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Negative-pion photoproduction from neutrons by linearly polarized photons in the first resonance region

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The angular dependence of the asymmetry for negative-pion photoproduction on neutrons by linearly polarized photons has been measured for photon energies 260, 300, 350, 400, 450, and 500 MeV at center-of-mass angles 60°, 75°, 90°, 150°, and 120°. The results are compared with theoretical models of low-energy single-pion photoproduction. The observed asymmetry below 400 MeV shows good agreement with predictions of dispersion-theoretical models by Berends, Donnachie, and Weaver and by Schwela. The asymmetry values in the 400–500 MeV energy region suggest that smaller M_{1-} amplitude is more favorable.

I. INTRODUCTION

In a systematic study on single-pion photoproduction from nucleons, one needs information about the pion production on neutrons $\gamma n \rightarrow \pi^- p$, $\pi^0 n$ which is still lacking to allow quantitative amplitude analyses. There has been renewed interest in the neutron-target processes, since Sanda and Shaw[1] suggested that the possible existence of isotensor electromagnetic current of the hadrons could explain an anomalous dip found in the difference between the total cross sections for the two processes, $\gamma n \rightarrow \pi^- p$ and $\gamma p \rightarrow \pi^+ n$, in the first-resonance region. An argument by Berardo *et al.*[2] that the detailed balance in the $\gamma n \rightarrow \pi^- p$ process seems to be violated has stimulated further investigation on the $\gamma n \rightarrow \pi^- p$ process.

This paper is concerned with the production asymmetry

$$\Sigma = (\sigma_\perp - \sigma_\parallel)/(\sigma_\perp + \sigma_\parallel)$$

with linearly polarized photons. The asymmetry is sensitive to the small partial-wave amplitudes such as E_{0+} and M_{1-}, while the modification in the large M_{1+} amplitudes as made in Ref. 1 has little effect on the value of the asymmetry. In this context, we will compare the results of the asymmetry measurement with current models of low-energy photoproduction.

II. LINEARLY POLARIZED PHOTON BEAM

A linearly polarized photon beam was produced from a single crystal of silicon set in a straight section of the 1.3-GeV electron synchrotron at the Institute for Nuclear Study, University of Tolyo.[3] The crystal was oriented so that the photon energies responsible for the photoproduction corresponded to those of the major coherent spike. For each crystal setting the spectrum of the bremsstrahlung was measured with a pair spectrometer. A typical measured spectrum is shown in Fig. 1, where the solid curve is the best fit with the formula by Tsuru *et al.*[4] Parameters for the angular divergence of the electrons and the contamination of the incoherent part were also determined from the fit. With the use of these parameters, the polarization of photons was calculated as shown by the dashed line in Fig. 1. The polarization error ΔP is estimated to be less than ± 0.01.

The polarization of photons was simultaneously measured by observing vertical emission angles of electron pairs[5,6] produced from 15-μ thick aluminum with wire spark chambers. The measured values of polarization are presented in Fig. 2, together with those obtained from the spectrum fitting for comparison.

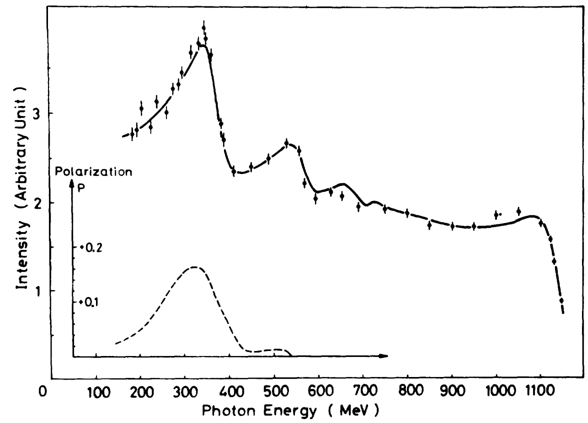

FIG. 1. A typical example of a measured spectrum. Its best theoretical fit is shown by a solid line. The values of polarization calculated from the fit are shown by a dashed curve.

III. MEASUREMENT OF THE ASYMMETRY RATIO

Events of the $\gamma d \rightarrow \pi^- pp$ reaction were identified by detecting the emitted pion and the recoil proton in coincidence. Produced pions were detected by a 700-MeV/c magnetic spectrometer set on a rotating platform. It consisted of a sector-type magnet with 50° deflection angle, three triggering scintillation counters, three layers of 20-bin scintillation counter hodoscopes, and a threshold gas Čerenkov counter to reject electrons. Its solid angle and momentum acceptances were 2.1×10^{-3} sr and ±0.07, respectively. The momentum resolution was approximately $\pm1.8\%$ for the momentum range of pions in the present experiment (160–420 MeV/c). Recoil protons were detected by a range counter telescope consisted of two triggering counters ($T1$, $T2$), a 5-bin hodoscope and five range counters with copper absorbers. The solid angle acceptance was 2.8×10^{-2} sr and its momentum resolution was approximately ±15 MeV/c. Background electrons in the range telescope were distinguished by measuring the pulse height in the $T2$ counter.

