Quarks and Hadron Spectroscopy – Lecture IV

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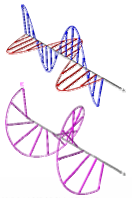
Main points of Lecture III



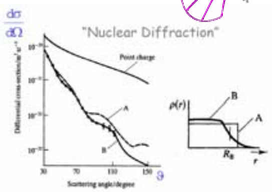
- Real photons - transverse or circular polarisation
- Virtual photons (electron scattering) additionally have longitudinal polarisation
- Only in past decade or so have we had photon/electron beams and detector systems of sufficient quality to attempt many important measurements
- Elastic electron scattering

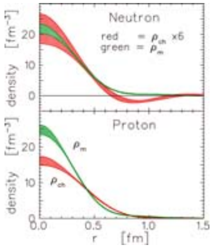
  Charge and magnetic scattering gives information on charge and magnetic form factors (G_E, G_M) – but need to disentangle!

  Can separate using Rosenbluth technique but method fails at high Q^2

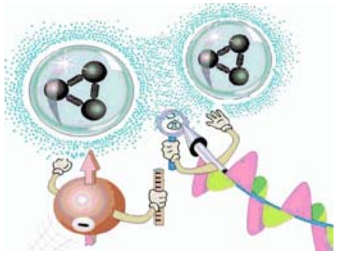
  Solution at higher Q^2 – Use polarisation transfer

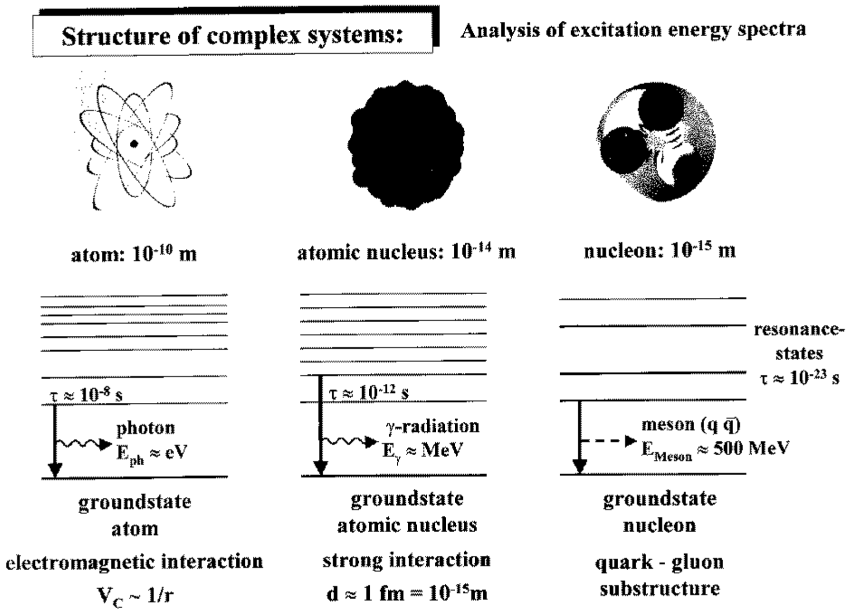
$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\left(\frac{\theta_e}{2}\right)$$





Nucleon excited states (resonances)

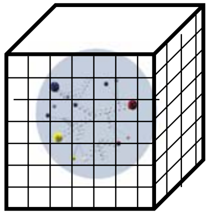




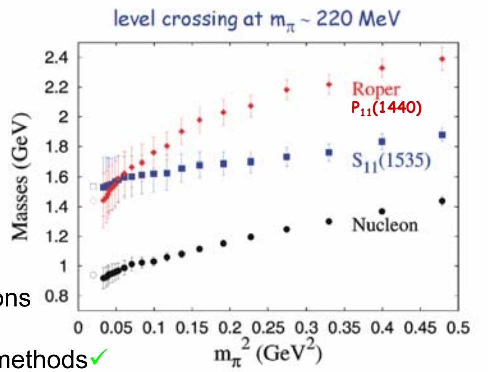
Structure of complex systems: Analysis of excitation energy spectra

atom: 10^{-10} m	atomic nucleus: 10^{-14} m	nucleon: 10^{-15} m
$\tau \approx 10^{-8}$ s	$\tau \approx 10^{-12}$ s	resonance-states $\tau \approx 10^{-23}$ s
photon $E_{ph} \approx$ eV	γ-radiation $E_\gamma \approx$ MeV	meson ($q\bar{q}$) $E_{Meson} \approx 500$ MeV
groundstate atom	groundstate atomic nucleus	groundstate nucleon
electromagnetic interaction $V_C \sim 1/r$	strong interaction d ≈ 1 fm = 10^{-15}m	quark - gluon substructure

Lattice QCD progress



S.J. Dong et al., Kentucky, GWU, JLab, Adelaide, hep-ph/0306199



level crossing at $m_\pi \sim 220$ MeV

- QCD – general theoretical description of strong interaction from constituent quarks and gluons

High energies – perturbative methods✓
Low energies -- More complicated

- Lattice QCD is one approach – but need calculations for light quark masses !
- Significant progress - basic calculations of masses of ground and excited states.
- Full lattice calculations of reactions some way off!! Effective degrees of freedom often employed to interpret data

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Even New QCD interpretations based on holographic dual of QCD give predictions for the nucleon spectrum!!

