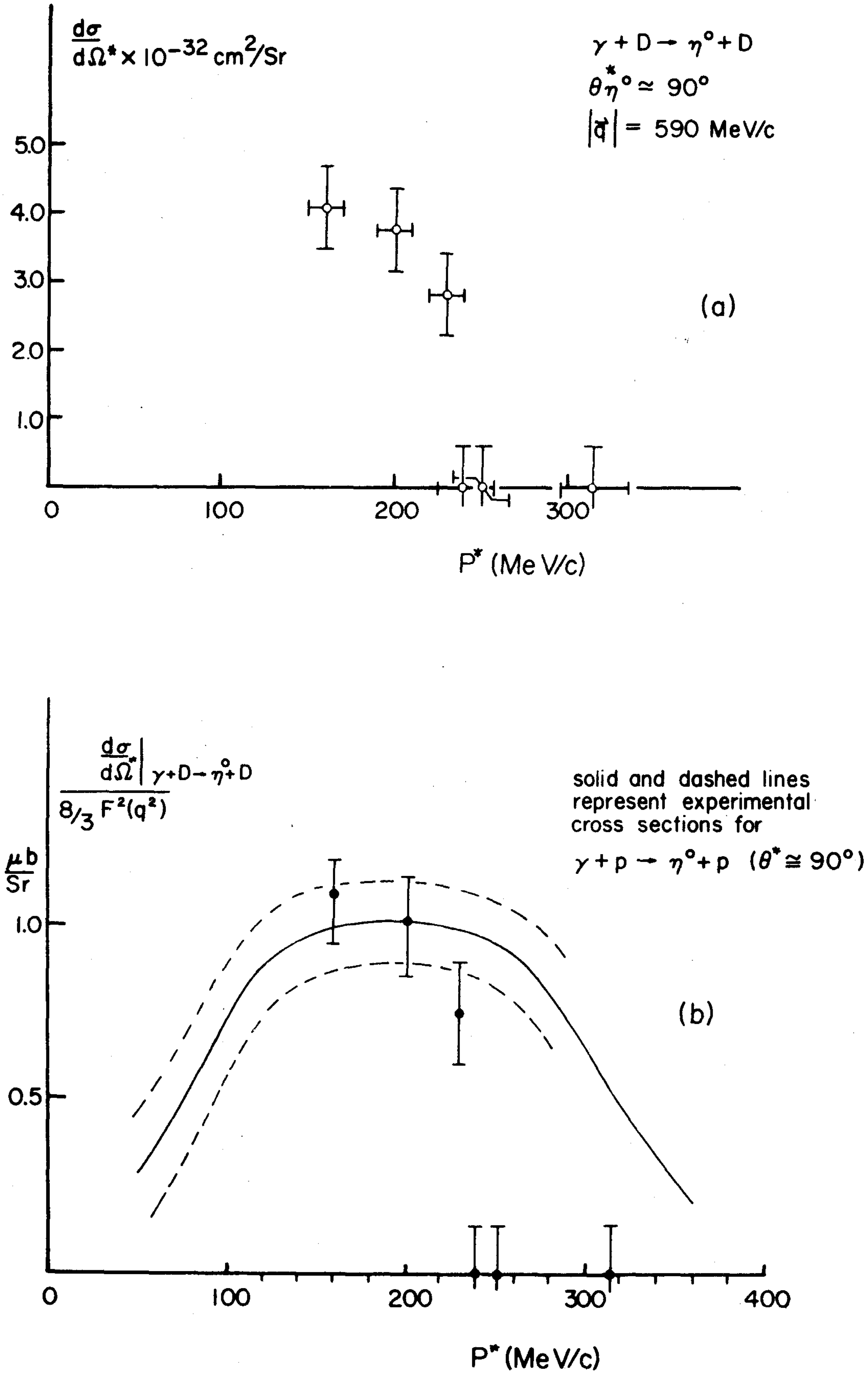

γ + D → η° + D
Kη° = 668 MeV
θ*η° = 110°
(a)
20
10
0
-10
500
600
700
800
900
η°
RELATIVE DEUTERON YIELD
200
100
π°
2π
400
500
600
700
800
900
ELECTRON ENERGY (MeV)
γ + D → η° + D
Kη° = 690 MeV
θ*η° = 95°
(b)
40
20
0
-20
600
700
800
900
η°
RELATIVE DEUTERON YIELD
600
400
200
2π
π
400
500
600
700
800
900
ELECTRON ENERGY (MeV)

FIGURE 1



$\frac{d\sigma}{d\Omega^*} \times 10^{-32}$ cm^2/Sr
$\gamma + D \rightarrow \eta^\circ + D$
$\theta^*_{\eta^\circ} \simeq 90^\circ$
$|\vec{q}| = 590$ MeV/c
5.0
4.0
3.0
2.0
1.0
0
100
200
300
(a)
P* (MeV/c)
$\frac{\left.\frac{d\sigma}{d\Omega^*}\right|_{\gamma+D\rightarrow\eta^\circ+D}}{8/3\, F^2(q^2)}$
$\frac{\mu b}{Sr}$
solid and dashed lines represent experimental cross sections for
$\gamma + p \rightarrow \eta^\circ + p$ ($\theta^* \cong 90^\circ$)
1.0
0.5
(b)
0
100
200
300
400
P* (MeV/c)

FIGURE 2