Measurement of the $E2/M1$ Ratio in the $N \rightarrow \Delta$ Transition using the reaction $p(\vec{\gamma}, p)\pi^o$

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The small electric quadrupole $E2$ amplitude of the predominantly magnetic dipole $M1$ $p \rightarrow \Delta(1232)$ transition has been measured using 270 to 420 MeV tagged linearly polarized photons in the $p(\vec{\gamma}, p)\pi^o$ reaction at the Mainz Microtron MAMI. Differential cross sections and photon asymmetries were determined by measuring the recoil proton in the cylindrically symmetric 4π detector DAPHNE. From the proton angular distributions the ratio $E2/M1 = -(2.5 \pm 0.2 \pm 0.2)\%$ at the maximum of the $\Delta(1232)$ resonance has been derived. [S0031-9007(96)02224-7]

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The concept of "color magnetic forces," introduced by de Rújula, Georgi, and Glashow [1] in 1975, implies the existence of contact and tensor forces due to the color hyperfine interaction between quarks. One consequence of these forces is the admixture of higher orbital angular momentum components in the s-state quark wave functions of the nucleon ground state and the dominant first excited state, the $\Delta(1232)$ resonance. The lowest angular momentum allowed is a d-state admixture. This leads to modifications to the predictions of nucleon models such as the isobaric mass splitting, nucleon and Δ decay probabilities, and the electric form factor of the neutron. A d-state admixture also allows for an electric quadrupole $E2$ transition in the $\gamma + N \rightarrow \Delta(1232)$ excitation, which otherwise is a pure magnetic dipole $M1$. In a visual way the d-state admixture can be interpreted as a "deformation" of the nucleon or the $\Delta(1232)$ resonance or both. The $M1$ and $E2$ transitions can be directly excited by photons and the subsequent pion decay can be observed. The amplitudes in the πN final state are usually denoted by $E^I_{l\pm}$ and $M^I_{l\pm}$, where E and M are the electric and magnetic multipoles, l is the orbital angular momentum of the photoproduced pion, the $\pm$ sign refers to the total πN angular momentum $j = l \pm \frac{1}{2}$, and I is the isospin of the πN system. The ratio $R_{\rm EM} = E2/M1 = E^{3/2}_{1^+}/M^{3/2}_{1^+}$ is therefore related to the tensor components in the effective quark-quark interaction.

In the old MIT bag model the ratio $R_{\rm EM}$ is simply equal to 0, while the nonrelativistic constituent quark model predicts a rather small negative value for $R_{\rm EM}$ with typical results ranging between -0.08% and -2% [2–5]. For the "relativized" quark models [6,7] values of the order of -0.1% are obtained. Larger negative values in the range -2.5% to -5.9% have been predicted by the Skyrme model [8,9] while cloudy bag model values range from -2.0% to -3.0% [10,11]. However, the theoretical values for the first two models have to be taken with some caution because they consider the bare "delta resonance contribution" only.

Multipole analyses [12–14] of the $N(\gamma, \pi)$ reactions constitute a first step in the extraction of the resonant $E^{3/2}_{1^+}$ amplitude from the experimental cross sections. The determination of the resonant $E^{3/2}_{1^+}$ amplitude is difficult because of two reasons. First, the electric quadrupole amplitude $E^{3/2}_{1^+}$ is very small compared to the dominant magnetic dipole $M^{3/2}_{1^+}$. Here it helps the measurements of polarization observables, since they contain an interference $E_{1^+}M_{1^+}$ term [15,16]. Second, the nonresonant contribution to the $E^{3/2}_{1^+}$ is large, which requires theoretical considerations as discussed at the end of this Letter [17,18].

