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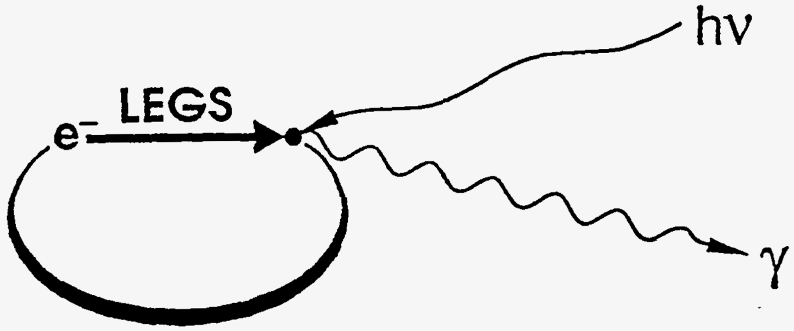

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Polarized Photon Facilities - Windows to New Physics

A. M. Sandorfi

Physics Department, Brookhaven National Laboratory
Upton, New York, 11973, USA

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LASER ELECTRON GAMMA SOURCE

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Polarized Photon Facilities – Windows to New Physics

A. M. Sandorfi
Physics Department, Brookhaven National Laboratory
Upton, New York, 11973, USA

The status of new and proposed sources of intermediate-energy polarized photons is reviewed. The N→Δ transition is discussed as an example of new physics that can be addressed at these facilities through precision measurements of polarization observables.

Scanning photonuclear literature of the past 30 years, one can find experiments conducted with high photon polarization, or with good energy resolution, or with high photon flux. But until very recently, one never encountered measurements with all three of these characteristics together. The turning point has been the new generation of electron accelerators that are now coming on line, and with them come a new generation of photon sources, all of high flux (~10^7 s^{-1}), high energy resolution (a few MeV), and promises of quite high polarizations. Polarization observables enhance interference effects that often remain hidden in spin-averaged, unpolarized measurements. New windows to such interference effects are being opened by the new generation of sources, and this has lead to significant progress on problems that for years have remained untouchable.

I've been asked to give an overview of new polarized photon sources, both those recently brought into operation as well as those still under development. The price of the new windows opened by polarized beams is a significant increase in complexity. I'll start this review with a description of the techniques used in producing polarized photons, focusing on the more unusual ones, and close with some examples of the dividends – what we learn for all the trouble.

1 New Facilities

Polarized γ rays can be produced in a variety of ways. The backscattering of laser light from relativistic electrons results in the highest polarizations, either linear or circular. This is just Compton scattering in the rest frame of a free electron. But, when the electron energy is several GeV the Lorentz boost throws all of the photons back through almost 180° and collapses all the cross section into what in the laboratory amounts to a beam of γ rays. Angular momentum conservation guarantees that the backscattered γ rays carry the same polarization as the instant laser light and, since lasers are 100% polarized, so are the photons scattered through 180°. Limitations in this method are associated with the complications in achieving the high luminosity in the laser-electron collision that is needed to produce a high γ-ray flux.

High photon fluxes are easy to produce by the bremsstrahlung of electrons in a high-Z radiator. If the initial electron beam is longitudinally polarized, then the resulting 0° bremsstrahlung is also circularly polarized to the same degree. The real difficulties here are associated with the production of polarized electrons. Impressive results have been obtained at SLAC, and successfully duplicated at Mainz, but not without Herculean efforts. In the absence of electron polarization, although the bremsstrahlung radiation at 0° to the beam axis is unpolarized, away from the electron axis it carries a degree of linear polarization. Lastly, the coherent bremsstrahlung of electrons in single crystals such as diamond and silicon has also been used to produce linear polarization. The subtraction of an incoherent background results in a peak, at about 1/3 of the electron energy. Both this technique, and off-axis bremsstrahlung, require careful definition of the angles involved, and the resulting polarizations are limited by the electron-beam divergence.

A compilation of the polarized photon facilities in North America and Europe is given in Table 1, together with a summary of their chief characteristics. In addition to these, a new laser-backscattering facility is under consideration for the 8 GeV SPring-8 synchrotron now under construction at Osaka, Japan, and the ROKK-II backscattering facility continues in Novosibirsk, Russia, although with very limited operations. All of these sources can potentially deliver total fluxes of ~10^7 sec^{-1} with energy resolutions of a few MeV.

