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THE SEARCH FOR MISSING BARYONS WITH A BEAM OF LINEARLY-POLARIZED PHOTONS

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The photoproduction of ω and ρ mesons from protons with a beam of linearly-polarized photons will be used to decouple baryon resonance production from t-exchange processes in the center-of-mass energy regime of 1.72 to 2.24 GeV at Hall B of Jefferson Lab. Both the ωN and ρN channels are expected to be a significant branch for baryon resonances. t-channel exchange contributions can only be disentangled by the use of a linearly-polarized photon beam. The measurement will employ a linearly-polarized beam of photons, produced by the approved Coherent Bremsstrahlung Facility, to measure the beam asymmetry as well as the spin density matrix elements of the decay spin-0 mesons of the parent vector meson. The spin density matrix elements and polarization asymmetry of the vector meson decay will be extracted as functions of the vector meson production angle θ_{cm} and the center-of-mass energy $\sqrt{s}$ in the center-of-mass frame. These measurements will expedite the search for baryon resonance contributions, and furthermore, will yield new physics information on diffractive, t- and u-channel processes. Our approved experiments will increase the world's data set by three orders of magnitude.

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1. Introduction

The photoproduction of vector mesons from nucleons touches upon such rich but disparate phenomena as the underlying symmetry of the quark degrees of freedom in the nucleon, the nature of the parity exchange between the incoming photon and the target nucleon, as well as the the strangeness content of the nucleon. In this paper, we shall focus on techniques of extracting baryon resonances in a *model-independent* way by employing a beam of linearly-polarized photons.

An important motivation for studying the spectrum of baryon resonances with photons is to obtain information on the photoproduction amplitudes of the individual resonances. Most of our knowledge of the baryon resonance spectrum has come from the reactions πN→ πN, γN→ πN, and πN→ $\pi\pi$N [1–3]. At center-of-mass energies below 1.7 GeV, the single pion production channel dominates both the pion and photoabsorption cross sections. As the c.m. energy increases towards 2.0 GeV the two- and three-pion decay channels become more dominant, and it is in this important energy region that the masses and partial widths of the resonances are poorly determined.

2. *Theoretical basis*

An outstanding problem in our current day understanding of baryon spectroscopy is the conundrum of the missing resonances. SU(6) $\otimes$ O(3) symmetric quark models predict far more resonances than have thus far been observed. One solution is to restrict the number of internal degrees of freedom by assuming that two quarks are bound in a diquark pair [4], thereby lowering the level density of baryon resonances. An alternate solution has been put forward by Koniuk and Isgur [5] and others [6–11]. In these calculations it has been found that the missing resonances tend to couple weakly to the πN channel but stronger to the ρN, $\pi\Delta$, and ωN channels. For example, in Table 1, we tabulate the supermultiplet[1] assignments with the corresponding star rating from the particle data group [12] for the measured and missing baryon resonances from the QCD-improved model of Cutkosky [13]. The supermultiplets enscribed within the boxes are fully consistent with the predictions of the diquark model. We remark that all of the boxed entries have at least a three-star rating. We also observe that the positive parity P11(1710) and P13(1870) resonances are inconsistent with the diquark model. The partial widths for the photon and hadronic couplings in the framework of Isgur-Karl [14] are contained in Table 2. We note that both F15(1955) and the P13(1870) are predicted to have primarily an ωN decay mode. Since most of our information on the baryon resonance spectrum comes from partial-wave analyses of πN $\to$ πN measurements, these 'missing states' will clearly have escaped detection. The models predict that these resonances will have a reasonable coupling to the photon. For this reason, an approved Hall–B experiment [15] using unpolarized electrons will search for resonances decaying via the ωN channel. The recently completed Hall-B g1 run with unpolarized and circularly-polarized photons will have a large amount of data in the baryon resonance region. Indeed, one of the experiments [16] is a dedicated search for missing baryons that decay through the two-pion channel. We