Until recently the medium energy electron accelerators were pulsed and the photon or electron fluxes usable were limited for coincidence experiments. Consequently, the precision of previous $R_{\rm EM}$ measurements was not sufficiently good to allow detailed tests of nucleon models. For example, in the Review of Particle Properties [19] four values $R_{\rm EM} = -(1.1 \pm 0.4)\%, -(1.5 \pm 0.2)\%, +(3.7 \pm 0.4)\%$, and $-(1.3 \pm 0.5)\%$ are given. Recently cw beams became available and new determinations of the $R_{\rm EM}$ ratio were performed. At the LEGS facility at Brookhaven National Laboratory the reaction $p(\vec{\gamma}, p)\pi^0$ was investigated [20,21]. However, in this work the reaction could only be studied below the peak of the $\Delta(1232)$ resonance because the photon energy was limited to $E_\gamma \leq 335$ MeV. The measured ratio $d\sigma_\parallel/d\sigma_\perp$, where $d\sigma_\parallel/d\Omega$ and $d\sigma_\perp/d\Omega$ are the differential cross sections for the photon polarization parallel and perpendicular to the reaction plane, was compared to model calculations of Refs. [22] and [15]. Since neither model could describe the energy dependence and the absolute value for $d\sigma_\parallel/d\sigma_\perp$, no value for $R_{\rm EM}$ was extracted although it was argued that $R_{\rm EM}$ should be more

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negative than -1.4% ($E_{1^+} \to 2E_{1^+}$) [23]. A measurement of the $p(e, e'\pi^0)p$ reaction at ELSA [24] gave the surprisingly large negative value of $(-12.7 \pm 1.5)\%$ for the ratio $R_{CM} = C2/M1$, where C2 refers to the Coulomb amplitude due to charge transitions in contrast to E2 which relates to the current transition.

The $p(\vec{\gamma}, p)\pi^0$ measurement reported in this Letter was performed with tagged linearly polarized photons produced at the 855 MeV Mainz Microtron MAMI [25]. Using the cylindrically symmetric DAPHNE detector [26], recoil protons from the $p(\vec{\gamma}, p)\pi^0$ reaction and the positive pions from the $p(\vec{\gamma}, \pi^+)n$ reaction were detected allowing the differential cross section $d\sigma_0/d\Omega$ and the photon asymmetry Σ to be measured simultaneously for the $p\pi^0$ and $n\pi^+$ channels, from which $d\sigma_\parallel/d\Omega$ and $d\sigma_\perp/d\Omega$ can be derived directly. $d\sigma_\parallel/d\Omega$ is particularly sensitive to the R_{EM} ratio because of the interference term $E_{1^+}M_{1^+}$. The photon energy region covered in this experiment was from 270 to 420 MeV, which spans the complete $\Delta(1232)$ resonance. In this Letter we present the results for the $p\pi^0$ channel [27].

The experiment used the Glasgow tagged photon spectrometer at MAMI [28,29]. Linearly polarized photons were produced by coherent bremsstrahlung in a 100 μm thick diamond crystal [30,31]. The tagger covers the photon energy range from 50 to 800 MeV with a resolution of about 2 MeV at intensities of up to 5×10^5 photons $\mathrm{s}^{-1}\,\mathrm{MeV}^{-1}$. The photon beam was collimated to produce a 10 mm beam spot at the liquid hydrogen target. The tagging efficiency was determined in separate measurements with a Pb-glass detector to be $\epsilon_\gamma = 55\%$. The stability of the photon intensity was continuously monitored throughout the experiment using an electron-positron-pair detector downstream of DAPHNE. In this way the photon intensity could be determined with a precision of $\pm 2\%$ [32]. The liquid hydrogen cryogenic target was contained in a 43 mm diameter, 275 mm long Mylar cylinder with a wall thickness of 0.1 mm. The target density was stabilized and known to an accuracy of $\pm 0.5\%$ by means of an automatic pressure and temperature control system. The protons from the $p(\vec{\gamma}, p)\pi^o$ reaction were detected in the large acceptance detector DAPHNE ($21° \leq \theta \leq 159°, 0° \leq \phi \leq 360°$). Good definition of charged particle tracks is provided with this detector by a central vertex detector which consists of 3 coaxial cylindrical multiwire proportional chambers providing a polar angular resolution of $\Delta\theta \leq 1°$ FWHM and an azimuthal resolution $\Delta\phi \leq 2°$ FWHM. This vertex detector is surrounded by a segmented $\Delta E - E - \Delta E$ plastic scintillator telescope with successive thicknesses of 10, 100, and 5 mm. The outermost layer is a lead-aluminium-scintillator sandwich designed to enhance the π^o detection efficiency and to provide additional energy loss measurements of charged particles.

