Spin asymmetries from $^{16}O(\vec{\gamma},p\pi^-)$ near Δ resonance energies

K. Hicks,[2] H. Baghaei,[5] A. Caracappa,[1] A. Cichocki,[5] G. Davenport,[2] R. Finlay,[2] V. Gladyshev,[5] T. Gresko,[5] S. Hoblit,[1] M. Khandaker,[6] O. Kistner,[1] F. X. Lee,[4] R. Lindgren,[5] M. Lucas,[3] L. Miceli,[1] B. Norum,[5] J. Rapaport,[2] A. Sandorfi,[1] R. Sealock,[5] L. C. Smith,[5] C. Thorn,[1] S. Thornton,[5] C. S. Whisnant,[3] and L. E. Wright[2]

[1] *Physics Department, Brookhaven National Laboratory, Upton, New York 11973*

[2] *Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701*

[3] *Department of Physics, University of South Carolina, Columbia, South Carolina 29208*

[4] *TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*

[5] *Department of Physics, University of Virginia, Charlottesville, Virginia 22903*

[6] *Physics Department, Virginia Polytechnic Institute & State University, Blacksburg, Virginia 24061*

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Spin asymmetries for the $^{16}O(\vec{\gamma},p\pi^-)$ reaction are reported for incident photon energies of 293 ± 20 MeV, proton angles ranging from 28° to 140° (lab), and pion angles of 35° to 115°. The data are compared with calculations in a quasifree plane-wave impulse approximation model. This model is in good agreement with the data at small momentum transfer q, but does not follow the trend of the data at large q. Sensitivity to the Δ-nucleus potential and to modification of the Δ lifetime from nuclear medium effects are explored using a simple modification of the Δ propagator in the calculations. [S0556-2813(97)50401-8]

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Pion photoproduction from hydrogen and deuterium targets has been used to determine the vertex couplings $g_{\gamma N\Delta}$, which measure the transition strength for electromagnetic excitation of the nucleon to the Δ resonance [1]. When the nucleon is embedded in the nucleus, the off-shell description of the $g_{\gamma N\Delta}$ vertex may change. In addition, the nuclear medium is expected to interact with the Δ resonance, resulting in a Δ-nucleus potential and new decay channels (such as $\Delta N \rightarrow NN$ for example). The description of these medium effects is of considerable interest, as it can substantially modify the pion-nucleon interaction in the nucleus. For example, the ratio between quasifree π^+-p and quasifree π^--p scattering with nuclear targets is substantially modified from the ratio for a proton target [2], showing strong evidence for a modified Δ in the nuclear medium. However, theoretical analysis of this reaction are clouded by questions of nuclear pion absorption mechanisms [3], and cannot reproduce the isospin ratios (i.e., the ratio of cross sections for quasifree scattering of π^+ and π^- probes). Pion photoproduction, with its electromagnetic vertex, has fewer theoretical ambiguities since excitation of the nucleon to the Δ is induced primarily through the M1 dipole interaction.

An experimental value for the Δ-nucleus potential has been sought for some time, since it could provide a comparison with theoretical models built on meson-exchange dynamics [4]. The data reported here, for $^{16}O(\vec{\gamma},p\pi^-)$ at photon energies near Δ-resonance energies, suggest an attractive Δ-nucleus potential, within the approximations of calculations [5].

The basic mechanism for inclusive pion photoproduction has been examined by comparing various theoretical calculations with cross-section data (see the review in Ref. [6]). For example, at photon energies ranging from 170 to 200 MeV, data for a ^{14}N target are in good agreement with calculations in the distorted-wave impulse approximation (DWIA) [7]. However, as the photon energy rises above 220 MeV, the DWIA predictions underestimate the data, up to a factor of about 2.5 at 320 MeV. Calculations using final-state interactions (FSI) in the Δ-hole model [8] do better, but even these predictions fall a factor of 2 below the data at 320 MeV. A reasonable conclusion is that the Born terms, which contribute most of the cross section at lower energies, are correctly modeled, but at higher energies, where the Δ has a stronger influence, there is something missing in the theoretical models. A measurement of the spin asymmetry provides an alternate and sensitive test of the interference effects between the Born and Δ terms.