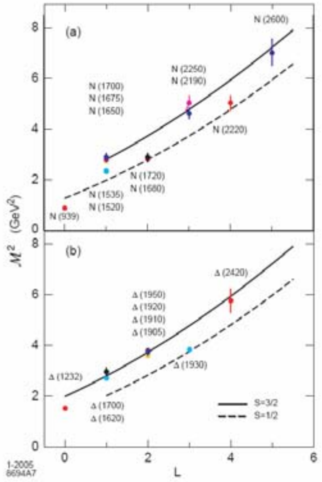
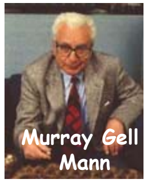


FIG. 2: Light baryon orbital spectrum for $\Lambda_{QCD} = 0.22$ GeV. Predictions for the nucleons are shown in (a) and for the Δ trajectories in (b). The lower dashed curves correspond to baryon states dual to spin-$\frac{1}{2}$ modes in the bulk and the upper continuous curve to states dual to spin-$\frac{3}{2}$ modes.

de Teramond & Brodsky
PRL 94 (2005) 201601
August 2005 issue of Physics World

Constituent quark model

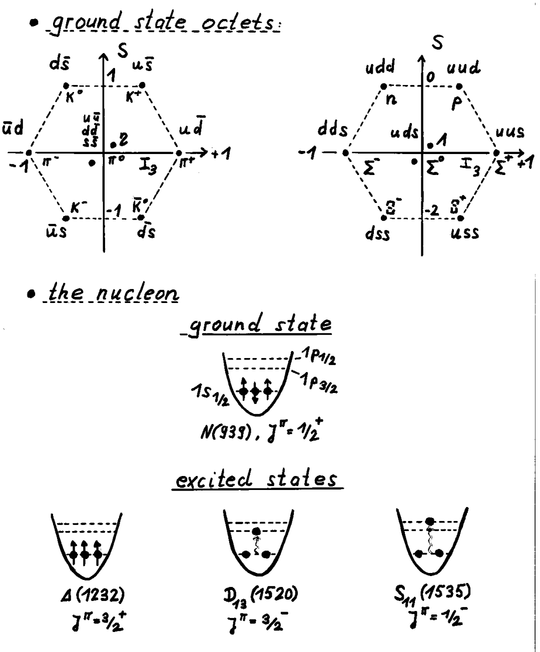
- Baryons are 3-quark systems
- Mesons are quark-antiquark systems
- Three “flavours” (SU(3)$_F$)



Murray Gell Mann

- (Perhaps surprisingly!) constituent quarks seem to be a reasonably effective d.o.f to describe the nucleon! Bare quarks must somehow be dressed by gluons and virtual sea quarks to make up constituent quarks.

Bare quark masses
u ~ 2-4 MeV/c^2
d ~ 4-8 MeV/c^2
Const. quarks
~ 300 MeV/c^2



“N” baryons I=1/2 , “Δ” baryons I=3/2

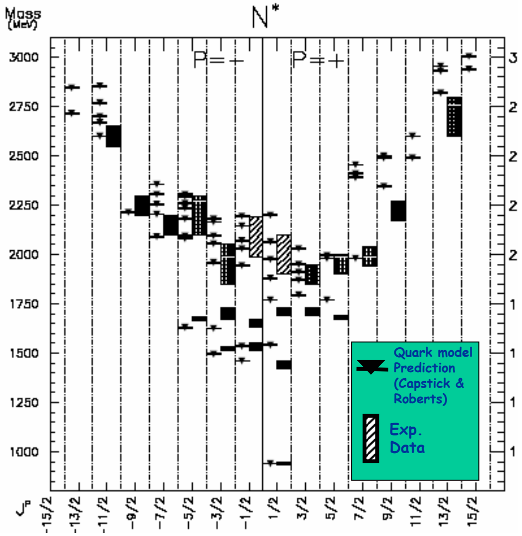
Missing resonances

Wrong effective degrees of freedom in theoretical model ?
Wrong experimental bias – probes, decay particles, observables ?

Very important to more firmly establish the nucleon excitation spectrum

CQMs with different q-q potentials give different predictions for number and ordering of higher lying excited states.

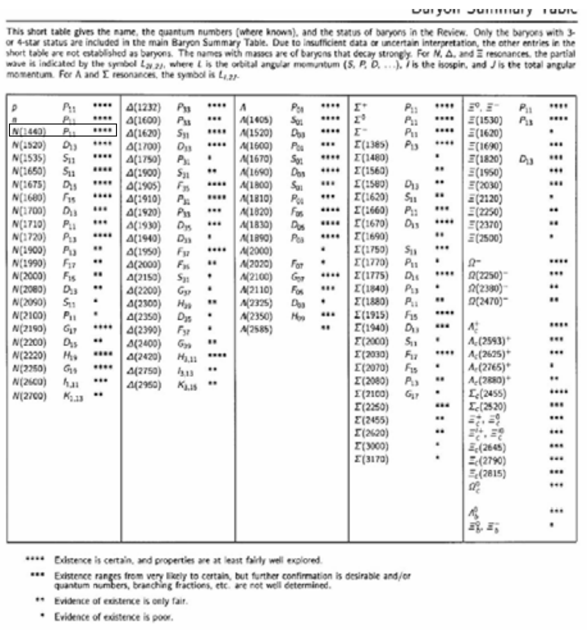
Knowledge of spectrum presently not sufficient to even determine whether nucleon dynamics are 3q or quark+di-quark !!