In the first step of the analysis events with only one charged particle were selected. The next step discriminated between protons and other charged particles (π^+, e^-, e^+). A detailed discussion of the range method used to identify protons and to determine their energy has been given previously [33]. Its most important feature is the simultaneous use of all of the measured energy losses in the scintillator layers of DAPHNE. In this procedure less than 1% of pions were misidentified as protons and the resolution of the measured proton momentum was 3% at 300 MeV/c. Low energy particles which stop in the first scintillator were identified by using a standard $\Delta E - E$ technique for which the wire chambers provide the ΔE signal and the scintillators provide the E signal.

The photon asymmetry Σ is given by the following expression:

$$\Sigma = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\parallel + d\sigma_\perp}, \tag{1}$$

which is connected to the differential cross section by

$$\frac{d\sigma(\theta,\phi)}{d\Omega} = \frac{d\sigma_0(\theta)}{d\Omega}[1 - \Sigma\cos(2\phi)], \tag{2}$$

where θ and ϕ are the polar and azimuthal angles of the pion with respect to the beam direction. DAPHNE has full 2π azimuthal coverage allowing a direct measurement of the $\cos(2\phi)$ dependence of the differential cross section which gives a simultaneous determination of the photon asymmetry Σ and the unpolarized cross section $d\sigma_0/d\Omega$. The statistical errors in $d\sigma_0/d\Omega$ are of the order of 1%. Figure 1 shows the cross sections $d\sigma_0/d\Omega$, $d\sigma_\parallel/d\Omega$, and $d\sigma_\perp/d\Omega$. At 300 MeV the new MAMI data are compared in Fig. 1 to the published LEGS data [20]. One also sees that the new data for the unpolarized cross section $d\sigma_0/d\Omega$ agree well with the existing Bonn data [34] and with new results from a measurement with the π^0 spectrometer TAPS at MAMI [35].

The differential cross sections can be expressed in terms of the s- and p-wave multipole amplitudes, assuming that the neutral pions are produced with angular momentum zero and one. Because of parity and angular momentum conservation only $E_{0^+}, E_{1^+}, M_{1^-}$, and M_{1^+} contribute. The multipoles can be combined into the coefficients A_j, B_j, and C_j in the following parametrization for the π^o angular distributions:

$$\frac{d\sigma_j(\theta)}{d\Omega} = \frac{q}{k}[A_j + B_j\cos(\theta) + C_j\cos^2(\theta)], \tag{3}$$

where q and k denote the center of mass momentum (cm) of the pion and the photon, respectively, and j indicates the parallel ($\parallel$), perpendicular ($\perp$), and unpolarized (0) components. The coefficients A_j, B_j, and C_j are quadratic functions of the s- and p-wave amplitudes. In particular, $d\sigma_\parallel/d\Omega$ is very sensitive to the E_{1^+} amplitude since

$$A_\parallel = |E_{0^+}|^2 + |3E_{1^+} + M_{1^+} - M_{1^-}|^2, \tag{4}$$

$$B_\parallel = 2\,\mathrm{Re}[E_{0^+}(3E_{1^+} + M_{1^+} - M_{1^-})^*], \tag{5}$$