Exclusive pion photoproduction enjoys some advantages over the inclusive measurements. The $A(\gamma,\pi)$ data, which requires the final nucleon to remain bound, makes the calculations very sensitive to the nuclear structure of the target. This sensitivity can be largely removed by allowing the final nucleon to leave the nucleus [5]. At quasifree kinematics, data from a nuclear target could be directly compared to measurements of $(\gamma,p\pi^-)$ on a deuterium target, after correcting for FSI effects on the outgoing p and π. The FSI can be modeled by optical potentials fit to elastic scattering data. Ambiguities in the FSI can also be removed by measuring the spin asymmetry Σ, which is a ratio of cross sections and insensitive to the choice of optical potential [5] or spectroscopic factor used in the calculations. In fact, the plane-wave impulse approximation (PWIA) gives almost identical predictions to Σ as for the DWIA, at near-resonance energies. The calculations for Σ are, however, sensitive to the parameters of the Δ propagator [5], which carries information on the Δ-nucleus potential.

Previous data for the exclusive $(\gamma,p\pi^-)$ reaction on a nuclear target are sparse. A recent publication, from data taken at MIT/Bates [9], measured cross sections as a function of the out-of-plane proton angle. These data were reported at two pion angles: one backward angle, 120°, which is dominated by the Born terms, and one forward angle, 64°, where the Δ resonance is predicted to have a bigger effect. The DWIA calculations overpredict the data for both pion angles [5], although the discrepancy is much larger at the forward pion angle data (by a factor of ~4). Calculations with the mass of the Δ reduced by 5% in the free-space propagator are in much better agreement with the data. The Δ propagator satisfies the Schrödinger equation

$$\left[E_\Delta - M_\Delta + \frac{1}{2} i\Gamma_\Delta - V_\Delta\right] G_\Delta(\mathbf{r},\mathbf{r}',\omega) = \delta^{(3)}(\mathbf{r}-\mathbf{r}'), \quad (1)$$

where E_Δ is the energy of the Δ in the center-of-mass frame, M_Δ and Γ_Δ are its mass and energy-dependent width, and the self-energy V_Δ represents the interaction of the Δ with the nuclear medium [4]. Hence a 5% reduction in the mass for the free-space propagator corresponds to $M_\Delta + V_\Delta = 0.95 M_\Delta$. Although the better agreement between the $0.95M_\Delta$ calculations and the Bates data are intriguing, data with smaller statistical errors, and more refined calculations, are needed to fully explore the possible medium modifications of the Δ. Reference [5] uses the nonrelativistic Schrödinger equation, as above, but is evaluated using relativistic kinematics.

The model of Lee, Wright, and Bennhold [5] is a DWIA calculation for exclusive quasifree pion photoproduction on complex nuclei, carried out with complete nonlocal momentum-space integrations. Other theoretical models are mentioned in Ref. [5]. The full Blomqvist-Laget production operator [1], with explicit dependence on the four-momentum of particles at the vertex along with the second $\gamma N\Delta$ coupling in the Δ channel [10], was used without the approximations contained in earlier versions of the operator. In particular, the operator was unitarized by introducing complex phases in the amplitudes and fixed by the pion photoproduction multipoles.

Harmonic oscillator wave functions were used to describe the bound-state nucleons, and hence these calculations are limited to the low momentum-transfer region ($q<200$ MeV/c). Spectroscopic factors determined from $(e,e'p)$ experiments are included directly in the nuclear matrix elements. The Δ propagator is evaluated using relativistic kinematics, with the Δ mass and width taken as the free values or modified (multiplied by a constant) by optional input parameters. Since the operator is evaluated at the kinematics determined by the incoming and outgoing particles, modifying the mass of the Δ (in order to model medium effects) will change the Δ amplitude. Although the Δ amplitude is much smaller (~0.1) than the Born terms at these kinematics, a change in the Δ mass can have a larger effect on the spin asymmetry through interference with the Born terms. A change in the Δ width would also be possible due to the additional channel of $\Delta N \rightarrow NN$ in the nucleus. The Δ width $i\Gamma_\Delta$, will not interfere with the (real) Born terms to first order.

As noted above, calculations for the spin asymmetry are nearly identical (within ~1%) for the PWIA and DWIA cases, so all calculations shown below do not include optical potentials for either the outgoing pion or proton. Similarly, calculations with and without the spectroscopic factors are virtually indistinguishable. As a result, the spin asymmetry data are mostly sensitive to modifications of the Δ propagator [5].