Present knowledge of the spectrum

ΔMass ~ ±20 MeV
ΔWidth ~ ±100 MeV!!

Large discrepancies between analyses of ***same*** experimental data (mainly from πN scattering) with different amplitude analysis methods



Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the main Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the short table are not established as baryons. The names with masses are of baryons that decay strongly. For N, Δ, and Ξ resonances, the partial wave is indicated by the symbol $L_{2I,2J}$, where L is the orbital angular momuntum (S, P, D, ...), I is the isospin, and J is the total angular momentum. For Λ and Σ resonances, the symbol is $L_{I,2J}$.

p	P_{11}	****	$\Delta(1232)$	P_{33}	****	Λ	P_{01}	****	Σ^+	P_{11}	****	Ξ^0, Ξ^-	P_{11}	****
n	P_{11}	****	$\Delta(1600)$	P_{33}	***	$\Lambda(1405)$	S_{01}	****	Σ^0	P_{11}	****	$\Xi(1530)$	P_{13}	****
$N(1440)$	P_{11}	****	$\Delta(1620)$	S_{31}	****	$\Lambda(1520)$	D_{03}	****	Σ^-	P_{11}	****	$\Xi(1620)$		*
$N(1520)$	D_{13}	****	$\Delta(1700)$	D_{33}	****	$\Lambda(1600)$	P_{01}	***	$\Sigma(1385)$	P_{13}	****	$\Xi(1690)$		***
$N(1535)$	S_{11}	****	$\Delta(1750)$	P_{31}	*	$\Lambda(1670)$	S_{01}	****	$\Sigma(1480)$		*	$\Xi(1820)$	D_{13}	***
$N(1650)$	S_{11}	****	$\Delta(1900)$	S_{31}	**	$\Lambda(1690)$	D_{03}	****	$\Sigma(1560)$		**	$\Xi(1950)$		***
$N(1675)$	D_{15}	****	$\Delta(1905)$	F_{35}	****	$\Lambda(1800)$	S_{01}	***	$\Sigma(1580)$	D_{13}	**	$\Xi(2030)$		***
$N(1680)$	F_{15}	****	$\Delta(1910)$	P_{31}	****	$\Lambda(1810)$	P_{01}	***	$\Sigma(1620)$	S_{11}	**	$\Xi(2120)$		*
$N(1700)$	D_{13}	***	$\Delta(1920)$	P_{33}	***	$\Lambda(1820)$	F_{05}	****	$\Sigma(1660)$	P_{11}	***	$\Xi(2250)$		**
$N(1710)$	P_{11}	***	$\Delta(1930)$	D_{35}	***	$\Lambda(1830)$	D_{05}	****	$\Sigma(1670)$	D_{13}	****	$\Xi(2370)$		**
$N(1720)$	P_{13}	****	$\Delta(1940)$	D_{33}	*	$\Lambda(1890)$	P_{03}	****	$\Sigma(1690)$		**	$\Xi(2500)$		*
$N(1900)$	P_{13}	**	$\Delta(1950)$	F_{37}	****	$\Lambda(2000)$		*	$\Sigma(1750)$	S_{11}	***			
$N(1990)$	F_{17}	**	$\Delta(2000)$	F_{35}	**	$\Lambda(2020)$	F_{07}	*	$\Sigma(1770)$	P_{11}	*	Ω^-		****
$N(2000)$	F_{15}	**	$\Delta(2150)$	S_{31}	*	$\Lambda(2100)$	G_{07}	****	$\Sigma(1775)$	D_{15}	****	$\Omega(2250)^-$		***
$N(2080)$	D_{13}	**	$\Delta(2200)$	G_{37}	*	$\Lambda(2110)$	F_{05}	***	$\Sigma(1840)$	P_{13}	*	$\Omega(2380)^-$		**
$N(2090)$	S_{11}	*	$\Delta(2300)$	H_{39}	**	$\Lambda(2325)$	D_{03}	*	$\Sigma(1880)$	P_{11}	**	$\Omega(2470)^-$		**
$N(2100)$	P_{11}	*	$\Delta(2350)$	D_{35}	*	$\Lambda(2350)$	H_{09}	***	$\Sigma(1915)$	F_{15}	****			
$N(2190)$	G_{17}	****	$\Delta(2390)$	F_{37}	*	$\Lambda(2585)$		**	$\Sigma(1940)$	D_{13}	***	Λ_c^+		****
$N(2200)$	D_{15}	**	$\Delta(2400)$	G_{39}	**				$\Sigma(2000)$	S_{11}	*	$\Lambda_c(2593)^+$		***
$N(2220)$	H_{19}	****	$\Delta(2420)$	$H_{3,11}$	****				$\Sigma(2030)$	F_{17}	****	$\Lambda_c(2625)^+$		***
$N(2250)$	G_{19}	****	$\Delta(2750)$	$I_{3,13}$	**				$\Sigma(2070)$	F_{15}	*	$\Lambda_c(2765)^+$		*
$N(2600)$	$I_{1,11}$	***	$\Delta(2950)$	$K_{3,15}$	**				$\Sigma(2080)$	P_{13}	**	$\Lambda_c(2880)^+$		**
$N(2700)$	$K_{1,13}$	**							$\Sigma(2100)$	G_{17}	*	$\Sigma_c(2455)$		****
									$\Sigma(2250)$		***	$\Sigma_c(2520)$		***
									$\Sigma(2455)$		**	Ξ_c^+, Ξ_c^0		***
									$\Sigma(2620)$		**	$\Xi_c^{\prime +}, \Xi_c^{\prime 0}$		***
									$\Sigma(3000)$		*	$\Xi_c(2645)$		***
									$\Sigma(3170)$		*	$\Xi_c(2790)$		***
												$\Xi_c(2815)$		***
												Ω_c^0		***
												Λ_b^0		***
												Ξ_b^0, Ξ_b^-		*