Table 1. The chief characteristics of polarized photon facilities in North America and Europe.

North-American Facility	E_γ^{MAX} (GeV)	Polarization $\vec{L}/\vec{C}$	Production method	Status
SAL	0.2 0.3	$\vec{L}$ $\vec{C}$	*off-axis / Coherent-brem* *brem from polarized-electrons*	1997 proposed
LEGS - BNL	0.5	$\vec{L}/\vec{C}$	*Laser-backscattering*	1990 → in operation
CEBAF/Hall-B1	1.5-2.0 4.0	$\vec{L}$ $\vec{C}$	*Coherent-brem* *brem from polarized-electrons*	planned 1996 +
CEBAF/Hall-B2	0.5 ++	$\vec{L}/\vec{C}$	*Laser-backscattering*	proposed
Duke/FELL	0.2	$\vec{L}$	*Laser-backscattering*	proposed
POLITE - Bates	0.6	" $\vec{L}/\vec{C}$ "	*forward electron scattering* $\{\theta_{e'} \rightarrow 0,\ Q^2 \rightarrow 0\}$	proposed

European Facility	E_γ^{MAX} (GeV)	Polarization $\vec{L}/\vec{C}$	Production method	Status
Mainz	0.4 0.8	$\vec{L}$ $\vec{C}$	*Coherent-brem* *brem from polarized-electrons*	1994 1996+
Bonn	0.9 2.2	$\vec{L}$ $\vec{C}$	*Coherent-brem* *brem from polarized-electrons*	1996+ ?
GRAAL	1.1–1.8	$\vec{L}/\vec{C}$	*Laser-backscattering*	1995+

The Saskatchewan Accelerator Laboratory (SAL) has been delivering high duty factor tagged bremsstrahlung beams up to ~280 MeV since 1989. The SAL group is now working on the development of linearly polarized photon beams from off-axis and coherent bremsstrahlung.

The Laser Electron Gamma Source (LEGS) facility at Brookhaven has been producing tagged polarized γ rays from laser backscattering since 1990 [1]. There, light from a laser is directed against electrons circulating in a storage ring of the National Synchrotron Light Source. The resulting γ-ray energy,

$$E_\gamma = \frac{4\gamma^2 \varepsilon_\ell}{1 + \frac{4\gamma\varepsilon_\ell}{m_e c^2} + (\theta\gamma)^2} \quad (1)$$

is determined by both the laser energy (ε_ℓ) and the ring energy ($\gamma = E_e / m_e c^2$), and is maximal when the angle (θ) between the γ ray and electron momenta vanishes, corresponding to complete 180° scattering. Through the fall of 1994, LEGS energies were limited to 330 MeV. Recent upgrades, in both the electron ring and in the laser increase the maximum γ ray energy to 470 MeV. The polarization of backscattered photons is 100% for exactly 180° scattering which corresponds to the maximum energy obtained at the Compton edge (θ=0). As the angle θ increases the polarization drops, with the result that photons of about half the maximum energy are ~ 50% polarized. However, most laser cavities can provide significant output powers at a variety of wavelengths, allowing the high energy edge to be positioned near the energy region of interest for a specific experiment. The polarization curves corresponding to various choices of laser wavelength (from the visible to the deep ultra-violet) and ring energy (2.5 to 2.8 GeV at LEGS) are shown in figure 1. The practice at LEGS is to switch to a different laser/E_e-ring combination before the polarization drops significantly, essentially following the solid curve in figure 1. This maintains γ-ray polarizations greater than 85% for most of the range of available beam energies.