[1] SU(6) is the symmetry group that describes the symmetry of the *spin-flavor* (SU(3) $\otimes$ SU(2)) wavefunction. The symmetry of the three quarks in the baryonic system (6 $\otimes$ 6 $\otimes$ 6) can be decomposed into an *antisymmetric* (**20**), a *mixed antisymmetric* (**70**), a *mixed symmetric* (**70**), and a *symmetric* (**56**) multiplet. For example, the nucleon is in the ground state and is in a relative *s*-wave state. This state is symmetric and hence belongs to the **56**-multiplet.

expect the identification of many of these resonances decaying through the ωN, ρN or $\Delta\pi$ modes to be difficult due to their broad widths and narrow spacing. The sensitivity afforded by linearly-polarized photons will provide additional constraints in identifying these resonances, and such a measurement is complementary to experiments employing electron and unpolarized photons.

Experimentally, several difficulties are immediately apparent. The number of resonances extracted either from the analyses of pion-production data or from the the-

TABLE 1. SU(6) $\otimes$ O(3) supermultiplet assignments from the QCD-improved model of Cutkosky [13] for the measured and missing *baryon resonances. The boxed supermultiplets are fully consistent with the diquark model. Star rating is from particle data group [12].*

N^*	Status	SU(6)⊗O(3)	Parity	Δ^*	Status	SU(6)⊗O(3)
P11(938)	****	$\boxed{(56,0^+)}$	+	P33(1232)	****	$\boxed{(56,0^+)}$
S11(1535)	****	$\boxed{(70,1^-)}$				
S11(1650)	****	$\boxed{(70,1^-)}$		S31(1620)	****	$\boxed{(70,1^-)}$
D13(1520)	****	$\boxed{(70,1^-)}$	−	D33(1700)	****	$\boxed{(70,1^-)}$
D13(1700)	***	$\boxed{(70,1^-)}$				
D15(1675)	****	$\boxed{(70,1^-)}$				
P11(1520)	****	$\boxed{(56,0^+)}$		P31(1875)	****	$\boxed{(56,2^+)}$
P11(1710)	***	$(70,0^+)$		P31(1835)		$(70,0^+)$
P11(1880)		$(70,2^+)$				
P11(1975)		$(20,1^+)$				
P13(1720)	****	$\boxed{(56,2^+)}$		P33(1600)	***	$\boxed{(56,0^+)}$
P13(1870)	*	$(70,0^+)$		P33(1920)	***	$\boxed{(56,2^+)}$
P13(1910)		$(70,2^+)$	+	P33(1985)		$(70,2^+)$
P13(1950)		$(70,2^+)$				
P13(2030)		$(20,1^+)$				
F15(1680)	****	$\boxed{(56,2^+)}$		F35(1905)	****	$\boxed{(56,2^+)}$
F15(2000)	**	$(70,2^+)$		F35(2000)	**	$(70,2^+)$
F15(1995)		$(70,2^+)$				
F17(1990)	**	$(70,2^+)$		F37(1950)	****	$\boxed{(56,2^+)}$

TABLE 2. Partial widths for photon and hadronic couplings to baryon resonances in the Isgur-Karl model [14]. The total hadronic width, summed over all channels, is also given. The units are MeV.