**** Existence is certain, and properties are at least fairly well explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

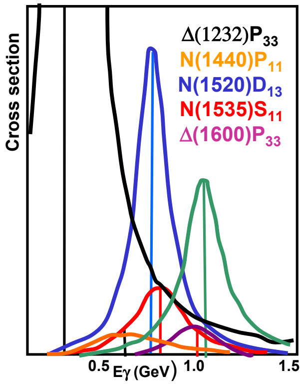
* Evidence of existence is poor.

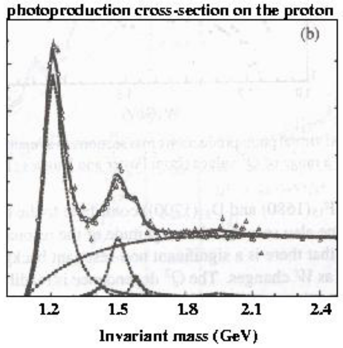
Nucleon excited states

- Most current research exploits advances in EM beam facilities – use meson photoproduction to study the excitation spectrum e.g.

$$\gamma + \mathrm{N} \rightarrow \mathrm{N}^* \rightarrow \mathrm{N} + \pi$$

- Resonances have short lifetimes - therefore broad widths (ΔEΔt ~ ħ)





Multipole amplitudes in meson photoproduction

Cast hadron current matrix elements as a multipole expansion of the Chew, Goldberger, Low and Nambu (CGLN) amplitudes

Multipole amplitudes characterised by the angular momentum quantum Numbers of the initial γN and final meson-baryon system

Multipole amplitudes function of Q^2, W only

$E_{l\pm}{}^{I}$, $M_{l\pm}{}^{I}$ E, M - electric or magnetic multipoles
l - orbital angular momentum of π
I – isospin (see this as well in some papers!)

$$F_1 = \sum_\ell [P'_{\ell+1}(x)E_{\ell+} + P'_{\ell-1}(x)E_{\ell-} + P'_{\ell+1}(x)M_{\ell+} + (\ell+1)P'_{\ell-1}(x)M_{\ell-}$$

$$F_2 = \sum_\ell [(\ell+1)P'_\ell(x)M_{\ell+} + \ell P'_\ell(x)M_\ell]$$

$$F_3 = \sum_\ell [P''_{\ell+1}(x)E_{\ell+} + P''_{\ell-1}(x)E_{\ell-} - P''_{\ell+1}(x)M_{\ell+} + P''_{\ell-1}(x)M_{\ell-}]$$

$$F_4 = \sum_\ell [-P''_\ell(x)E_{\ell+} - P''_\ell(x)E_{\ell-} + P''_\ell(x)M_{\ell+} - P''_\ell(x)M_{\ell-}]$$

$$\boxed{\begin{aligned} F_5 &= \sum_\ell [-(\ell+1)P'_\ell(x)S_{\ell+} + \ell P'_\ell(x)S_{\ell-}] \\ F_6 &= \sum_\ell [(\ell+1)P'_{\ell+1}(x)S_{\ell+} - \ell P'_{\ell-1}(x)S_{\ell-}] \end{aligned}}$$

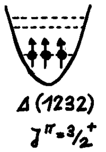
Virtual photons only!!

ℓ	J	L_γ	Notation
0	1/2	1	E_{0+}
1	3/2	2	E_{1+}
1	1/2	1	M_{1-}
1	3/2	1	M_{1+}
0	1/2	1	S_{0+}
1	1/2	0	S_{1-}
1	3/2	2	S_{1+}

Multipole amplitudes

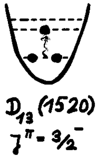
$E_{l\pm}{}^{I}$, $M_{l\pm}{}^{I}$ E, M - electric or magnetic multipoles
l - orbital angular momentum of produced π
I - isospin