The $^{16}O(\vec{\gamma},p\pi^-)$ reaction was measured at the Laser Electron Gamma Source (LEGS) facility located at the National Synchrotron Light Source of Brookhaven National Laboratory [11]. The linearly-polarized photons between 210 and 330 MeV were produced by backscattering ultraviolet laser light from 2.6 GeV electrons. The γ-ray energy was determined, with an uncertainty of about 5 MeV, from magnetic analysis of the scattered electrons in a tagging spectrometer [12]. The beam flux was continuously monitored with e^+e^- pair creation detectors, located downstream of the target. Beam polarization was calculated using the measured value of the laser polarization (typically ~99%) and the kinematics of Klein-Nishina scattering [13]. The polarization direction was cycled between orientations parallel and perpendicular to the scattering plane, at intervals of roughly five minutes. The computer data acquisition deadtime was low, typically about 5%. The relative deadtime for each polarization state was measured to an uncertainty of less than 1%.

The target consisted of liquid H_2O contained within a thin-walled (0.75 mm) plastic chamber, of dimensions 50.4 mm by 57.4 mm by 100 mm long. The collimated photon beam was about 20 mm by 40 mm, and centered on the target to within 1 mm. An empty target run was also mea-

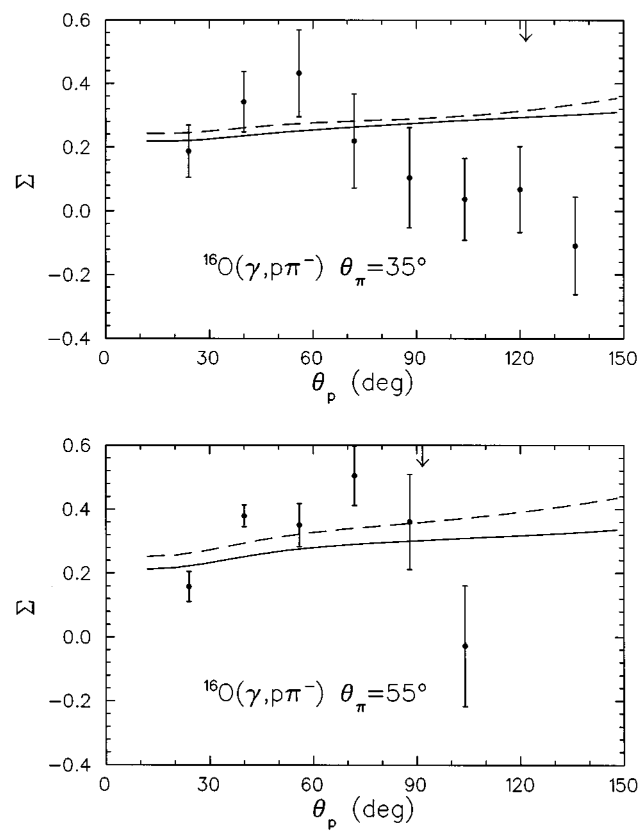

FIG. 1. Spin asymmetry for the photon polarization in-plane and normal to the scattering plane, at pion angles of 35° and 55°, as a function of proton angle (lab), at an average photon energy of 293 MeV. The curves represent PWIA calculations with the Δ mass at its free value (solid) and reduced by 5% (dashed). The arrow shows the location of a momentum transfer to 200 MeV/c.

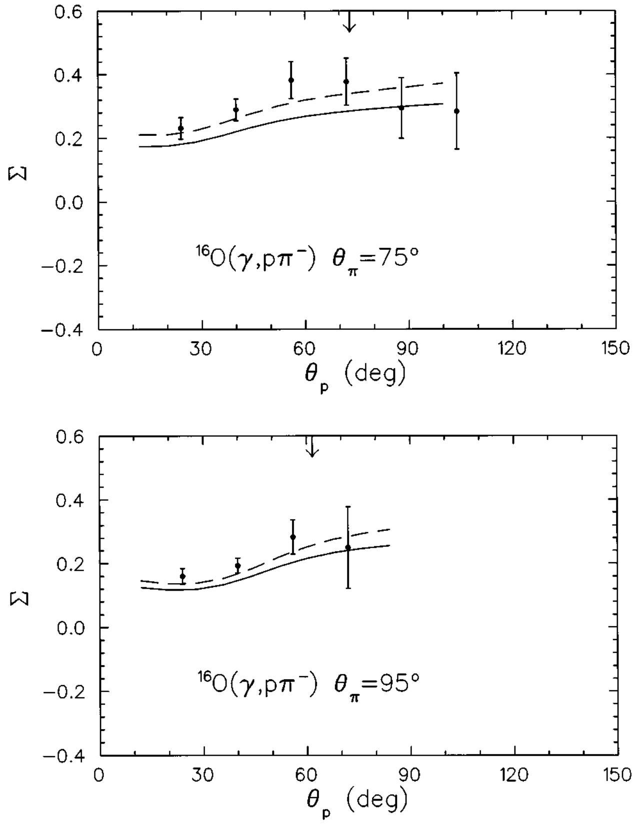

FIG. 2. Same as Fig. 1 except for pion angles of 75° and 95°.