Mass	J^π	γp	πN	$\pi\Delta$	ρN	ωN	Total
N(1490)	$1/2^-$	1.3	28.	2.9	40.	0.	98.
N(1655)	$1/2^-$	0.72	76.	67.	102.	1.4	262.
N(1535)	$1/2^-$	0.58	85.	52.	27.	0.	164.
N(1745)	$3/2^-$	0.009	13.	317.	26.	2.9	360.
N(1670)	$5/2^-$	0.013	30.	86.	5.3	0.	130.
N(1405)	$1/2^+$	0.026	46.	5.8	0.1	0.	52.
N(1705)	$1/2^+$	0.23	45.	13.	36.	0.8	108.
N(1890)	$1/2^+$	0.057	19.	12.	22.	37.	96.
N(2055)	$1/2^+$	0.009	1.4	3.2	1.7	32.	39.
N(1710)	$1/2^+$	1.0	42.	4.4	156.	32.	242.
N(1870)	$3/2^+$	0.027	10.	19.	2.3	98.	149.
N(1955)	$3/2^+$	0.021	1.2	88.	56.	90.	236.
N(1980)	$3/2^+$	0.031	1.2	96.	71.	55.	223.
N(2060)	$3/2^+$	0.0001	0.3	31.	15.	98.	145.
N(1715)	$5/2^+$	0.29	50.	4.4	20.	1.4	77.
N(1955)	$5/2^+$	0.24	0.2	64.	67.	184.	324.
N(2025)	$5/2^+$	0.001	1.7	67.	66.	180.	316.
N(1955)	$7/2^+$	0.006	9.6	36.	18.	53.	126.
Δ(1685)	$1/2^-$	0.34	11.	64.	64.	$--$	139.
Δ(1685)	$3/2^-$	1.0	24.	146.	289.	$--$	459.
Δ(1925)	$1/2^+$	0.0	28.	35.	37.	$--$	112.
Δ(1240)	$3/2^+$	0.46	121.	0.	0.	$--$	121.
Δ(1780)	$3/2^+$	0.14	29.	74.	32.	$--$	139.
Δ(1975)	$3/2^+$	0.030	0.	59.	35.	$--$	94.
Δ(1940)	$5/2^+$	0.059	16.	41.	45.	$--$	103.
Δ(1975)	$5/2^+$	0.51	1.	41.	388.	$--$	430.
Δ(1915)	$7/2^+$	0.27	56.	30.	88.	$--$	178.

oretical predictions is large. In addition, the resonance widths are broad (typically ≈ 150 MeV), and one is faced with the problem of disentangling many overlapping resonances. In general, a complete phase-shift analysis is required to extract the helicity amplitudes for the various resonances. An analysis of this sort demands both unpolarized photoproduction data, and a complete set of polarization experiments (i.e. polarized beam, polarized target, polarization of the final-state particles, and any combination thereof) [17] in order to extract fundamental information from the set of bilinear combinations of helicity amplitudes obtained from any one of these experimental conditions. The quantities to be measured in our experiments with linearly-polarized photons are the spin density matrix elements of the vector meson, which we discuss below.

2.1. The decay angular distribution of vector mesons

In our approved Hall–B experiments E94-109 (ρ) [18], E98-109 (ϕ) [19] and E99-013 (ω) [20][2], we shall employ a beam of linearly-polarized photons from the approved Coherent Bremsstrahlung Facility [21]. For details on the design and recent results from the CLAS detector, see Refs. 22 and 23. The idea is to measure the decay products from the vector meson resulting from the reaction $\vec{\gamma} p \to V\mathrm{N}$ in the energy range of $1.1 \le \mathrm{E}_\gamma \le 2.2$ GeV. Here, $\mathrm{V} = (\rho,\ \omega,\ \text{or}\ \phi)$. In a practical sense, we will be measuring the angular momenta, and thus the spin density matrix elements $\rho^j_{\alpha\beta}$, which determine the angular distribution of the daughter spin-0 mesons that decay from the parent vector meson. The density matrices are formed of bilinear combinations of the helicity amplitude matrices, H:

$$(\rho^0, \rho^j) = H(\frac{1}{2}\mathbf{I}, \frac{1}{2}\sigma^j)H^\dagger \qquad j = 1, 2, 3\,.$$

The upper index is related to photon spin by the Pauli spin matrices, the lower indices, $\alpha, \beta = -1, 0, 1$, correspond to the possible helicity states of the vector meson. The complete angular distribution $\mathrm{W}(\cos\theta, \phi, \Phi)$ reads [24]:

$$\begin{aligned} W(\cos\theta,\phi,\Phi) \;=\; W^0(\cos\theta,\phi,\rho^0_{\alpha\beta}) \;&-\; P_\gamma \cos 2\Phi\, W^1(\cos\theta,\phi,\rho^1_{\alpha\beta}) \\ &-\; P_\gamma \sin 2\Phi\, W^2(\cos\theta,\phi,\rho^2_{\alpha\beta}) \qquad (1) \end{aligned}$$