$M_{1+}{}^{3/2}$

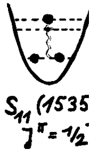


Dominant multipoles

$E_{2-}{}^{1/2}$, $M_{2-}{}^{1/2}$



$E_{0+}{}^{1/2}$, $M_{2-}{}^{1/2}$

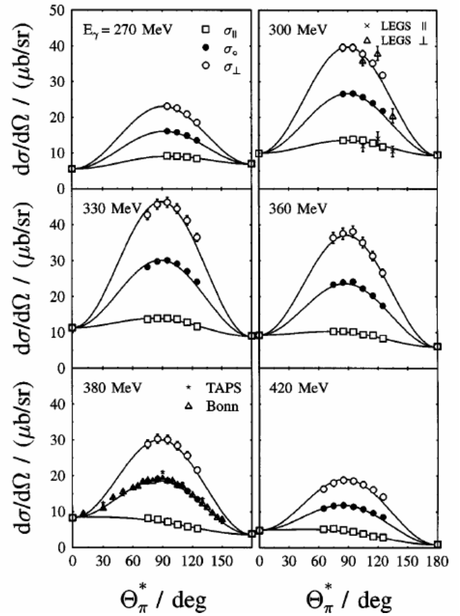


E2/M1 ratio of the p→Δ transition

A good example of the power of Polarisation observables

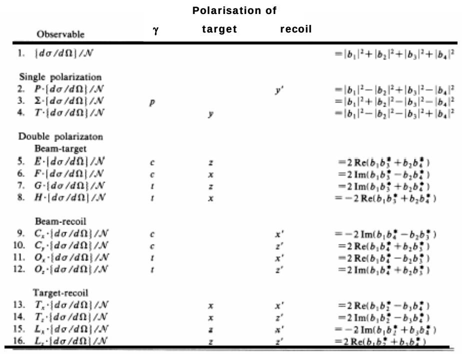
- Use PWA of accurate photon asymmetry, σ data to extract ratio E2/M1 = $E_{1+}^{3/2} / M_{1+}^{3/2}$
- Colour hyperfine interaction between quarks allows E2 transition in p→Δ transition. Otherwise a pure M1 transition
- Indicates "deformation" of nucleon or Δ – Learn about tensor components in effective quark-quark interaction

$E2/M1 = -(2.5 \pm 0.2 \pm 0.2)\%$ **PRL 78 606 (1997)**



Double polarisation observables in meson photoproduction

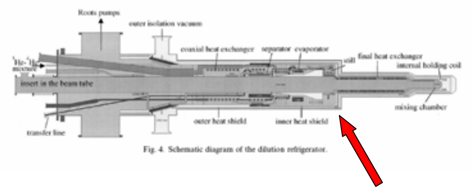
$$\rho_f \frac{d\sigma}{d\Omega} = \frac{1}{2}\left|\frac{d\sigma}{d\Omega}\right|_{\text{unpol}} \{1 - P_\gamma \Sigma \cos 2\varphi + P_x(\mathcal{P}_\gamma F + P_\gamma H \sin 2\varphi) + P_y(T - P_\gamma P \cos 2\varphi) + P_z(\mathcal{P}_\gamma E + P_\gamma G \sin 2\varphi)$$
$$+ \sigma_{x'}[\mathcal{P}_\gamma C_{x'} + P_\gamma O_{x'} \sin 2\varphi + P_x(T_{x'} - P_\gamma L_{z'} \cos 2\varphi) + P_y(P_\gamma C_{z'} \sin 2\varphi - \mathcal{P}_\gamma O_{z'})$$
$$+ P_z(L_{x'} + P_\gamma T_{z'} \cos 2\varphi)]$$
$$+ \sigma_{y'}[P - P_\gamma T \cos 2\varphi + P_x(\mathcal{P}_\gamma G - P_\gamma E \sin 2\varphi) + P_y(\Sigma - P_\gamma \cos 2\varphi) + P_z(P_\gamma F \sin 2\varphi - \mathcal{P}_\gamma H)]$$
$$+ \sigma_{z'}[\mathcal{P}_\gamma C_{z'} + P_\gamma O_{z'} \sin 2\varphi + P_x(T_{z'} + P_\gamma L_{x'} \cos 2\varphi) + P_y(-P_\gamma C_{x'} \sin 2\varphi + \mathcal{P}_\gamma O_{z'})$$
$$+ P_z(L_{z'} - P_\gamma T_{x'} \cos 2\varphi)]\} \ .$$



