NUCLEAR PHYSICS

LEGS Facility Overview

The Laser Electron Gamma Source facility (LEGS) provides intense, polarized, monochromatic γ-ray beams by Compton backscattering laser light from relativistic electrons circulating in the X-Ray Ring of the National Synchrotron Light Source at Brookhaven National Laboratory. Such a beam has a high degree of polarization (~90%) with very low background and the energies of the photons are well determined by measuring the loss of energy of the struck electrons. Photon Energies up to 330 MeV can be obtained with the present laser shining on 2.58 GeV electrons. With a new frequency-quadrupled laser that is now under development and the possibility of 2.8 GeV electrons, photon energies up to 470 MeV can be obtained.

LEGS has its high degree of polarization because the interaction of the laser photons with relativistic electrons preserves the polarization of the photons. By orienting the linear or circular polarization of the laser to give the desired polarization for the γ-rays, measurements can isolate specific contributions to nuclear reaction amplitudes. If the linear polarization (direction of the electric field vector) is in the plane of the reaction, the cross section is sensitive to electric multipole moments. This cross section is denoted as $\sigma_{||}$. If the linear polarization is perpendicular to the reaction plane, the cross section is sensitive to magnetic multipole moments. This cross section is symbolized by $\sigma_{\perp}$. The data is usually presented in terms of $\sigma_{||}/\sigma_{\perp}$, or $\sigma_{||} - \sigma_{\perp}$, or as the asymmetry $\Sigma = \frac{\sigma_{||} - \sigma_{\perp}}{\sigma_{||} + \sigma_{\perp}}$. Comparing these cross sections permits the separation of effects due to static charge distributions from those due to spin and current distributions. Thus this polarization degree of freedom is extremely important in the understanding of nucleon and nuclear structure.

Since 1990, experiments have concentrated on single polarization observables (polarized beams on unpolarized targets) in nuclear reactions involving the Δ resonance. The Δ resonance is the first excited state of the nucleon with an energy of 294 MeV above the mass of the proton and a width of 120 MeV. It decays with a 99.4% branch to pion-nucleon (πN) final states and a 0.6% branch to γN. By studying photon induced nuclear reactions in the energy region of this excitation, it is possible to measure fundamental quantities such as the deformation of the Δ, to test models describing the internal structure of the nucleon and the Δ and the transition between them, and to study the effects of Δs produced inside of nuclei. Highlights of the last two years are given below. An updated status of LEGS, including recent publications, is available on the World Wide Web via http://WWW.LEGS.BNL.GOV/~LEGS/ .

In 1997 a new phase of operations will begin, focusing on double-polarization measurements with circularly polarized photon beams and longitudinally polarized nucleon targets. This work requires the development of (i) a new frozen-spin hydrogen-deuteride target that provides high polarizations for both nuclear species, and (ii) a new large acceptance detector array for measuring total reaction cross sections in both neutral and charged-particle channels. Progress on these instrumentation developments is an ongoing effort of the LEGS Spin Collaboration (LSC) and is discussed in the last section.

The E2 $N \rightarrow \Delta$ Transition from $p(\vec{\gamma},\pi)$ and Compton Scattering

In constituent quark models, a tensor interaction mixing quark spins with their relative motion is needed to reproduce the observed baryon spectrum. This necessarily results in a D-wave component in the nucleon wave function which breaks spherical symmetry and leads to a static deformation for the Δ. The Δ is photo-excited mainly by M1 radiation. However, the D-state component results in a small E2 transition strength. The magnitude and sign of the E2/M1 mixing ratio are quite sensitive to the internal structure of the proton. Isolating the $N \rightarrow \Delta$ transition requires a decomposition of the multipoles into resonant and background (non-resonant) components. This decomposition requires a model, and model dependences enter the analysis of π-production and Compton scattering in different ways. These two final states have different E2 sensitivities and both have been studied at LEGS.

The $p(\vec{\gamma},\pi^0)$ and $p(\vec{\gamma},\gamma)$ reactions were separated by detecting photons in a high resolution NaI(Tl) spectrometer in coincidence with the recoil protons whose trajectories were tracked through wire (drift) chambers and whose energies were measured both by energy deposition and by time of flight in an array of plastic scintillators. This arrangement is shown in Figure 47. The full data set consisted of 3 sets of runs with different NaI and scintillator-bar orientations chosen to provide overlap angles. The π°/Compton separation for the full data set centered at 90° in the center of momentum (c.m.) is shown in

Figure 48 where the γ-ray energy is plotted against the recoil proton energy. Here the γ and proton recoil energies for Compton scattering, as calculated from the tagged beam energy and the proton recoil angles measured in the drift chambers, have been subtracted from the measured energies. Compton scattering is clearly resolved here, and in *all* other runs.