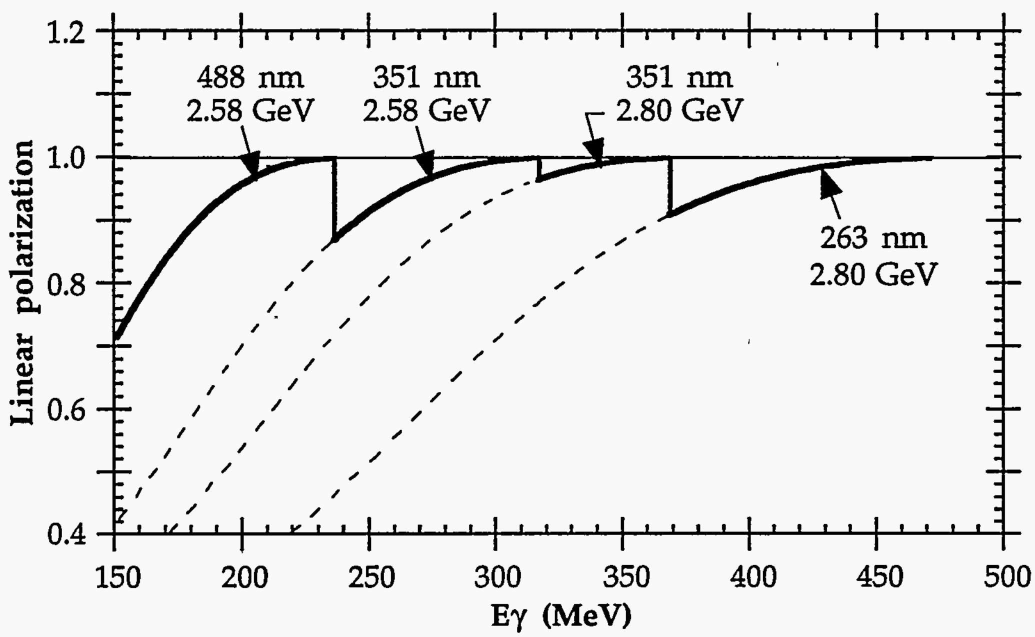

Figure 1. Gamma-ray beam polarization curves for different choices of laser wavelength (in nm) and electron ring energy (in GeV) used at the LEGS facility. High polarizations are maintained by switching operating modes before the polarization falls significantly, effectively following the heavy solid curve.

At CEBAF, the real photon bremsstrahlung tagger in Hall-B has been constructed for use with the CLAS detector and is awaiting beam. Experiments using linearly polarized photons produced via coherent bremsstrahlung in diamond have been approved, and it is hoped that circularly polarized photons will be available from polarized electrons in the very near future. In addition to these *conventional* sources, a novel laser backscattering capability has been proposed for use with CLAS [2]. The plan uses an Argon-Ion laser to pump a high finesse optical cavity, so that collisions with electrons would take place within the cavity. The technique here is the analog of that employed at LEGS. There, electrons are stored in a magnetic ring and given multiple chances to collide with a laser photon. In the CEBAF cavity, laser photons would be stored in an optical ring and given multiple chances to collide with an electron. (The power stored in the optical cavity depends critically on extremely high reflectance mirrors and damage to the optics from forward synchrotron radiation, though much less intense than at storage ring facilities such as LEGS, is a concern. Promising solutions to this potential problem are under study.) With such a cavity operating in the visible (515 nm), scattering against 4 GeV electrons would produce 0.5 GeV polarized photons. With a frequency-doubled cavity (257 nm) and 6 GeV electrons, the photon energy would be increased to 1.8 GeV. (If this capability were extended to the proposed CEBAF-Phase II upgrade, 4.2 GeV beams could be produced by backscattering against 10 GeV electrons.) In addition to the higher polarizations that are achievable, the shape of laser backscattered spectra makes this option increasingly attractive at high energies. Bremsstrahlung and laser-backscattered distributions, with a common end point of 1.8 GeV, are plotted in figure 2. Here, their relative magnitudes have been adjusted so that for both, the area within the dotted lines between 0.4 and 1.7 GeV corresponds to a flux of 10^7 sec^{-1}, typical for a broad band tagger. The bremsstrahlung spectrum is much larger at the lower energies, which is just where the cross sections are typically the largest (from the excitation of the Δ resonance at ~340 MeV photon energy). As a result, in the absence of a very selective trigger, the ratio of true-to-accidental coincidences between photon interactions and electron tags can easily be an order of magnitude larger with laser generated photons at high energies. This is illustrated in Table 2 where values for this ratio are given for pion photo-production from the proton at 1.5 GeV. For such cases, the low energy part of the tagged spectrum is a significant liability. For laser backscattering, the correlation between energy and angle evident in eqn. 1 can be used to collimate out low energy photons, leading to a further increase in the true-to-accidental ratio. This could easily make or break many experiments.