Observable	γ	Polarisation of target	recoil	
1. $\{d\sigma/d\Omega\}/\mathcal{N}$				$= \|b_1\|^2 + \|b_2\|^2 + \|b_3\|^2 + \|b_4\|^2$
Single polarization				
2. $P \cdot \{d\sigma/d\Omega\}/\mathcal{N}$			y'	$= \|b_1\|^2 - \|b_2\|^2 + \|b_3\|^2 - \|b_4\|^2$
3. $\Sigma \cdot \{d\sigma/d\Omega\}/\mathcal{N}$	p			$= \|b_1\|^2 + \|b_2\|^2 - \|b_3\|^2 - \|b_4\|^2$
4. $T \cdot \{d\sigma/d\Omega\}/\mathcal{N}$		y		$= \|b_1\|^2 - \|b_2\|^2 - \|b_3\|^2 + \|b_4\|^2$
Double polarizaton				
Beam-target				
5. $E \cdot \{d\sigma/d\Omega\}/\mathcal{N}$	c	z		$= 2\,\mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$
6. $F \cdot \{d\sigma/d\Omega\}/\mathcal{N}$	c	x		$= 2\,\mathrm{Im}(b_1 b_3^* - b_2 b_4^*)$
7. $G \cdot \{d\sigma/d\Omega\}/\mathcal{N}$	t	z		$= 2\,\mathrm{Im}(b_1 b_3^* + b_2 b_4^*)$
8. $H \cdot \{d\sigma/d\Omega\}/\mathcal{N}$	t	x		$= -2\,\mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$
Beam-recoil				
9. $C_x \cdot \{d\sigma/d\Omega\}/\mathcal{N}$	c		x'	$= -2\,\mathrm{Im}(b_1 b_4^* - b_2 b_3^*)$
10. $C_y \cdot \{d\sigma/d\Omega\}/\mathcal{N}$	c		z'	$= 2\,\mathrm{Re}(b_1 b_4^* + b_2 b_3^*)$
11. $O_x \cdot \{d\sigma/d\Omega\}/\mathcal{N}$	t		x'	$= 2\,\mathrm{Re}(b_1 b_4^* - b_2 b_3^*)$
12. $O_z \cdot \{d\sigma/d\Omega\}/\mathcal{N}$	t		z'	$= 2\,\mathrm{Im}(b_1 b_4^* + b_2 b_3^*)$
Target-recoil				
13. $T_x \cdot \{d\sigma/d\Omega\}/\mathcal{N}$		x	x'	$= 2\,\mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$
14. $T_z \cdot \{d\sigma/d\Omega\}/\mathcal{N}$		x	z'	$= 2\,\mathrm{Im}(b_1 b_2^* - b_3 b_4^*)$
15. $L_x \cdot \{d\sigma/d\Omega\}/\mathcal{N}$		z	x'	$= -2\,\mathrm{Im}(b_1 b_2^* + b_3 b_4^*)$
16. $L_z \cdot \{d\sigma/d\Omega\}/\mathcal{N}$		z	z'	$= 2\,\mathrm{Re}(b_1 b_2^* + b_3 b_4^*)$

- 4 complex amplitudes - 16 observables in meson photoproduction
- To fix the 4 amplitudes unambiguously need to measure 8 real quantities
- dσ + 3 single polarisation + 5 double polarisation
- Cannot choose from same set

Polarisation observables



Polarised targets at Mainz, Bonn and Jlab

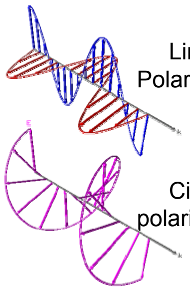
Longitudinal ✓

Transverse in future ??

$\gamma + \mathbf{N} \rightarrow \mathrm{N} + m$

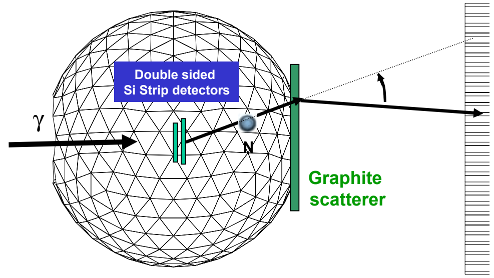
Recoil polarisation

Proposed polarimeter for Crystal Ball



Linear Polarisation ✓

Circular polarisation ✓



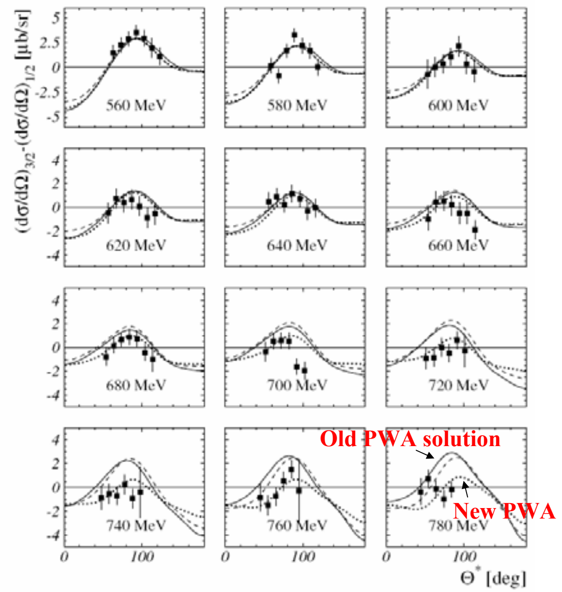
TAPS Detector

528 BaF_2 crystals

E double-polarisation observable

- First measurement obtained recently (PRL 88 232002 (2002)
- Showed need for large (60%!!) revision of properties (e.g. helicity amplitudes) for "well established" D_{13}(1520) resonance

(Mass and width D_{13}(1520) established to ± 10 MeV)



Cx double-polarisation observable

First measurement of beam + recoil observable Cx (2003)

Partial wave
Analyses of
World's data

Poor description of new double polarisation data highlight how resonances and coupling to photons not well constrained by presently available data

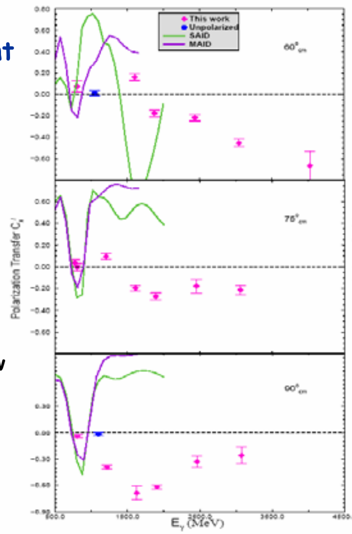


FIG. 11: Top to bottom: Polarization transfer $C_{x'}$ in neutral pion photo-production at θ_{cm} = 60°, 75°, 90° in the fixed lab frame. Only statistical uncertainties are shown. The two curves, SAID [27], and MAID [28] are described in the text.