In p(γ,π), the observable most sensitive to an E2 component is the cross section, $\sigma_{||}$, for π° production by linearly polarized photons whose electric vector is oriented parallel to the reaction plane. The corresponding cross section for the perpendicular orientation, $\sigma_\perp$, is completely insensitive to E2 excitation at all but extreme angles. Thus, the ratio $\sigma_{||}/\sigma_\perp$ maximizes E2 sensitivity, while dividing out systematic uncertainties. The first new measurements of this ratio over a limited angular range suggested E2 transition strengths significantly larger than expected from previous multipole analyses. In our 1994 LEGS Progress Report, and at the SPIN'94 Conference, we presented the results of new measurements of this π° polarization ratio taken over a large angular range. These were compared to the model predictions of Davidson, Mukhopadhyay and Wittman (DMW). This model contains five free parameters, the electric and magnetic coupling constants at the $\gamma N\Delta$ vertex (G_E and G_M), and three constants parameterizing the off-shell behavior. In addition to the polarization ratios, cross sections are needed to fix these 5 parameters. Since absolute cross sections from our experiments were not available at the time, our polarization data was combined with previously published unpolarized results from other laboratories. The results of fitting this composite data set to the DMW parameters gave a value for G_E/G_M (the $N\rightarrow\Delta$ part of the E2/M1 mixing ratio) of $-2.7\pm0.1\%$. (The error of $\pm 0.1\%$ reflected only the variations in the methods of unitarizing the pion amplitudes.)

The analyses of the LEGS experiments are now complete. We present here a selection of cross section and polarization data for both Compton scattering and π°-production and examine the consistency of previous E2/M1 determinations in the light of the full data set. The 90° excitation functions for the

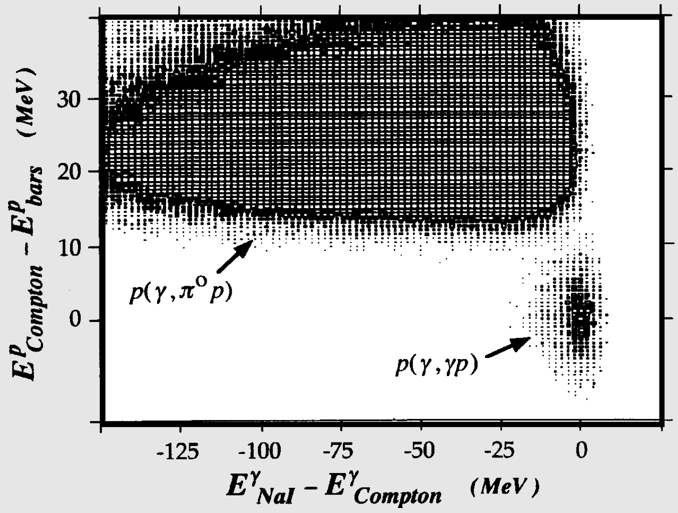

Figure 48: The π°/Compton separation with the detectors of Figure 47.

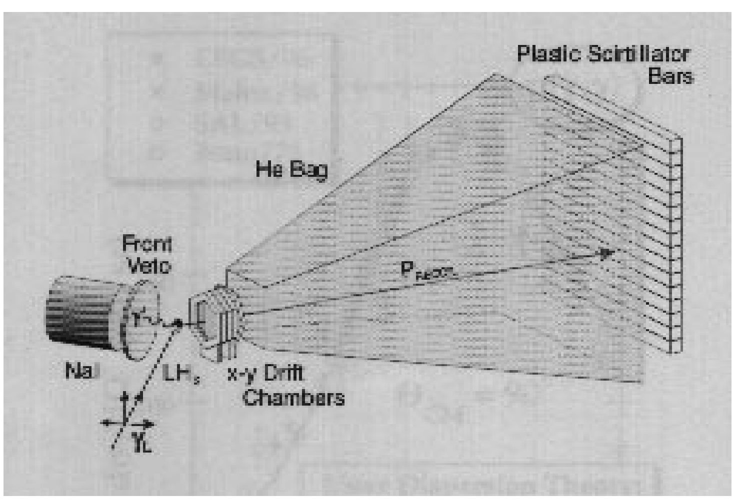

Figure 47: The detector arrangement used to separate the (γ ,π) and (γ ,γ) reactions (see text).

two reactions are shown below in Figures 49 and 50.

