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Radiative Width of the η Meson*

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The cross section for the phtotproduction of η mesons by the Primakoff process has been measured at bremsstrahlung energies of 5.8, 9.0, and 11.45 GeV. A value of 0.324 $\pm$0.046 keV was obtained for the partial width of the η meson decaying into photon pairs. This result is a factor of 3 lower than the previously accepted value.

The η meson was originally classified in SU(3) as the $I=0$ member of the pseudoscalar octet. Application of U-spin conservation led to the prediction that the radiative partial width of the η^0 should be about 22 times the width of the π^0. In 1967 Bemporad *et al.*[1] reported an experimental value for the η^0 partial width which was 5 times larger than the predicted value. Attempts to explain the discrepancy using the usual symmetry-breaking terms were not successful. The use of octet-singlet mixing can account for the large ratio of widths and leads to predictions for the radiative width of the other isosinglet meson, generally assumed to be $X^0(958)$. We have recently remeasured the radiative width of the η^0 and the π^0 meson by the Primakoff effect method. The results of the experiment on the η^0 meson are presented in this Letter. A preliminary analysis of the experiment on the π^0 indicates that our results for the π^0 width will not be very different than the accepted value of 7.8 eV.[2] We will present the results of the π^0 experiment shortly.

The cross section for the photoproduction of η^0 mesons contains a contribution from single-photon exchange. Primakoff[3] pointed out that this amplitude may be expressed in terms of the η's partial decay width into photon pairs, $\Gamma(\eta \to 2\gamma)$. To describe production from a nucleus of atomic number Z, one sums the amplitudes from the individual protons.[4,5] The resulting amplitude may be written as

$$T_C = [8\alpha Z^2 \Gamma(\eta \to 2\gamma)]^{1/2} (\beta/\mu)^{3/2} (k^2/\Delta^2) \times \sin\theta\, F_C(k, \theta). \quad (1)$$

Here α is the fine-structure constant; k is the photon energy; $\mu = 0.549$ GeV, β, and θ are the mass, velocity, and direction, respectively, of the η; Δ^2 is the square of the four-momentum transfer; $F_C(k, \theta)$ is the Coulomb form factor. In addition to production in the Coulomb field, there is an amplitude for production in the hadronic field. In the case of a nuclear target of atomic weight A, the amplitude may be written as

$$T_N = A L \sin\theta\, F_N(k, \theta), \quad (2)$$

where $F_N(k, \theta)$ is the nuclear form factor and L is an angular-independent constant.[4] This expression is thought to be valid over a small angular range in the forward direction. $L \sin\theta$ represents the nucleon spin-nonflip amplitude (averaged over neutron and proton). The amplitudes are normalized so that the differential cross section $d\sigma/d\Omega$ is given by the sum of a term for Coulomb production, $(d\sigma/d\Omega)_C = |T_C|^2$, a term for nuclear production, $(d\sigma/d\Omega)_N = |T_N|^2$, plus an interference term, $(d\sigma/d\Omega)_{CN} = 2\,\mathrm{Re}(T_C T_N^*)$.

A separation of the amplitudes by measuring this cross section at several points may be accomplished because of the distinct angular and energy dependences of the two contributions. Isolating the Coulomb contribution by measuring the angular distribution is complicated by the interference term. In our energy range the magnitude of the nuclear amplitude is small in comparison with the Coulomb amplitude. In this case the coherent nuclear contribution tends to change the width of the Primakoff peak. The magnitude of the effect depends on the atomic species and, hence, by measuring the angular distribution for several targets one can make a separation. The energy dependence of the nuclear contribution is not known so it cannot be used as a check on the separation. The energy dependence of the Primakoff amplitude is known. Assuming that this energy dependence is distinct from that for nuclear production, cross-section measurements at several energies which yield the same value for $\Gamma(\eta \rightarrow 2\gamma)$ would be convincing evidence that the Coulomb term had been isolated correctly.

The experiment consisted of passing a photon beam through a complex nuclear target and measuring the number of η's that are produced near the forward direction. The two photons from the radiative decay of the η were detected in a pair of shower counter hodoscopes. Data were recorded for five targets (beryllium, aluminum, copper, silver, and uranium) at incident bremsstrahlung energies of 5.8, 9.0, and 11.45 GeV. Charged particles produced in the target were deflected horizontally away from the counters by a sweep magnet. A counter hodoscope consisted of eighty pieces of lead glass (type F-2), 4.5 cm $\times$4.5 cm$\times$49 cm long, each viewed end on by an Amperex XP1010 photomultiplier tube. They were stacked in a close-packed array, eight high by ten wide. One hodoscope was located above the beam and the other an equal distance below. The distance from the target to the hodoscopes was 445.3 cm for the 5.8-GeV data and 466.1 cm for the 9.0- and 11.45-GeV data. The distance between centers of the hodoscopes was 98.3, 64.0, and 53.4 cm for the respective energies.