All digital signals from hodoscopes, range counters and ADC's were transferred to the on-line computer TOSBAC3400, where on-line analysis and storage of data were performed. The data taking was carried out in about fifteen runs for each data point, and the polarization of the photon beam was changed in each run in order to avoid systematic errors. The asymmetry with unpolar-

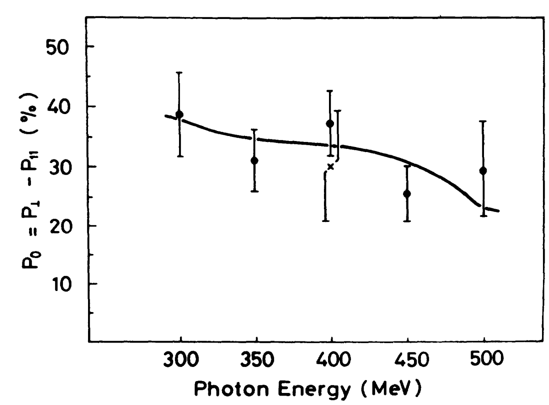

FIG. 2. The polarization values obtained by the direct measurement are shown by circles or by a cross. The error bars indicate statistical errors only. The solid line is drawn for easy visualization of the polarization values calculated by fitting the measured spectrum.

ized photons was also observed to exclude false asymmetries which might be caused by instrumental biases.

A contribution from the double pion production $\gamma d \to \pi^+\pi^- pn$ by the higher-energy part of the bremsstrahlung was kinematically allowed in our detection system. To estimate this background contamination, positive pions and protons were detected by reversing the polarity of the pion magnet under otherwise identical conditions. The contamination was confirmed to be less than 5% in all data points.

The energy spread of the photons in the lab system (k_l) and in the neutron rest frame (k_f) was restricted within ±5% around the central photon energy. The spread of the center-of-mass production angle is about ±3.5°.

The ratio R of the photoproduction cross sections for photons with the polarizations $P_\perp$ (>0) and $P_\parallel$ (<0) was determined by $R = Y_\perp / Y_\parallel$ where $Y_\perp$ and $Y_\parallel$ are the numbers of events per unit intensity of the relevant photons, respectively. The asymmetry Σ was derived from the observed ratio R by the formula $\Sigma = (R-1)/(\overline{P}_\perp - R \cdot \overline{P}_\parallel)$, where $\overline{P}_\perp$ and $\overline{P}_\parallel$ are polarizations averaged over the photon energy spread.

IV. RESULTS AND DISCUSSION

The results of the present experiment are given in Table I, where the errors are statistical ones.

Since the present measurement is concerned with a ratio, various systematic errors can be reduced considerably. However, there still remain ambiguities of the asymmetry ($\Delta\Sigma$) as follows: ±(1–3%) due to uncertainty of polarization, ±(2–3%) from ambiguity in the photon energy, and ±(0–1%) by contamination with double pion background.

Since a neutron in a deuterium nucleus is not free, the following deuteron effects have been taken into account: (1) The binding effect of target particle can be estimated according to Goldberger and Watson.[7] The difference between the scattering amplitude for free neutrons and that for bound neutrons is estimated to be less than 2% in kinematical range for the present experiment. (2) The effect of the Pauli principle on the measured asymmetry is calculated with the use of the amplitudes of Ref. 8 and Hulthén's wave function, following the formalism of Chew and Lewis.[9] The correction to the asymmetry is less than 2.4% in the present experiment (see Table I). (3) The effect of rescattering of the emitted pion by the other nucleon is almost canceled out since only the ratios were measured. In summary, corrections due to deuteron effects are estimated to be smaller than the statistical errors in the present experiment.