$$C_\parallel = 12\,\mathrm{Re}[E_{1^+}(M_{1^+} - M_{1^-})^*]. \tag{6}$$

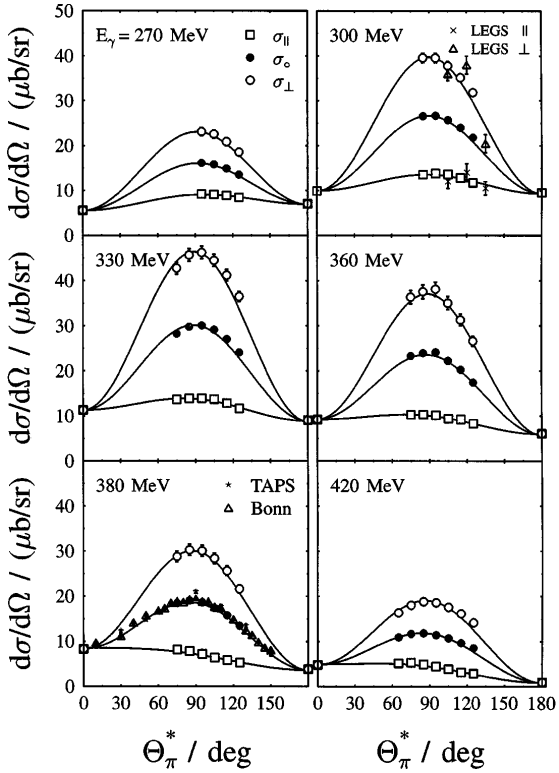

FIG. 1. Differential cross sections for the new MAMI data [27], $d\sigma_0/d\Omega$ (full circle), parallel $d\sigma_\parallel/d\Omega$ (open square), and perpendicular part $d\sigma_\perp/d\Omega$ (open circle) for the $p(\vec{\gamma},p)\pi^0$ reaction. At $E_\gamma = 300$ MeV the data are compared to the results from LEGS [20] and at $E_\gamma = 380$ MeV to the results from Bonn [34] and TAPS [35]. The solid lines are fit results from the parametrization of Eq. (3).

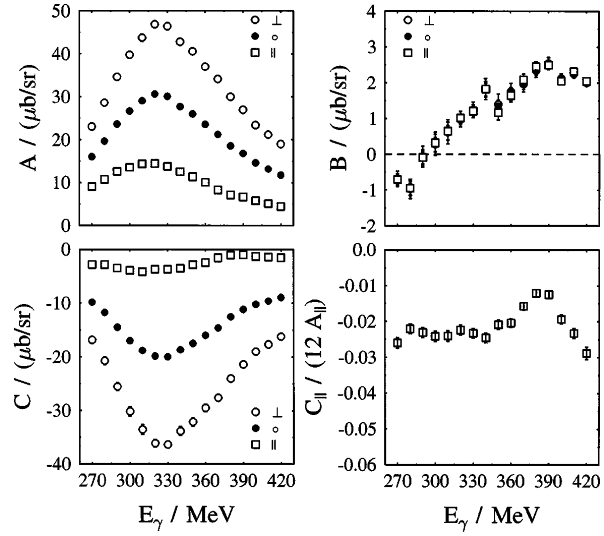

FIG. 2. The A_j, B_j, and C_j coefficients for the angular distributions $d\sigma_0/d\Omega$, parallel $d\sigma_\parallel/d\Omega$, and perpendicular part $d\sigma_\perp/d\Omega$ for the $p(\vec{\gamma},p)\pi^0$ reaction and the ratio $R = C_\parallel/12A_\parallel$.

The coefficients A_j, B_j, and C_j, determined from a least squares fit of Eq. (3) to the pion cm differential cross sections, are shown in Fig. 2 as a function of the tagged photon energy. Furthermore, the ratio

$$R = \frac{\mathrm{Re}(E_{1^+}M_{1^+}^*)}{|M_{1^+}|^2} \simeq \frac{1}{12}\frac{C_\parallel}{A_\parallel} = \frac{\mathrm{Re}[E_{1^+}(M_{1^+} - M_{1^-})^*]}{|M_{1^+} - M_{1^-}|^2} \tag{7}$$

obtained for the sixteen photon energies from $E_\gamma = 270$ to 420 MeV is also shown in Fig. 2. Up to 350 MeV the ratio $C_\parallel/12A_\parallel$ is constant -2.5%, whereas above 350 MeV some energy dependence is seen. The amplitudes in Eq. (7) relate to the $p(\vec{\gamma},p)\pi^0$ channel, but in order to get the $I = 3/2$ and $I = 1/2$ isospin decomposition over the whole energy range, data from the $p(\vec{\gamma},\pi^+)n$ reaction are also required. However, at the maximum of the $\Delta(1232)$ resonance ($E_\gamma = 340$ MeV) the ratio is simply given by

$$R = \frac{\mathrm{Im}E_{1^+}}{\mathrm{Im}M_{1^+} - \mathrm{Im}M_{1^-}} = \frac{\mathrm{Im}E_{1^+}^{3/2}}{\mathrm{Im}M_{1^+}^{3/2}} = R_{\mathrm{EM}}$$
$$= (-2.5 \pm 0.2 \pm 0.2)\%\,, \tag{8}$$

since at this point the real part of $\mathrm{Re}(M_{1^+} - M_{1^-})$ is zero and the imaginary parts $\mathrm{Im}\,M_{1^+}$ and $\mathrm{Im}\,M_{1^-}$ are purely isospin $I = 3/2$. The systematic error of 0.2% absolute comes from the limited angular efficiency for detecting the recoil proton with DAPHNE and from ignoring isospin 1/2 contributions. Furthermore, at the resonance peak contributions from partial waves $l \geq 2$ are zero, and the s- and p-wave assumption holds exactly [36]. Below and above the $\Delta(1232)$ resonance contributions from $l \geq 2$, which arise from interference terms with the real part of the M_{1^+} amplitude (e.g., $\mathrm{Re}\,M_{1^+}\mathrm{Re}\,E_{2^-}$), are of the order of 10%.