There had been a long standing discrepancy between earlier Compton measurements and dispersion calculations that used π-production as input. The LEGS measurement was designed to remove all of the uncertainties associated with separating Compton scattering from the π° channel by a large overdetermination of kinematic parameters. Both reactions are completely specified by two kinematic observables. In this experiment, six quantities were measured: the beam energy, the scattered γ-ray energy, the polar and azimuthal angles of the recoil proton, and the proton's time of flight to the detector and the energy it deposited in the detector. This large degree of over-determination has two important consequences. First, it guarantees an accurate separation of the two competing channels (Figure 48). Secondly, it enables all detector efficiencies to be evaluated directly from the data itself, without resorting to simulations and thus avoiding their associated uncertainties. The data shown as solid points in Figure 49 reflect all statistical and *polarization-dependent* systematic errors. Additional systematic scale errors are less than 2%. Near the peak of the Δ, our results are substantially higher than the earlier measurements (open squares). Other recently published measurements from Mainz (crosses) and from Saskatoon (SAL) (circles) are in excellent agreement. Data from earlier experiments at Cornell (1961), Tokyo (1964), Illinois (1967), and Bonn (1976) at energies higher or lower than the Δ peak are either consistent or slightly lower than these new measurements. Why the earlier results are so dramatically lower near the resonance energy is not known.

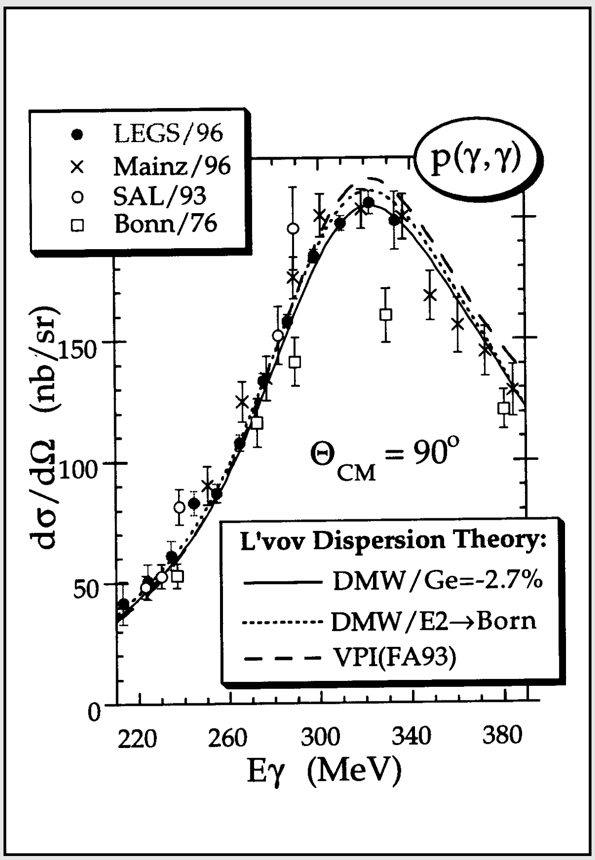

Figure 49: LEGS Compton scattering cross sections at 90° (solid points.), compared with recent data from Mainz and SAL, and earlier data from Bonn. In addition to the indicated errors, the systematic scale uncertainties are ~2% (LEGS), 5% (Mainz), 3.9% (SAL), and 4.4% (Bonn).