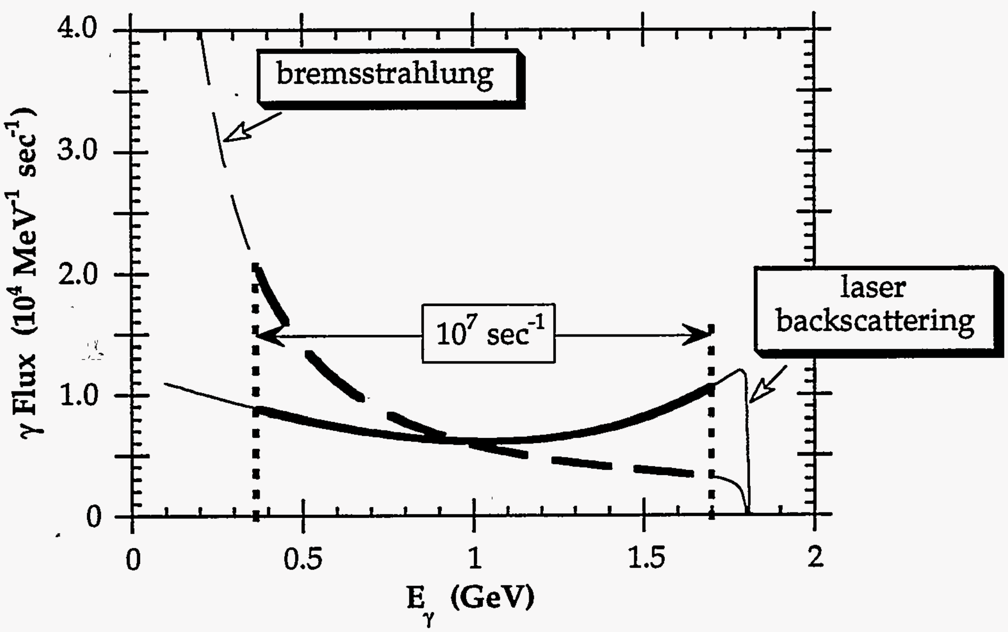

Figure 2. Bremsstrahlung and laser-backscattered spectra, with intensities adjusted to give the same flux of 10^7 sec^{-1} within the interval indicated by the heavy lines.

Table 2. True-to-accidental ratios for the $p(\gamma,\pi)$ reaction, assuming the flux profiles of figure 2.

Source	True/Accidental Ratio @ 1.5 GeV
bremsstrahlung	~ 1/1
laser	~ 10/1
laser with collimation	~ 50/1

At Duke University, a proposal is being developed to use a new free electron laser facility to produce an extremely intense source of polarized gamma rays in the 75-to-185 MeV energy range. At the Duke Free Electron Laser Lab (DFELL), coherent undulator radiation from a single bunch of 1.3 GeV electrons produces polarized laser light in the deep ultra-violet. (The gain of free electron lasers is so high that relatively poor reflectance metal mirrors, which are not significantly affected by synchrotron radiation, can be used in the laser cavity.) By filling an appropriately timed 2^{nd} bunch of the storage ring, backscattered polarized γ-rays can be produced. This collision process is self-aligning and readily leads to total intensities of 2×10^9 sec^{-1}. Although such high rates cannot be tagged, the emittance of the ring is so small that a collimator can be used to pass only the highest energies to the nuclear target (eqn. 1). The resulting beam would then consist solely of 1×10^7 photons sec^{-1}, all within a 0.5 MeV bin and with a linear polarization of 100%. Although experiments at different energies would have to be performed sequentially, the very high flux of this source would permit difficult measurements of quite small cross sections.

An extreme forward-angle electron scattering capability is being proposed for the Bates South Hall Ring (SHR) to be used in conjunction with internal polarized gas targets. The project POLITE (POLarized photon and Internal Target Experiment) relies on the potentially high effective degree of polarization of the virtual photons exchanged in (e,e') reactions at very forward angles where $Q^2 \sim 0$. For such kinematics there is a direct correspondence with real photo-reactions. Scattered electrons would be momentum analyzed in a ring dipole equipped with a stack of wire (drift) chambers for tracking. Development tests are planned when SHR operations resume.