An event trigger was generated if a photon of energy greater than 1.5 GeV entered each counter hodoscope and the sum of their energies was greater than about 60% of the bremsstrahlung end-point energy. The information recorded for an event trigger allowed a determination of the energy ($\Delta E/E = 0.05$, rms) and the position ($\Delta s = 0.45$ cm, rms) of the photons. Using the target position as a second point on the photon path, the momentum vector of each photon could be constructed.

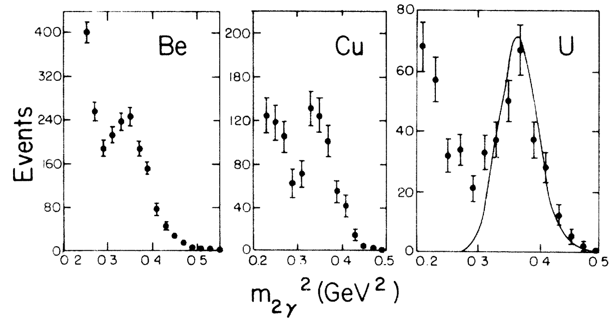

FIG. 1. Mass-squared spectra at 9.0 GeV. (The mass scale corresponds to the on-line energy calibration of the counters.)

In order to compare data with theory, it is necessary to establish the range of incident photon energies included in our data sample. The upper limit is best defined by the synchrotron energy and is known to about 0.5%. The lower limit may be set on the basis of the measured η energy, and an early analysis was made with events selected in this way.[6] However, the lower bound may be determined more precisely on the basis of the measured opening angle between the two photons.[7] The maximum opening angle was restricted to 0.220, 0.137, and 0.110 rad at the respective machine energies. A minimum opening-angle cut was also made. It did not establish a kinematic bound but was useful for eliminating non-η events. In Fig. 1, several of the two-photon mass spectra are shown for events selected with these criteria. A well-defined mass peak is seen sitting on the side of a falling background. The angular distribution of the events in the mass peak shows a sharp peak near 0° (see Fig. 2). It is this peak that we associate with the Primakoff and coherent nuclear processes. The angular distribution of the events outside the η mass region does not show this forward enhancement. Accordingly, we were able to assume that the background under the η mass peak would not change the amount of Coulomb production cross section found by a fitting procedure.[8]

The form factors[4] in Eqs. (1) and (2) were expressed as integrals over the charge density $\rho(r)$ and evaluated numerically for a Woods-Saxon distribution:

$$\rho(r) = \frac{\rho_0}{1 + \exp[(r-c)/t]}. \qquad (3)$$

The nuclear radius c was taken as 2.2, 3.05,

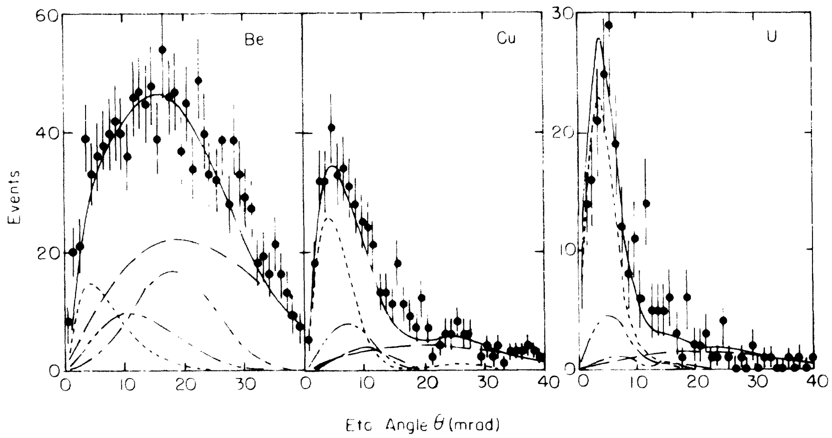

FIG. 2. Angular distributions at 9 GeV (first data set). The vertical axis is the number of events detected in 1-mrad bins. The curves denote the following functions: short-dashed line, $0.308n_C(\theta)$; dash-dotted line, $1.25n_N(\theta)$; dash–double-dotted line, $0.620n_{CN}(\theta, -0.63)$; long-dashed line, $3.13n_b(\theta)$; solid line, $n(\theta)$.