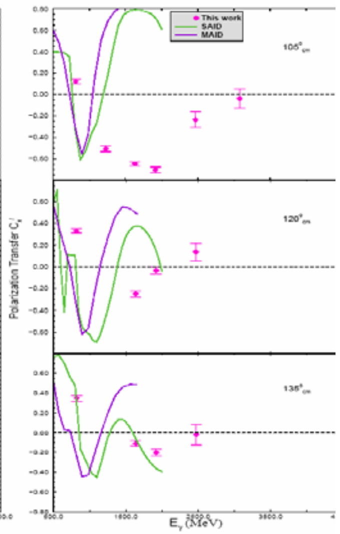
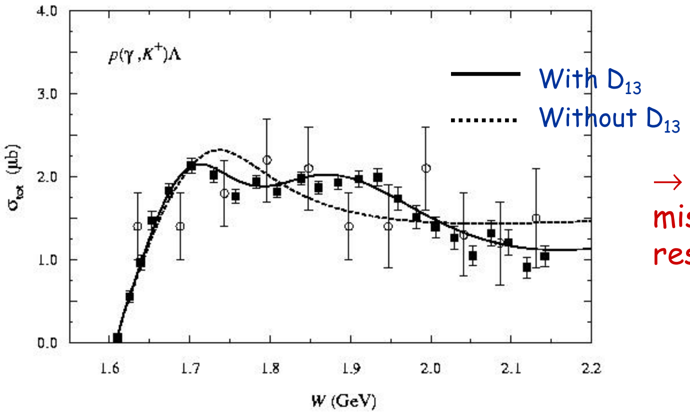


FIG. 12: Top to bottom: Polarization transfer $C_{x'}$ in neutral pion photo-production at θ_{cm} = 105°, 120°, 135° in the fixed lab frame. Only statistical uncertainties are shown. The two curves, SAID [27], and MAID [28] are described in the text.

Also look in other decay channels to find sensitivity to resonances that may not strongly decay into Nπ



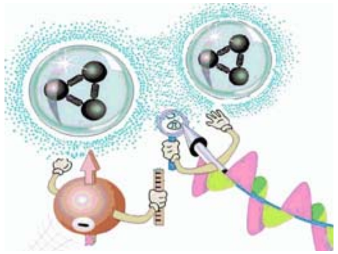
With D_{13}
Without D_{13}

→ "evidence" of missing D13 resonance!

Also Nη production - Only couple to I=1/2 resonances
Also Nω, Nϕ – Missing resonances prefer to decay to vector mesons?

Mart & Benhold, Phys. Rev. C 61 012201(R) (1999)

Nucleon resonance properties



Magnetic moments of nucleon resonances

- Magnetic moments – reflect spatial distribution and dynamics of components of nucleon (μ=iA). Familiar for nucleons (and nuclei)

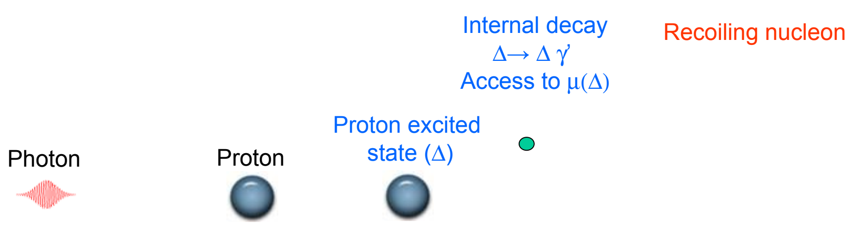
μ_p = 2.7 μ_N
μ_n = -1.9 μ_N

- Average of quark spins and the quark currents - elegant test of various theoretical models of the structure of the hadron
- Long lived particles – can measure precession in a B field
  BUT nucleon resonances are short lived - How can we measure their magnetic moments?

Magnetic moment measurements would be sensitive to the various theoretical descriptions of the nucleon
e.g. Predictions for Δ(1232)

Theory	(μ_{Δ^+}/μ_N)	References
LCQCD	2.2± 0.4	T.M. Aliev *et al.*, Phys. Rev. D **62**, 053012 (2000).
QCDSR	2.19± 0.50	B.L. Ioffe, Nucl. Phys. **B188**, 317 (1981);
		F.X. Lee, Phys. Rev. D (**57**), **1801** (**1998**).
Latt.	2.46± 0.31	D.R. Leinweber *et al.*, Phys. Rev. D **46**, 3067 (1992).
χPT	2.1± 0.2	M.N. Butler *et al.*, Phys. Rev. D **49**, 3459 (1994).
RQM	2.38	F. Schlumpf, Phys. Rev. D **48**, 4478 (1993).
NQM	2.73	K. Hikasa *et al.*, Phys. Rev. D **45**, S1 (1992).
χQSM	2.19	H.C. Kim *et al.*, Phys. Rev. D **57**, 2859 (1998).
χB	0.75	S.T. Hong and D.P. Min, nucl-th/9909004.