Coherent bremsstrahlung sources have been developed for the new high duty factor electron machines at Mainz and Bonn [3]. The excellent emittance of these new accelerators allows angle definitions that are superior to previous applications of this technique and have lead to linear photon polarizations ranging from 30% to 60% depending upon collimation. Circularly polarized beams are planned for the near future and the recent achievement of 75% longitudinal electron polarization at Mainz promises correspondingly high γ-ray polarizations.

Finally, the first 1.1 GeV linearly polarized beams have just been obtained at the GRAAL facility in Grenoble [4]. This is a laser backscattering facility similar to LEGS operating at the new 6 GeV European electron Synchrotron Radiation Facility (ESRF). With the appropriate choice of lasers, the GRAAL energy range could extent to about 1.8 GeV.

Although there is some overlap among these new facilities, many of their programs are complementary and can be expected to provide a vigorous attack on many key physics issues.

2 Examples of New Physics: the $N \rightarrow \Delta$ transition

I'd now like to motivate the considerable effort going into the development of the new facilities by illustrating some of the uniquely new information available from polarized photo-reactions. One nice example involves the structure of the proton and the breaking of spherical symmetry by spin dependent forces. In the constituent quark model one starts with an infinite confining potential like an harmonic oscillator, to which is usually added another potential that breaks the degeneracy as much as one can while still preserving SU(6) symmetry. At this point, one has a spectrum of states with even-orbital angular momentum. To go from here to the observed half-integral baryon spectrum, it is necessary to couple in the intrinsic spins of the quarks, which is accomplished through a tensor interaction. However, there is a consequence to this. Just as the N-N tensor force breaks the spherical symmetry of the deuteron, so too this tensor interaction breaks the symmetry of the nucleon. There are a very large number of papers investigating the nucleon's intrinsic deformation, and a wide range of predictions, which means that if we can measure a quantity related to this deformation we have a new way of discriminating between models.

We take the classic nuclear physics approach. For nuclei, we measure deformation with a B(E2) value, the E2 transition strength between the ground and first-excited states. We do the same thing for the nucleon. The first-excited state of the nucleon is the $\Delta(1232)$ resonance. This is excited primarily by a magnetic dipole transition. But if it is indeed deformed, there must be an E2 component buried amid the M1 strength. The Δ decays with a 99.4% branch to the π-nucleon channel and with an 0.6% branch back to the ground state (Compton scattering). Both contain information on the E2 strength. The most straightforward of the two are the (γ,π) reactions which have large cross sections. But there are two complications here. One is that the predicted E2 strength is only a few % of the M1 transition. The other is that Born amplitudes, and final state interactions (pion rescattering), can also produce a pion as the result of E2 absorption in the initial state, without ever producing a Δ in the intermediate state, and model dependence necessarily enters into the background-resonance decomposition.

Since the deformation of interest is caused by a spin-dependent interaction, it should not be surprising to learn that signatures of this effect are enhanced in polarization observables. The process most sensitive to the E2/M1 ratio in Δ excitation turns out to be π^0 production with linearly polarized photons [5]. The cross section measured with the photon's electric vector perpendicular to the reaction plane turns out to be nearly independent of the E2 transition strength over most of the angular range, while there is considerable sensitivity in the parallel kinematics, particularly at 90^0 center of mass (CM). Thus, the ratio of parallel–to–perpendicular cross sections, $\sigma_{\|}/\sigma_{\perp}$, provides an E2 sensitive observable that is largely free from systematic effects.