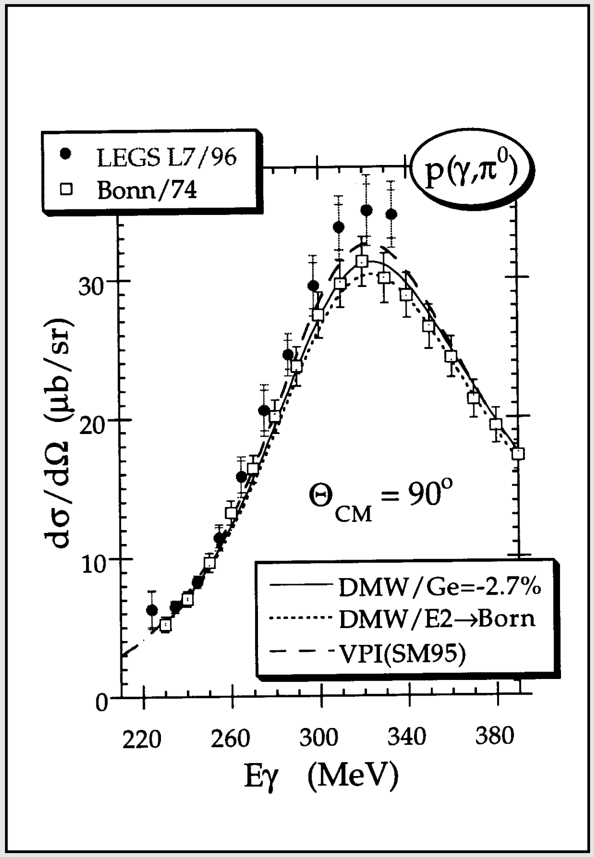

Figure 50: The LEGS π° cross sections at 90° (solid points) compared with earlier data from Bonn. Two error bars are shown for each point, the smaller reflects the measurement error (statistical, and other sampled uncertainties) and the larger includes systematic scale errors added linearly (see text).

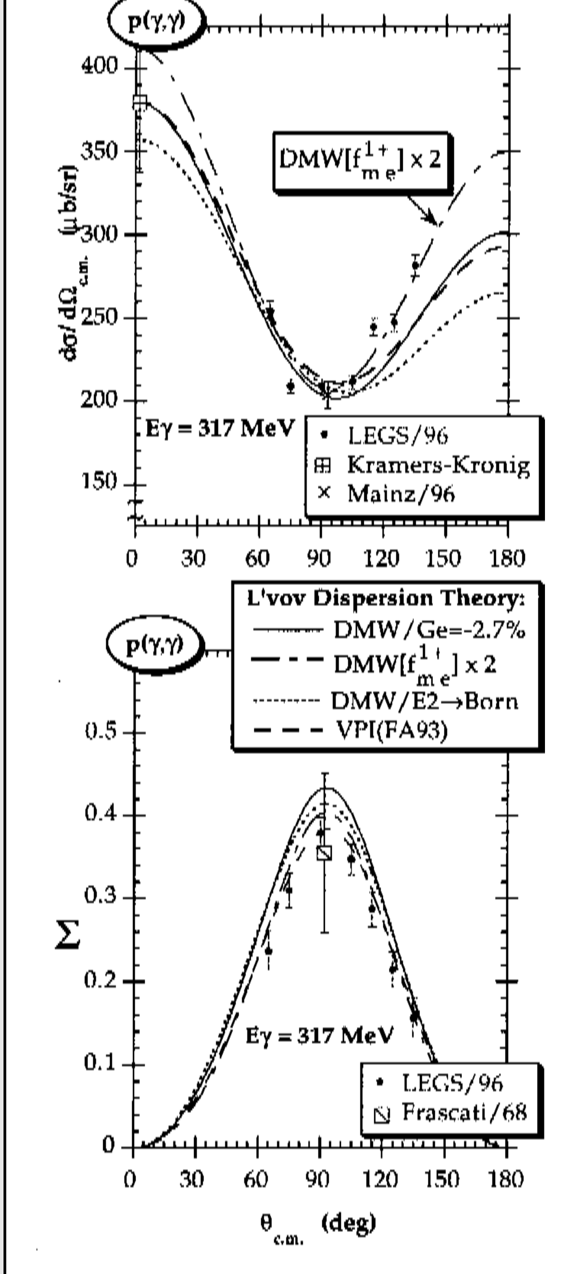

Figure 51: Angular distributions for the unpolarized cross section and linear polarization asymmetry in p(γ,γ) from LEGS (solid circles).

Angular distributions of the cross sections and linear polarization observables for Compton scattering and π°-production for energies near the Δ peak are shown as the solid points in Figures 51 and 52. The recent Mainz 90° Compton cross section is plotted in the top panel of Figure 51. For the Compton asymmetry, the only previously published datum (from Frascati) is also shown. For π° production, the results of applying the most restrictive cuts to the LEGS data ("*Compton-like*" kinematics), are shown with statistical errors as the crosses at 90° and 120° in the top panel of Figure 56. Also plotted are the older Bonn and Lund cross sections and a Khar'kov asymmetry measurement.