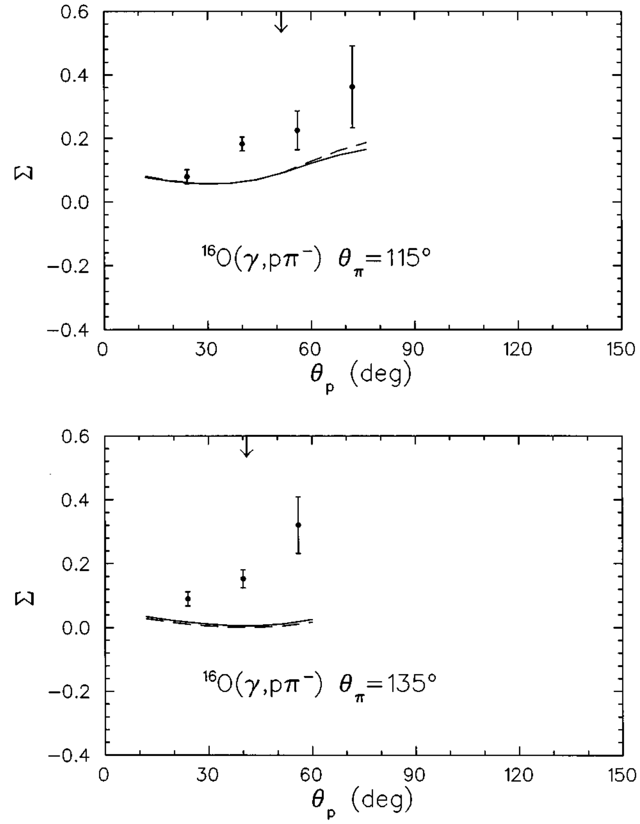

FIG. 3. Same as Fig. 1 except for pion angles of 115° and 135°.

sured in order to subtract a background from the cell walls (typically 2%). In addition, the background subtraction from accidental coincidences was small (<3%).

The proton detectors were two layers of plastic scintillators bars with dimension 160 by 10 by 10 cm^3, along with a thin ΔE scintillator, 160 by 11 by 0.635 cm^3, in front. The bars were placed 105 cm from the target, oriented perpendicular to the scattering plane. Each detector was viewed by a photomultiplier tube at each end, which allowed a software cut on the out-of-plane position to within a few cm. Detectors were placed at in-plane angles of 20° to 140°, in 8° steps. A more detailed description of these detectors is given in Ref. [14]. For pion detection, CsI detectors 8.9 cm by 8.9 cm by 15.2 cm long were placed opposite the proton bars in pairs at a distance of 58 cm and angles of 35° to 135° in steps of 20°, except at 95° where several thick plastic scintillators were used. A thin scintillator, 6.35 mm thick, was placed in front of the CsI detectors to get a ΔE measurement for particle identification. Details of these detectors are described in Ref. [15]. The energy calibration of the CsI detector pulse height was determined by measuring protons from photodisintegration of deuterium, from a D_2O target, combined with proton and pion energy-loss calculations. The pulse-height calibrations of the scintillator bars were similarly determined. The energy calibrations were used for a software limit on the missing mass, which eliminated low-energy background coincidences between the CsI detectors and scintillator bars.

As mentioned above, the previous data for the exclusive $A(\gamma,p\pi^-)$ reaction measured only cross sections with limited statistics. The data from Bates Laboratory [9] are significantly smaller than the DWIA calculations, but it is not clear whether this is due to effects such as distortions or spectroscopic factors, or due to medium modifications of the Δ in the nucleus. The spin asymmetry is sensitive to the latter, but not to the former effects.