TABLE I. The asymmetries Σ for the reaction $\gamma d \to \pi^- pp$ are shown in the table. Only statistical errors are listed. The data are without any corrections for the deuteron effects. $\Delta\Sigma_p$ is the correction due to the Pauli exclusion principle and is defined by $\Delta\Sigma_p = \Sigma^{(BDW)} - \Sigma_p^{(BDW)}$. Here $\Sigma^{(BDW)}$ denotes the asymmetry for the reaction $\gamma n \to \pi^- p$ calculated with the BDW amplitudes. $\Sigma_p^{(BDW)}$ denotes the asymmetry for the reaction $\gamma d \to \pi^- pp$, calculated by using the BDW amplitudes and taking into account the Pauli principle in the Chew-Lewis formalism.

k_f (MeV)	θ^* (degree)	Σ (%)	$\Delta\Sigma_p$ (%)
260	105	32.2 ± 9.5	1.7
300	90	23.6 ± 5.6	2.4
	105	37.5 ± 6.1	1.6
	120	33.0 ± 5.7	1.0
350	75	46.5 ± 6.3	1.9
	90	53.5 ± 6.0	1.4
	105	35.6 ± 6.9	1.0
	120	43.5 ± 7.6	0.7
400	60	57.8 ± 6.3	0.9
	75	61.7 ± 5.2	0.8
	90	63.5 ± 5.6	0.6
	105	44.9 ± 6.2	0.5
	120	34.0 ± 6.0	0.3
450	60	73.1 ± 7.2	0.6
	75	73.7 ± 6.2	0.5
	90	69.2 ± 6.6	0.3
	105	51.1 ± 9.5	0.2
	120	36.7 ± 7.3	0.1
500	60	62.5 ± 6.9	0.5
	90	55.6 ± 7.8	0.2

Theoretical calculations of the asymmetry of the reaction $\gamma n \to \pi^- p$ in the first-resonance region have been made by Berends, Donnachie, and Weaver[8] (hereafter referred to as BDW), Schwela,[10] Walker,[11] Noelle and Pfeil,[12] and Pfeil and Schwela.[13]

The calculated asymmetries are shown in Fig. 3 in comparison with the experimental values. Calculations by BDW and Schwela are based on dispersion theory. The present data seem to agree with BDW's calculation below 400 MeV. At 450 MeV and 500 MeV, however, the measured asymmetries are higher than the calculated ones. This fact confirms a previous conclusion that the BDW amplitudes with a large M_{1-} component give too small asymmetry.[14] Walker's calculation based on an isobar model agrees well with our results below 350 MeV, but at 400 MeV and 500 MeV the calculated values are higher than the observed ones. Note that Walker gives a small M_{1-} ampli-