There have been three measurements of the $p(\gamma,\pi)$ reaction at LEGS over the last few years [5-7]. The most recent (Exp. L7) covered a large range of angles and energies. The first extraction of an E2/M1 mixing ratio from these new data was reported at the Spin'94 conference [7]. The LEGS Exp. L7 results for the $\sigma_{\|}/\sigma_{\perp}$ ratio at 90^0 CM are shown in figure 3 as solid circles, along with are previous data taken at Khar'kov [8] using bremsstrahlung in diamond crystals (open symbols). The curves are calculations using the effective Lagrangian model of Davidson, Mukhopadhyay and Wittman (DMW) for pion photoproduction [9]. The dotted line results from turning off all the E2 strength [total $E_{1+}(\tau=3/2)\rightarrow 0$ in the DMW calculation]. Although this is quite far from the data, most of this "E2 signal" results from interferences with E2 components of the Born amplitudes and is quite uninteresting. The dashed-dot curve is obtained by including the full Born contribution while setting the resonant part of the E2 strength to zero. It is the differences between this dashed-dot curve and the data that represent the E2 *signal* of interest, and the sensitivity is maximal at 90^o. Modeling the $N\rightarrow\Delta$ transition requires a decomposition of each of the amplitudes into resonant and background terms, and this decomposition is not unique. The solid curve gives the full calculation in which we have fitted the electric and magnetic $\gamma N\Delta$ couplings (G_E and G_M) to our new data, yielding the ratio $G_E / G_M = 2.7\pm0.1$ % [7]. Here, the 0.1 % uncertainty reflects the variations obtained with different resonance–background decompositions.

The unitarization procedures of the DMW model inherently include the effects of pion rescattering. As a result, it's most appropriate to compare this G_E / G_M value with "E2/M1" from those models of hadron structure that contain pion fields. The negative phase of the mixing ratio implies an oblate intrinsic shape, and the value of –2.7% is close to the low-end of predictions coming from Skyrme models of the nucleon, -3 to -5%, but somewhat larger than chiral-bag predictions, -1 to -2% [10]. It is also a factor of 2 larger than the *accepted* value found in the literature of a couple of years ago, and this reflects the impact of the new polarization data [11].

The results of recent $p(\gamma,\pi)$ experiments at Mainz, using coherent bremsstrahlung in diamond,