where

$$\begin{aligned} W^0(\cos\theta,\phi,\rho^0_{\alpha\beta}) &= \frac{3}{4\pi}[\frac{1}{2}\sin^2\theta + \frac{1}{2}(3\cos^2\theta - 1)\rho^0_{00} \\ &\quad -\sqrt{2}\,\mathrm{Re}\,\rho^0_{10}\sin 2\theta\cos\phi - \rho^0_{1-1}\sin^2\theta\cos 2\phi], \\ W^1(\cos\theta,\phi,\rho^1_{\alpha\beta}) &= \frac{3}{4\pi}[\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta \\ &\quad -\sqrt{2}\,\mathrm{Re}\,\rho^1_{10}\sin 2\theta\cos\phi - \rho^1_{1-1}\sin^2\theta\cos 2\phi], \end{aligned}$$

[2] These three Hall–B experiments will collect data from the g8 running period of 43 days.

$$W^2(\cos\theta, \phi, \rho^2_{\alpha\beta}) \quad = \quad \frac{3}{4\pi}[\sqrt{2}\,\mathrm{Im}\,\rho^2_{10}\sin 2\theta\sin\phi + \,\mathrm{Im}\,\rho^2_{1-1}\sin^2\theta\sin 2\phi].$$

P_γ is the degree of linear polarization of the photon beam and θ and ϕ are the polar and azimuthal angles of the normal to the ω decay plane with respect to a quantization axis z in the production plane. For the ρ meson, the direction of the decay π^+ in the rest frame of the vector meson defines the polar and azimuthal angles with respect to the production plane. The most commonly used reference frames for the decay distributions are either the *helicity* or the *Gottfried-Jackson* frame.[3] Thus, with linearly-polarized photons, one has access to six more independent spin density matrix elements than can be obtained in an unpolarized vector meson photoproduction experiment. By using the CEBAF Large Acceptance Spectrometer (CLAS) and the photon tagger, with the Coherent Bremsstrahlung Facility, we will accurately measure the decay angular distribution (and hence the spin density matrix elements) as functions of the scattering angle and the incident photon energy with high precision.

At high photon energies the measured density matrix elements give rise to an angular dependence that is characteristic of natural-parity exchange (pomeron exchange) in the t channel and of s-channel helicity conservation, as one would expect if the helicity of the vector meson mimics that of a real photon. For a polarization of unity ($P_\gamma = 1$), s-channel helicity conservation demands that the three-pion (two-pion) products of the ω (ρ) have a decay angular distribution given by $\sin^2\theta\cos 2\psi$, and this is reflected in the data. The decay products from the ω and ρ lie preferentially in the plane where Φ, the angle made by the photon electric polarization vector and the production plane, is equal to the azimuthal decay angle.

Another way to determine this feature is to measure the photon asymmetry parameter

$$\Sigma \equiv \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp}\,.$$

Here, $\sigma_\parallel$ ($\sigma_\perp$) is the cross section for the pions from ω decay ($\theta = \pi/2, \phi = \pi/2$) to emerge in the plane of the photon polarization (or perpendicular to it). In terms of the differential cross section, $W(\cos\theta, \phi, \Phi)$, Σ can be recast as

$$\Sigma = \frac{W(\cos\frac{\pi}{2}, \frac{\pi}{2}, \frac{\pi}{2}) - W(\cos\frac{\pi}{2}, \frac{\pi}{2}, 0)}{W(\cos\frac{\pi}{2}, \frac{\pi}{2}, \frac{\pi}{2}) + W(\cos\frac{\pi}{2}, \frac{\pi}{2}, 0)}\,.$$

For purely diffractive photoproduction, $\Sigma = 1$, when $P_\gamma = 1$. Any deviation from this value is an indication that nondiffractive processes are present, i.e. in the

[3] In the helicity frame, the z-axis is defined as the direction opposite the outgoing proton in the total c.m. system. In the Gottfried-Jackson frame, the z-axis is defined as the direction of the incoming photon in the rest frame of the ω. The decay angles θ and ϕ are defined as the polar and azimuthal angles of the unit vector $\mathbf{n}$, which is equal to the normal to the decay plane of the ω. Φ is the angle between the photon polarization vector and the production plane. For the ρ and ϕ mesons, either one of the decay spin-0 mesons define the azimuthal and polar angle with respect to the production plane in the rest frame of that vector meson.

extreme case of pure pion exchange, there is a flip in parity whereby $\Sigma = -1$. The analysis of angular momenta in the Gottfried-Jackson frame reflects helicity conservation in the t channel in the case that all matrix elements are zero except $\rho^1_{11} = -\mathrm{Im}\ \rho^2_{1-1} = \frac{1}{2}$.