4.28, 5.14, and 6.8 fm for the respective targets.[9] A value of $t=0.55$ fm was used for the skin thickness. Reabsorption of the η in nuclear matter is included in the form factor (we used a total η-nucleon cross section of 30 mb). For fitting data an isotropic background term was added to the cross section and a set of free parameters was introduced:

$$\frac{d\sigma}{d\Omega}=a_C\left(\frac{d\sigma}{d\Omega}\right)_C+a_N\left(\frac{d\sigma}{d\Omega}\right)_N+(a_Ca_N)^{1/2}\left(\frac{d\sigma}{d\Omega}\right)_{CN}+a_b\left(\frac{d\sigma}{d\Omega}\right)_b. \tag{4}$$

The background term was taken to be $(d\sigma/d\Omega)_b=A^{0.75}$ μb/sr, the A dependence having been determined from the event rate at large angles. The value of $\Gamma(\eta\to 2\gamma)$ in Eq. (1) was set equal to 1 keV so that the fitted value of a_C is the partial width in keV. The magnitude of the nucleon amplitude, L, was set to equal $4k$, corresponding to a spin-nonflip nucleon amplitude comparable to the cross section for photoproduction from hydrogen at $\Delta^2=0.1$ GeV^2.[10] a_N may then be interpreted as giving the ratio between the value of $|L|^2$ required by the data and what had been estimated from the hydrogen cross section. A fourth parameter φ, the phase of L, is buried in $(d\sigma/d\Omega)_{CN}$.

Using Eq. (4), the number of events $n(\theta)$ to be expected in a 1-mrad interval at angle θ was calculated by integrating over the incident photon spectrum[11] and folding in the angular resolution of the detector.[6] The result may be expressed as

$$n(\theta)=a_Cn_C(\theta)+a_Nn_N(\theta)+(a_Ca_N)^{1/2}n_{CN}(\theta,\varphi)+a_bn_b(\theta), \tag{5}$$

where the n_i's are the number of events computed for the individual components of the cross section.

The data on all five targets at a single bremsstrahlung energy were fitted with the four parameters. The results are listed in Table I.[12] The errors listed are the statistical uncertainties obtained from the fitting procedure. Several fitted angular distributions of the first data set at 9.0 GeV are shown in Fig. 2. The last entry in Table I is the result of fitting the data on a single uranium target by fixing the phase angle. Several values of φ between -1.5 and $+3.0$ rad were tried. The error in this case reflects the range of answers. These data were accumulated approximately six months after the main run with a counter geometry in which the target-to-hodoscope distance had been increased to 1144 cm.

The sensitivity of our result for the η decay rate to the parameters used in the form-factor calculation was tested by varying them individually and refitting the data. Variation of the nuclear radius by 10%, the skin thickness by 10%, and the η-nucleon cross section by 10 mb produced changes in the fitted value of a_C of 0.0015, 0.005, and 0.005, respectively. For comparison, the value of a_N in these fits changed by 0.2, 0.25, and 0.2.

The values of a_C and a_N that we find are com-

TABLE I. The fitted values of the cross-section parameters.

Machine energy (GeV)	Targets	a_C	a_N	Φ (rad)	a_b	χ^2 per degree of freedom
5.8	Be, Cu, U	0.343 ± 0.054	0.25 ± 0.24	−1.03 ± 0.50	2.26 ± 0.10	136.6/86
9.0 (1st)	All 5	0.308 ± 0.029	1.25 ± 0.37	−0.63 ± 0.54	3.13 ± 0.22	213.4/146
9.0 (2nd)	All 5	0.287 ± 0.031	1.18 ± 0.29	0.89 ± 0.41	2.86 ± 0.22	193.5/146
11.45	All 5	0.350 ± 0.018	1.02 ± 0.20	1.0 ± 1.9	0.0 (fixed)	112.6/127
11.45	U only	0.35 ± 0.05	0.24 ± 0.60	1.0 (fixed)	7.9 ± 1.2	46.9/41

patible with the data published by Bemporad *et al.*[13] We do indeed find a better fit to their angular distribution using their values, $a_C = 1.0$, $a_N = 0.0$. We have concluded that the limitations on their experiment, primarily in energy, did not permit them to distinguish between these two solutions.

Our final value for the η decay width into photon pairs is $\Gamma(\eta \to 2\gamma) = 0.324 \pm 0.046$ keV. The quoted error includes 5.3% for statistical accuracy, 12.2% for the systematic uncertainties related to the accepted photon spectrum, and 2.5% for the uncertainties in the values of parameters used in the form-factor calculations. Using the branching ratio for the two-photon decay mode, 0.38,[2] the full width of the η meson is 0.85 ± 0.12 keV.

We wish to thank Professor D. Yennie for suggesting various approaches to evaluating the factors. Professor A. Silverman worked with us during the early stages of the experiment, and we have benefitted from the many discussions with him. Dr. David Larson participated in the measurements on the π^0 and as a consequence helped with some of the data checks in this experiment. We are indebted to E. von Borstel and the crew of the Wilson Synchrotron Laboratory for their efforts toward providing us with the fine machine operation that was necessary for this experiment.

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[12]The event sample in this analysis is identical to that used to arrive at the results given in Ref. 7. The distinction between those results and the fits reported in this paper arise from the recalculation of the form factors using the Woods-Saxon density distribution and including the terms dropped by Morpurgo.

[13]We are indebted to Bemporad *et al.* for freely discussing their experiment with us (Ref. 1) and sending us the experimental details we required.