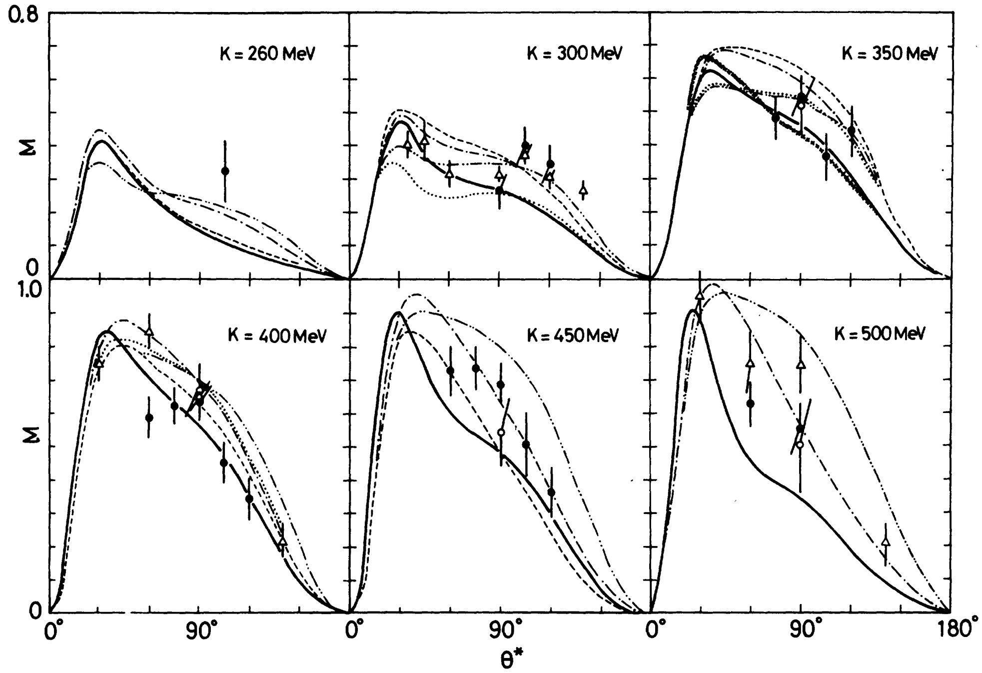

FIG. 3. The asymmetry for $\gamma d \rightarrow \pi^- pp$: from this experiment (•); from Ref. 14 (○); from Ref. 15 (△). The error bars indicate statistical errors only. The curve are the predictions by Ref. 8 (——), Ref. 10 (—·—), Ref. 11 (—··—), Ref. 13 (---), and Ref. 12 (···). The curve ××× (at 350 MeV) is depicted to show that the modification of the large M_{1+} amplitude has little effect on the value of the asymmetry, where all multipoles except $M_{1+}^{(3)}$ are taken from the BDW evaluation and $M_{1+}^{(3)}$ is assumed to be 80% of that of Ref. 8.

tude. At 300 MeV and 400 MeV, the present exper- agrees with the results by Pfeil and Schwela, in which the M_{1-} amplitude has nearly the same value as that by BDW. However, the calculated asymmetries are lower at 450 MeV.

Noelle and Pfeil[12] have suggested that the Sanda-Shaw dip in $\Delta = (k/q)(\sigma^{\pi^-} - \sigma^{\pi^+})$ near the first resonance can be fitted well by modifying the $E_{0+}^{(0)}$ wave without introducing the isotensor current. The energy dependence of the $E_{0+}^{(0)}$ amplitude of their model is stronger than the predictions by dispersion theories. The measured asymmetry is higher at 300 MeV but lower at 400 MeV in comparison with their model, suggesting that such a strong energy dependence of the $E_{0+}^{(0)}$ wave is undesirable.

In conclusion, we want to remark that new phenomenological analyses including the $\gamma n \rightarrow \pi^- p$ process in the first-resonance region are required.

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Neutrino mass limits from the $K_L^0 \to \pi^{\pm} l^{\mp} \nu$ decay spectra*

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A magnetic spectrometer at the Bevatron has been used to study the low-neutrino-energy ends of the $K_{\mu 3}$ and K_{e3} spectra. The spectra are found to agree well with the $V-A$ predictions for massless neutrinos. The upper limits (90% confidence level) are 650 keV for the muon-neutrino mass and 450 keV for the electron-neutrino mass.

I. INTRODUCTION

The most precise limits on the muon-neutrino mass have been set by measuring the energy[1] or momentum[2] of the muon in $\pi \to \mu\nu_\mu$ decays. While this method is straightforward, it is quite sensitive to the value of the pion mass. A determination of the muon-neutrino mass is presented here which is practically independent of the uncertainty in the pion mass. The method used is to examine the low-neutrino-energy ends of the $K_L^0 \to \pi^{\pm}\mu^{\mp}\nu$ ($K_{\mu 3}$) and $K_L^0 \to \pi^{\pm}e^{\mp}\nu$ (K_{e3}) spectra. As will be shown, the use of $K_L^0 \to \pi^+\pi^-$ ($K_{\pi\pi}$) events for mass scale calibration decreases the sensitivity of the neutrino mass determinations to previously measured particle masses.

A comparison of the results and methods of muon-neutrino mass determinations is shown in Table I. It should be noted that for all methods the quantity actually measured is the square of the rest mass; hence, reducing the mass limit by one half involves an experiment which is four times as sensitive.

Also determined in this experiment is a limit on the mass of the electron neutrino. Very precise measurements[3] of the positron spectrum from tritium beta decay have set limits on the electron-neutrino mass of ~60 eV. The comparatively crude limits set by the present experiment (450 keV) offer both a check on the experimental method for determination of the muon-neutrino mass and a new limit on the mass of electron neutrinos from strangeness-changing decays. The latter result is significant when one considers the paucity of experimental evidence on the existence of different types of neutrinos.

In addition as a test of *CPT* invariance, the spectra for neutrinos are compared with the corresponding spectra for antineutrinos. Our limits on the mass differences are much more stringent than those implied by comparison of π^+ and π^- lifetimes.

II. EXPERIMENTAL METHOD

A. General

The $V-A$ theory of weak interactions predicts little dependence of the K_{l3} matrix element on the neutrino mass. However, the boundary of the Dalitz plot is modified for a nonzero neutrino mass.

In the present experiment the measured invariant mass $m_{\pi l}$ of the two charged secondaries is simply related to the neutrino energy in the kaon center-of-mass system by

$$E_\nu = \frac{m_K{}^2 - m_{\pi l}{}^2 + m_\nu{}^2}{2m_K}$$

$$\cong \frac{(m_K + m_{\pi l})}{2m_K}(m_K - m_{\pi l})$$

$$\cong m_K - m_{\pi l}\,.$$