Three sets of curves for p(γ,π°) are plotted in Figures 50 and 52. The solid curves are calculations in which the parameters of the DMW model were optimized to reproduce a combination of the LEGS π° polarization ratio results, together with the Bonn unpolarized cross sections. This was the exercise carried out with the first new results that yielded the value of -2.7 % for G_E/G_M. The result of turning off the E2 part of the N→Δ transition in this calculation (i.e setting G_E=0) is shown as the dotted curve. (Setting the entire E2 amplitude, including Born contributions, to zero produces dramatic effects but is not terribly informative.) For comparison, the predictions of current VPI multipole analyses are shown as the dashed curves. Although the DMW and VPI predictions are both quite close to the π° polarization data, the cross section predictions indicate a need for some readjustment of parameters.

Compton scattering provides an additional constraint on this problem. The imaginary parts of the Compton amplitudes can be calculated from (γ,π) multipoles using s- and u-channel unitarity (s,t, and u are the standard Lorentz-invariant Mandelstam variables) and dispersion integrals can be written for their real parts. The solid, dotted, and dashed curves in Figures 49 and 51 have been calculated by L'vov in this way using as input the pion multipoles corresponding to the three calculations in Figures 50 and 52. In particular, the predictions of the solid and dashed curves started with the DMW model (adjusted to give G_E=-2.7% of G_M) and with recent VPI multipole analyses of π-production, while the dotted curves were obtained by setting the $E2^{j=3/2}$ Compton multipoles to their s- and u-channel Born and t-channel pole values.

The Compton cross sections at back angles are quite sensitive to E2/M1 interference and these *are not reproduced* by either the solid or dashed curves. The prediction corresponding to the solid curve also gives the poorest description of the polarization asymmetry. The leading E2 interference term, f^{1+}_{me} corresponding to E2

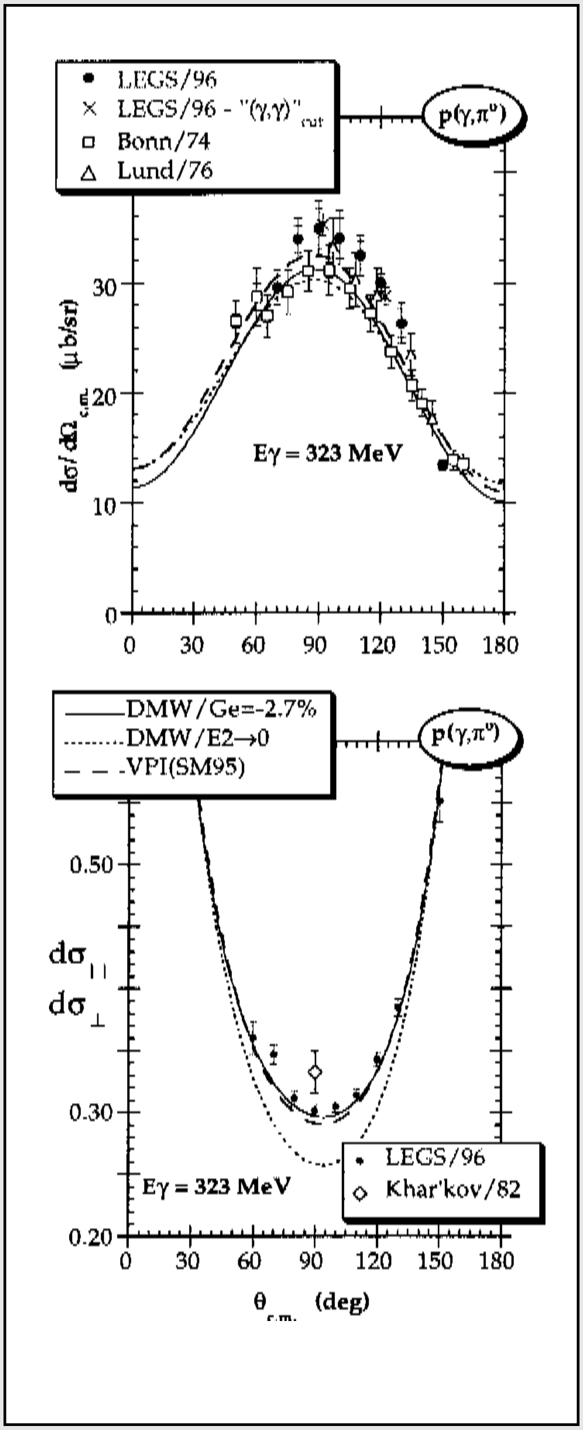

Figure 52: Angular distributions for the unpolarized cross section (top) and polarization ratio (bottom) in p(γ,π°) from LEGS (solid circles).