The quantities to be measured in our approved experiments [18–20] are the spin density matrix elements of the photoproduced vector meson (cf. Eq. (1)). These observables, three from unpolarized photoproduction experiments, and six additional ones with a linearly-polarized beam of photons [24], are extracted in the rest frame of the vector meson by measuring the polar and azimuthal angular distributions of the decay spin-0 mesons. Linearly-polarized photons, furthermore, serve as a parity filter to distinguish between *natural* ($J^\pi = 0^+$) and *unnatural* ($J^\pi = 0^-$) parity exchange [25,26]. Of these nine quantities, all but two will be identically equal to zero if the photoproduction of the vector meson is mediated by either pomeron or pseudo-scalar exchange (including π, η, and η' processes [27]). A sign change for the density matrix element, ρ^1_{1-1} delineates these two processes. A direct measurement of the decay angular distributions, therefore, allows one to readily distinguish between contributions from natural- and unnatural-parity exchange. Of the other seven spin density matrix elements, a significant departure from zero will indicate other production mechanisms. For multiple pions in the final state, such nonzero density matrix elements would signal the existence of new baryon resonances that decay through the $\Delta\pi$, ρN, or ωN channel. Due to the narrow decay width (8.4 MeV) of the ω meson and to isospin selectivity, the ω meson channel will serve as a clean signal for extracting N* resonances; Δ^* resonances cannot decay through the ω mode since they possess an isospin of 3/2.

It is by simply extracting these density matrix elements of the spin-0 decay products as functions of the Mandelstam variables, s and t, that we shall obtain a *model-independent* pool of data. These density matrix elements form the meeting ground between theory and experiment. Through their models, theorists predict the helicity amplitudes, and from the decay angular distribution data, experimentalists extract the *bilinear combinations of these helicity amplitudes* or the *density matrix elements*. Accurate and precise measurements of the evolution of these density matrix elements over a wide range of center of mass energies and four-momentum transfers squared will constrain the theory, and thereby give insight into the underlying production mechanisms.

3. *Experiments*

Many experiments have been performed on the photoproduction of the ρ° [28–35] including two polarization experiments [36,37]. Most of these experiments were performed at photon energies exceeding 3 GeV, and at very low t. The experiments performed with linearly-polarized photon beams at SLAC [37] used a bubble-chamber detector and hence suffered from low statistics. The results from this experiment can be explained purely in terms of the vector dominance model, which is consistent with natural-parity exchange in the t channel and is s-channel helicity conserving, as would be expected from diffractive photoproduction. Very few data exist in the energy regime near $\sqrt{s} = 2.0$ GeV .