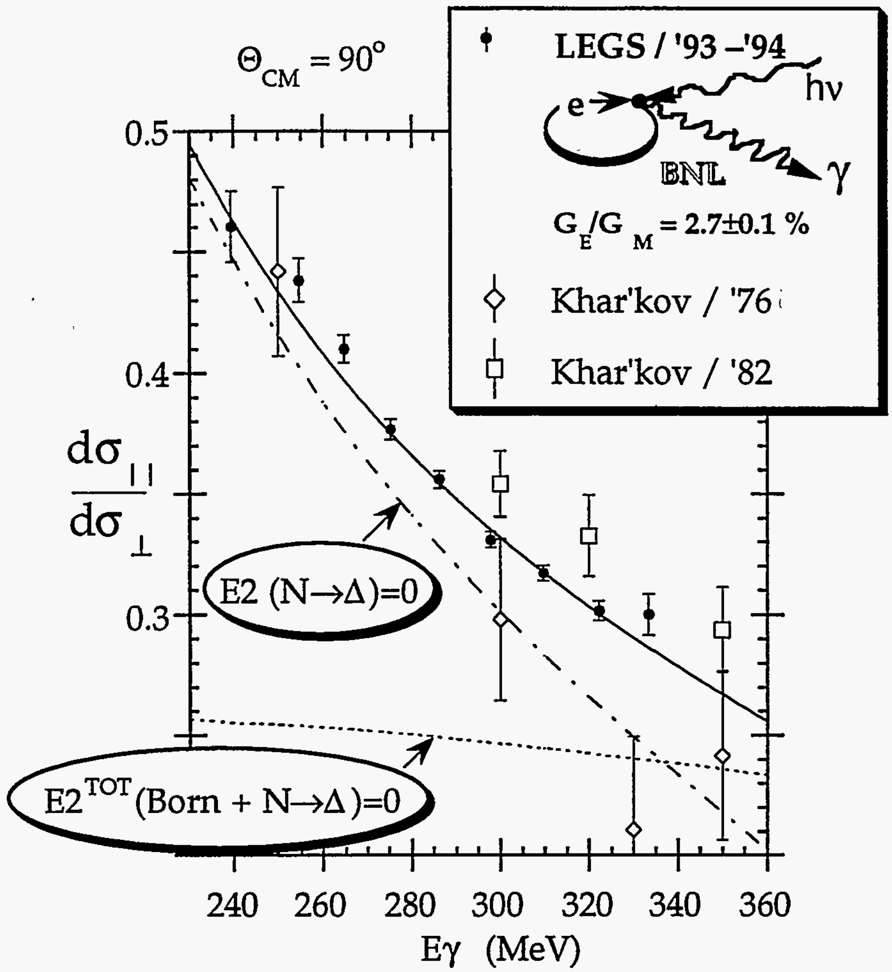

Figure 3. The E2-sensitive observable $\sigma_{||}/\sigma_{\perp}$ for the $p(\vec{\gamma},\pi^o p)$ reaction. New results from Exp. L7 are plotted as solid circles, along with data from Khar'kov [8]. The curves are calculations using the model of DMW [9]: the dotted curve is produced by setting the total E2 to 0; the dashed-dot curve corresponds to $E2(N \rightarrow \Delta) = 0$; and the solid curve results from a fit, varying the electric and magnetic γNΔ couplings.

have been presented at this conference by T. Walcher and by R. Beck [12], who reported an "E2/M1" value of 2.5±0.2 %. This looks to be in excellent agreement with the LEGS value. However, lest one conclude that the N→Δ question is completely settled, it's worth pointing out that the apparent agreement is in fact too good since the two groups are not quoting the same physical quantity. The Mainz group have performed a multipole analysis and have associated the ratio of the imaginary parts of the $E_{1+}(\tau=3/2)$ and $M_{1+}(\tau=3/2)$ multipoles at the peak of the resonance (340 MeV) with "E2/M1". Motivation for this approach comes from the observation that the parts of the amplitudes associated with Δ excitation become purely imaginary at the resonance energy, while the non-resonant s- and u-channel Born graphs are purely real and so should not contribute. Unfortunately, what sounds like a simple way of avoiding a model dependent resonance–background separation is greatly complicated by the unitarization process. Watson's theorem requires that the full photoproduction amplitude below 2π threshold be expressible as $\mathcal{A}^*\exp(i\delta_{\pi\pi})$, where $\mathcal{A}$ is real. This form has been used in the Mainz analysis, with $\mathcal{A}$ as the search parameter in a fit to the data. The πN elastic phase, $\delta_{\pi\pi}$, goes through 90° at the resonance energy so that $\sin(\delta_{\pi\pi})\to 1$, bringing the full non-resonant Born terms, which are comparable to the resonant E2 component, into the imaginary part of the amplitude. The magnitude of this background contribution depends upon the details of how unitarization is implemented. In the calculations of figure 3 this effect is actually rather minimal because DMW have used a more elaborate (and of course model-dependent) unitarization factor, multiplying their real tree-level Lagrangian amplitudes by $\cos(\delta_{\pi\pi})*\exp(i\delta_{\pi\pi})$. Without the $\cos(\delta_{\pi\pi})$ factor the non-resonant components of the imaginary parts of the amplitudes at 340 MeV should be substantially larger. This is the origin of the concern that the value of G_E/G_M from the LEGS analysis and the value of "E2/M1" from the Mainz analysis appear to be numerically too close to one another.

Resonance photon couplings provide an important test of Baryon structure. Model dependence in their extraction can never be completely avoided, and one will always have to rely on comparisons with the predicted energy dependence of observables to test the resonance–background separation. But the apparent freedom in unitarization factors enters because of incompletely specified amplitudes, and here future polarization experiments can make a significant impact. An unambiguous determination of the π-photoproduction amplitudes requires accurate knowledge, in both isospin channels, of 7 quantities: the unpolarized cross section, the 3 single-polarization observables, and a minimum of 3 out of 12 possible double-polarization observables [13]. There is not even a single energy where such a complete set of data exists. In the absence of this direct information, one can only hope to reduce the ambiguities in the photoproduction amplitudes by building in consistency with the resonance structure of πN scattering. This has lead to the existing *Isobar-inspired* multipole analyses which seem to provide a reasonable general description of the $N(\gamma,\pi)$ process, although not without puzzling incompatibilities in certain spin observables [14]. Real progress here will come from appropriately chosen single and double polarization measurements. This is a central goal of most of the new polarized photon facilities.

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