photoexcitation followed by M1 decay, is dominated by the $N \rightarrow \Delta$ transition. Doubling this amplitude results in the long-dashed/short-dashed curves in Figure 51 which seem to describe most of the cross section data although the asymmetry calculation remains a little high.

The new Compton results clearly show the deficiencies in our earlier estimate of G_E/G_M= -2.7% which was driven solely by the pion polarization data. A complete determination of the E2 component in N→Δ requires a simultaneous fit to both Compton scattering and π-production. This is presently underway.

Deuteron PhotoDisintegration and Coupled NΔ/NN Interactions

Although the Δ resonance dominates nuclear reactions from pion threshold to about 1 GeV, its interaction with the nucleon is still poorly known. Understanding nuclear reactions in this energy region necessarily requires a consistent treatment of the NΔ and NN interactions. The NN force can be studied directly using nucleon-nucleon reactions but the NΔ interaction must be inferred from processes with the two nucleon deuteron such as $\pi D \rightarrow \pi NN$ and $\pi D \rightarrow NN$ for which the Δ plays a prominent role in the intermediate state. Because of the strong coupling of the Δ to πN, realistic models must satisfy three-body unitarity, connecting reactions starting from NN, πD, or γD entrance channels leading to NN, πD, or πNN final states. While elastic scattering and breakup reactions for the deuteron are reasonably well understood because the interaction with a single nucleon dominates, pion and photon absorption channels have proven to be problematic. Since the effects of the NΔ interaction are the largest near the energy of the Δ resonance and since both the cross section and the polarization observables have been shown to be strongly affected by the NΔ interaction, the LEGS collaboration measured cross sections and asymmetries in the same experiment for the first time in order to remove ambiguities in existing data.

Five independent measurements of the $D(\vec{\gamma},p)n$ reaction have been carried out at LEGS with three different detector systems, different photon end-point energies from different laser wavelengths, different polarizations and two different liquid deuterium targets. These measurements overlap in various kinematic regions between 113 and 325 MeV, and the agreement in the regions of overlap is excellent. By taking weighted averages of overlapping measurements, a “net” data base has been constructed and is available from the LEGS WWW page.

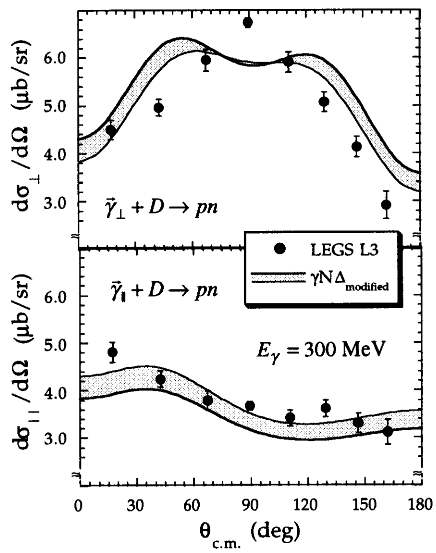

Figure 53: Angular distributions at 300 ± 5 MeV.

Selections of these data at 300 MeV are compared to recent coupled-channel calculations in Figure 53 (note the suppressed zero).The calculations are in agreement with cross sections measured with linear polarization parallel to the reaction plane but fail to account for the data taken with perpendicular kinematics. The shaded band reflects uncertainties in the pion meson exchange currents used in the calculations.

At present, there is no clear explanation for the success of the coupled-channel calculations in one polarization kinematics and their failure for the orthogonal state. Spin observables provide a considerably more sensitive test of the angular momentum modeling than do cross sections. Although the model parameters of the calculations presented here were fitted to NN phase shifts, all assumed static NN potentials, with retardation effects included only in the NΔ and NN-NΔ-transition potentials. The additional use of retarded potentials in the NN interaction could significantly alter the angular momentum mixing.