The spin asymmetry, Σ, is the ratio of the difference to the sum of the cross sections with the photon's linear polarization oriented parallel or perpendicular to the scattering plane,

$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}, \tag{2}$$

where σ denotes the differential cross section summed over all neutrons in the target. The measured Σ for the $^{16}O(\vec{\gamma},p\pi^-)$ experiment are shown in Figs. 1–3 at various pion scattering angles, as a function of the proton scattering angle. Both data and calculations have been averaged over all proton and pion energies at the given angles, for energies large enough so that the outgoing particles escape the target volume and pass completely through the thin ΔE scintillators. In order to obtain reasonable statistical errors, the data were averaged over photon energies from $272 < E_\gamma < 314$ MeV, making it impossible to separate contributions from the $1p_{3/2}$ and $1p_{1/2}$ orbitals.

The momentum transfer to the residual nucleus, q, is largely determined by the proton angle. Table I gives the value of q for the proton angle of each data point in the figures, calculated as a weighted average over the available kinematics using the theoretical cross section as the weighting factor. The smaller angles have a modest value of q,

TABLE I. Missing momentum q, taken as an average weighted by the cross section over all pion energies at the given angle pairs, in units of MeV/c.

θ_π (deg)	θ_p (deg) 24	40	56	72	88	104	120	136
35	105.7	107.4	116.7	133.0	156.4	179.7	199.6	215.4
55	94.9	98.4	116.8	152.9	192.8	227.6	254.6	274.0
75	90.4	102.6	141.1	195.8	247.4	289.8	320.4	340.2
95	92.7	119.9	181.8	248.8	308.1	354.8	385.6	403.6
115	101.0	151.7	229.0	304.0	368.2	415.7	443.4	458.2
135	115.8	190.5	276.8	356.8	423.0	467.5	489.2	501.3

TABLE II. Chi-squared per point for the data compared with the calculations using the unmodified mass (M_Δ) and the Δ mass reduced by 5% (M^*_Δ).

θ_π (deg)	$(\chi^2)_{M_\Delta}$	$(\chi^2)_{M^*_\Delta}$
35	1.57	1.66
55	4.48	2.87
75	3.10	0.67
95	3.08	0.93
115	11.51	11.45
135	19.00	20.90

which increases with angle. The location of $q=200$ MeV/c is plotted in the figures for each pion angle as an arrow along the top scale. The harmonic oscillator wave functions used in the calculations are not expected to be valid for q larger than $\sim$200 MeV/c, thus we have limited the calculations to angles that do not extend beyond a q of 300 MeV/c. The larger q would be better modeled by calculations with Woods-Saxon wave functions.

Also plotted in Figs. 1–3 are PWIA calculations where the mass of the Δ has been reduced by 5%, shown by the dashed curves. Reducing the mass of the Δ is a first-order approximation to modeling an attractive Δ-nucleus potential, and a 5% change reflects a $\sim$60 MeV well depth. Of course, this can only be used as an indication of whether the calculations are sensitive to this potential, and not to set rigid limits on the range of the potential depth. In order to quantify the comparison, the χ^2 per data point for the range $q<200$ MeV/c for both curves is given in Table II. The data at $\theta_\pi=75°$ and $\theta_\pi=95°$ show slightly better agreement with the modified Δ mass curves, but both calculations give acceptable chi-squared values when $\theta_\pi<100°$. More advanced calculations, perhaps using the Δ-hole model [8,4] and Woods-Saxon wave functions, would be useful. Previous cross section data for the $^{16}O(\gamma,\pi^- p)$ reaction [9] show better agreement with a reduced Δ mass [5], although the statistical errors for these measurements are quite large. Cross sections from the present measurement at LEGS are under analysis, and will be submitted for publication in the near future.

We have presented the first measurements of the spin asymmetry for exclusive pion photoproduction from a nuclear target. For momentum transfers less than about 200 MeV/c, where the harmonic oscillator wave functions used in the calculations are expected to be reliable, the results are in good agreement with PWIA calculations averaged over the same kinematics. A change in M_Δ will model, to first order, a Δ-nucleus potential. However, neither the data nor the calculations are sufficiently accurate to determine a range for the depth of this potential. Nonetheless, the calculations do account for the general trends in the spin asymmetry data below 200 MeV/c, indicating that the essential physics input for this reaction has been included. In particular, the ambiguities in treating the FSI of the pion and proton which are present when comparing the DWIA calculations with cross section data for the $(\gamma,\pi^- p)$ reaction (see Ref. [9]) are absent in the comparison of PWIA calculations with spin asymmetry data.

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