In the photon energy regime near 1.6 GeV ($\sqrt{s}$ = 1.95 GeV), one would expect to see some indication of resonances that decay through the ω and ρ° channels. Data taken at DESY [31], (averaging over the photon energy in the range of 1.4 < E_γ < 1.8 GeV) have been compared with the one-pion-exchange model of Friman and Soyeur [39]. The agreement between the data and the fit is good for $|t| < 0.5$ (GeV/c)^2. In the central region, near $\theta_{cm} = 90°$, however, the extrapolated curve underpredicts the data by an order of magnitude. The preliminary results from a SAPHIR vector meson photoproduction experiment [39] using an unpolarized tagged photon beam in the energy range of $1.0 \leq E_\gamma \leq 2.0$ GeV show strong indications of s-channel resonance contributions. With increasing center-of-mass energy, the exponential fall-off with t ($d\sigma/dt \propto e^{-b|t|}$) as predicted by diffractive models becomes more pronounced – at least in the low-t range. In the mid-t range, however, there are marked departures from the predicted values. It is precisely in this t range where contributions from ω production via s-channel resonances are expected to be most enhanced. This behavior has been confirmed by the angular distribution of the decay pions (in the helicity frame of the ω). In this lower energy range of $\sqrt{s} = 2$ GeV, one observes that the decay pions follow a $\cos^2\theta$ distribution [39] at mid-t in the helicity frame. This result is completely contrary to the $\sin^2\theta$ distribution that should occur for $0^\pm$ parity exchange processes. The almost flat differential cross section near threshold and the non-SCHC decay angular distribution in this energy range as well as the steep increase of the total cross section from threshold strongly hint towards the presence of underlying baryon resonances. An example of such a resonance in this energy regime ($\sqrt{s} \approx 1.78$ GeV) has been observed in the reaction $p\pi^+ \to p\pi^+\pi^+\pi^-\pi^0$ [40].

To study the ρ photoproduction in the absence of a diffractive background, one can turn to the charge-exchange channel γp$\to$ ρ^+n. Although the data for this reaction are sparse, we expect an increase of the interval in t for which the resonant cross section is a large percentage of the total. This is due primarily to the lowering of the low-t nonresonant background compared with that for the γp$\to$ ρ^0p reaction. There are considerably fewer data for charged ρ photoproduction than for ρ^0 photoproduction; and *no experiments at all have been performed with linearly-polarized photons.* A search for resonance production decaying via a charged ρ has been studied only for γn$\to$ ρ^-p [32]. The cross section (for $1.4 < E_\gamma < 2.5$ GeV) is not at all described by a purely one-pion-exchange mechanism, and has a plateau above $|t| = 1.0$ (GeV/c)^2. A large enhancement of the cross section is seen in the range $1.5 < E_\gamma < 2.2$ GeV. This is precisely the region where resonance effects should be the greatest. We expect the cross section for ρ^+ from the reaction γp$\to$ ρ^+n to be comparable to that of the ρ^- from the γn$\to$ ρ^-p channel.

4. *Summary*

In this paper, we have discussed a means for extracting baryon-resonance production from diffractive and t-channel exchange mechanisms in a *model-independent* way by making use of a beam of linearly-polarized photons. We shall extract the spin density matrix elements of the daughter spin-0 mesons that decay from the parent vector meson. Our approved Hall–B experiments, which employ the Coherent Bremsstrahlung Facility, will go far in addressing the issue of the underlying symmetry of the quark degrees of freedom in the nucleon, as well as the nature of the parity exchange in photonuclear reactions.

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TRAGANJE ZA NEDOSTAJUĆIM BARIONIMA SNOPOM LINEARNO POLARIZIRANOG ZRAČENJA

Fototvorba ω i ρ mezona na protonima snopom linearno polariziranih fotona će se rabiti za odvajanje rezonantne tvorbe bariona od procesa izmjena t kvarkova pri energijama 1,72 do 2,24 GeV u Hali B u Jeffersonovom laboratoriju. Očekuje se da su ωN i ρN kanali važne grane za barionske rezonancije. Doprinos izmjene t-kanalom može se razdvojiti samo upotrebom linearno polariziranih fotona. Mjerenja će se raditi linearno polariziranim snopom fotona proizvedenim odobrenim sustavom "Coherent Bremsstrahlung Facility", a mjerit će se asimetrija kao i matrični elementi spinske gustoće u raspadu spin-0 mezona roditeljskog vektorskog mezona. Matrični elementi spinske gustoće i polarizacijska asimetrija u raspadu vektorskih mezona će se izvesti kao funkcije kuta tvorbe θ_{cm} i energije u centru-mase $\sqrt{s}$ u sustavu centra-mase. Ta će mjerenja ubrzati potragu za doprinosima barionskih rezonancija, te nadalje, dati fizičke podatke o difraktivnim procesima u t- i u-kanalnim procesima. Ova odobrena mjerenja povećat će skup svjetskih podataka za tri reda veličine.