The present result, $R_{\mathrm{EM}} = -(2.5 \pm 0.2)\%$, at the maximum of the $\Delta(1232)$ resonance is more than 4 times the values from Berends *et al.* [13], $R_{\mathrm{EM}} = -(0.6 \pm 0.5)\%$, and Pfeil *et al.* [12], $R_{\mathrm{EM}} = -(0.3 \pm 0.3)\%$, which are the standard multipole data sets for the determination of the $E2/M1$ ratio. However, before the new R_{EM} value can be compared to predictions of different nucleon models, the meaning of the $E2/M1$ ratio in these models has to be clarified. The resonant isospin 3/2 amplitudes $E_{1^+}^{3/2}$ and $M_{1^+}^{3/2}$ normally calculated in models are not the physically observed ones. The measured ratio R_{EM} contains nonresonant background amplitudes beside the resonant ones and, therefore, a direct comparison to models may be meaningless. There are various methods of extracting the pure resonant components of the $E_{1^+}^{3/2}$ and $M_{1^+}^{3/2}$-amplitudes which are discussed in more detail in Refs. [15,16].

Recently, the "speed plot technique," a standard procedure to extract the resonance properties in the πN multipole analysis [37], was applied to the new photo production data of this experiment [38]. The speed SP of the scattering amplitude T is defined by

$$SP(W) = \left| \frac{dT(W)}{dW} \right|, \tag{9}$$

where W is the cm energy. In the resonance region the energy dependence of the full amplitude $T = T_R + T_B$ is determined by the strongly varying resonance contribution T_R while the background contribution T_B should be a slowly changing function of the energy. Applying this model independent method, the physically observed value $R_{\mathrm{EM}} = -(2.5 \pm 0.2)\%$ changed to the value $R_{\mathrm{EM}} = -3.5\%$ for the pure resonance part [38]. This value can be compared to nucleon models, which include a pion cloud (cloudy-bag model, chiral-bag model, Skryme model). The problem of separating the background and resonance amplitudes has been studied in a more fundamental way in Ref. [17]. The authors consider in a schematic model the "bare" Δ resonance, the "background" represented by the Born terms, and an interference term of both. The sum of the bare Δ and the interference term is called "dressed" Δ. They conclude that it is not possible to separate the bare Δ contribution from the interference term "dressing" it by a measurement. A direct comparison of pure quark models, like the constituent quark model, with the result of this Letter may be therefore doubtful. A complete model has to consider the question of the nonresonant background [39].

To summarize, the differential cross sections $d\sigma_{\parallel}/d\Omega$, $d\sigma_{\perp}/d\Omega$, and $d\sigma_0/d\Omega$ for the reaction $p(\vec{\gamma}, p)\pi^o$ have been measured for the first time with good accuracy in the $\Delta(1232)$ region. From angular distributions the ratio $R_{\mathrm{EM}} = \mathrm{Im}\, E_{1+}^{3/2}/\mathrm{Im}\, M_{1+}^{3/2} = -(2.5 \pm 0.2 \pm 0.2)\%$ at the maximum of the $\Delta(1232)$ resonance has been derived. In order to obtain an isospin decomposition of the E_{1^+} and M_{1^+} amplitude over the whole energy range a simultaneous analysis of the $p(\vec{\gamma}, p)\pi^0$ and the $p(\vec{\gamma}, \pi^+)n$ channels is now in progress [36]. In addition, further measurements have been performed using the π^o spectrometer TAPS to detect neutral pions instead of recoil protons in the $p(\vec{\gamma}, \pi^o)p$, $d(\vec{\gamma}, \pi^o p)n$, and $d(\vec{\gamma}, \pi^o n)p$ reactions. These measurements will allow one to derive the R_{EM} ratio for the neutron.

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