Magnetic moment of the 1st excited state of proton (Δ^+)



Internal decay

$\Delta \rightarrow \Delta\,\gamma'$

Access to $\mu(\Delta)$

Recoiling nucleon

Proton excited state (Δ)

Photon

Proton

$\gamma + p \rightarrow \Delta \rightarrow \Delta\gamma'$

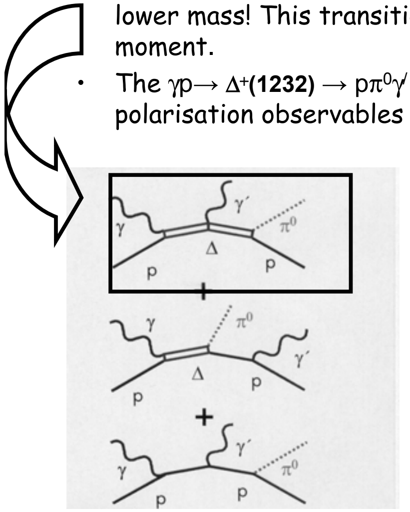
$\quad\hookrightarrow p\pi^0$

γ'

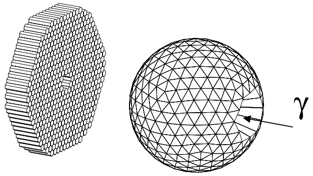
Meson (π, η ..)

Magnetic moment of the 1st excited state of proton (Δ^+)

- Resonances can radiatively decay back to themselves at a lower mass! This transition rate tells you about the magnetic moment.
- The $\gamma p \rightarrow \Delta^+$**(1232)** $\rightarrow p\pi^0\gamma'$ reaction cross sections and polarisation observables sensitive to this quantity.



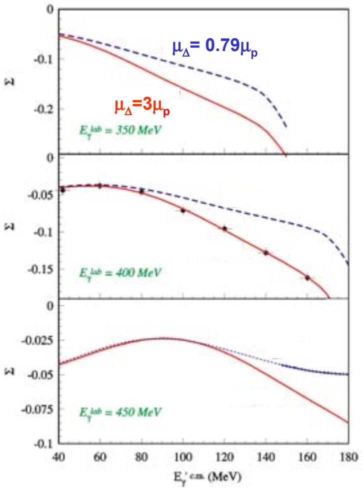
Crystal Ball at Mainz - Ideal detector system to catch the decay photon (γ') from the Δ(1232)

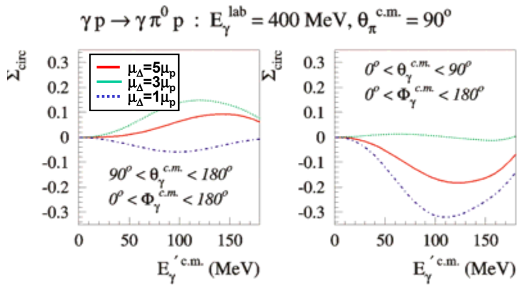


Δ(1232) detected from $p\pi^0$ (or $n\pi^+$) decay
Main Δ(1232) experiment ran at MAMI in 2005
S_{11}(1535) measurement planned next

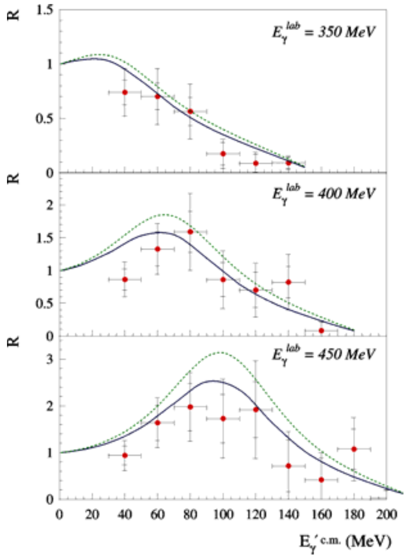
$p(\vec{\gamma},p)\pi^0\gamma$ to measure $\mu(\Delta^+)$

- ×100 in statistics
- measure γ beam polarisation observables
- Both **$p\pi^0$** *and* **$n\pi^+$** decay of Δ^+





Magnetic moment of Δ^+(1232): Pilot measurement



TAPS detectors only

$\gamma p \rightarrow \pi^0 p\ \gamma'$ data

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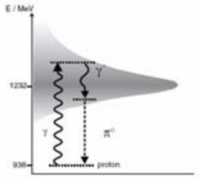
$$\boxed{R = \frac{1}{\sigma_\pi}\frac{d\sigma}{dE'_\gamma}E'_\gamma}$$



🟩 μ_Δ=1

🟦 μ_Δ=7 (units: μ_N)