The Excited States of the Proton

Nuclei have energy levels which can decay by particle emission; so, also, can nucleons. These energy levels are important information on nucleon structure.

The first nucleon resonance was discovered in 1951 in the reaction pion + nucleon $\rightarrow$ pion + nucleon (both scattering and charge exchange) and also in the reaction gamma + nucleon $\rightarrow$ pion + nucleon. This resonance, at a mass of 1236 MeV and of width 120 MeV, dominates low-energy pion scattering. The ratio of π^+ elastic scattering to π^- elastic scattering to charge exchange was found to be 9:2:1, showing the interaction was in a state of pure isotopic spin $I = \frac{3}{2}$. The angular distribution showed that the angular-momentum state was $J = \frac{3}{2}^-$ and the total cross section at the peak of the resonance was $(2J + 1)\pi\lambda\!\!\!^{-2}$ in agreement with a resonance in this state.

Some years later, two further resonances appeared in π^0 photoproduction and were rapidly confirmed in πN scattering; πp total cross-section measurements have been continued to high energies. Further resonances have been found up to 3230 MeV, as shown in the table, which overlap and appear superposed on a large background. Inelastic processes can occur at these high energies so that the resonance parameters are more numerous and it is hard to find all the quantum numbers and to be sure that we have found all the resonances. However, the isotopic spin can be simply determined by a comparison of π^+p and π^-p scattering.

Over the last six years,[1] there have been detailed measurements on the angular distribution of πp elastic and charge-exchange scattering and asymmetries from polarized targets up to the resonance at $M = 1920$ MeV. It is easy to show on general invariance grounds that there are two invariants to be determined at each energy and angle. The staffs of several laboratories have been engaged in this work: Rutherford, England and Saclay, France; Brookhaven, Argonne, and Berkeley in the U.S.A. The measurements are enough to enable a detailed phase-shift analysis to be carried out.

These phase-shift analyses[1] confirm the existence of dominant resonances and assign the rest of the quantum numbers and the inelasticity. The inelasticity of the higher mass states if often less than $\frac{1}{2}$, making the phase shift go through 0° rather 90° at the resonance. The surprise is the discovery of new, weak, highly inelastic resonances at nearby energies. Also, the widths of the "old" resonances are smaller than a superficial look would indicate. Above $M = 1920$ MeV, the phase-shift analyses are not complete. Polarization data and interference effects in backward (180°) pion-proton scattering[2] can give the spins and parities of the dominant states as noted, but cannot assure us that resonances have not been missed.

TABLE OF RESONANCES[a]

Notation	Mass (MeV)	Spin	Parity	Isotopic spin	Width (MeV)
N_α	939	1/2	+	1/2	Stable
	1688	5/2	+	1/2	110
N_γ	1518	3/2	−	1/2	105
	2190	7/2	−	1/2	200
	2650	(11/2)	−	1/2	300
	3030	(15/2)	(−)	1/2	400
	1400	1/2	+	1/2	200
	1570	1/2	−	1/2	130
	1670	5/2	−	1/2	140
	1700	1/2	−	1/2	240
Δ_δ	1236	3/2	+	3/2	120
	1920	7/2	+	3/2	200
	2420	(11/2)	+	3/2	275
	2850	(15/2)	(+)	3/2	300
	3230	(19/2)	(+)	3/2	440
	1670	1/2	−	3/2	180
	2080				40
	2190				40

[a] Listed according to trajectories. Guessed assignments are in parentheses.

The arrangement of the resonances in the table suggests three Regge trajectories (sets of rotational states), N_α, N_γ, Δ_δ. Barger and Cline[2] show that for these trajectories the angular momentum is a linear function of M^2 with the same slope for each trajectory. If this assignment has a simple meaning, the other, weaker resonances presumably lie on parallel trajectories; the presence of the further members of the trajectory can be hidden until a detailed phase-shift analysis is done, just as the presence of the weaker resonances around $M = 1500$–1700 MeV was hidden. Two resonances of width 40 MeV have been reported in bubble-chamber work at 2080 and 2190 MeV,[3] which may or may not be these weak processes.

As in nuclear physics, study of these resonances by photon excitation adds dynamical information. The dominant resonances at $M = 1235$, 1525, 1688, 1920, 2190, and 2420 MeV stand out in photoproduction experiments and a careful study shows that the $M = 1400$, $I = \frac{1}{2}$, $J = \frac{1}{2}^+$ resonance must be excited also. A systematic study, as in πp scattering, is hard. Four (instead of two) invariant amplitudes are needed, and experiments are more difficult. The dominant resonances have also been seen in electroproduction. Here six amplitudes are needed and they vary with momentum transfer.

Some help can be obtained by using the pion-nucleon amplitudes to reduce the number of variables. The 1235-MeV excitation is completely predicted using dispersion relations. The higher resonances with their inelasticity, are not, though a start has been made.[4]

Although we cannot yet ask the general questions, we can sometimes answer some specific questions to check the assignments. For example, $SU3$ puts the nucleon in an octet. The Regge recurrences should be members of an octet also. In a recent experiment[5] this has been verified by showing that the decay for the resonance at $M = 1688$ MeV into ηN is less than 0.027 of the decay into πN; this ratio should be 3 for a 27-plet and can be small only for an octet with a ratio of couplings $N^*N\pi/N^*N\eta$ similar to the ratio for the nucleon $NN\pi/NN\eta$.

An early, erroneous discovery of the ηN decay of the $M = 2650$ resonance put this as a 27-plet. The corrected data similarly place this resonance as a member of an octet.

The quark model suggests that the photo-excitation of the $M = 1235$ resonance is a pure magnetic dipole and that the form factor of its electro-excitation is equal to the magnetic iso-vector form factor seen in elastic electron scattering, $G_{MV}(q^2)$. These are so far borne out by experiment[6,7] although a 2% admixture of electric quadrupole intensity is suggested by photoproduction.[8] The model also predicts that all the resonances on the same trajectory be excited solely by magnetic excitation. This is an exciting question for the future. Electroproduction experiments[7] assign a large longitudinal (Coulomb) excitation for the next two resonances (1525 and 1688 MeV) in agreement with experiment.

Symmetry models prohibit photo-excitation of certain resonances.[9] The assignment (on a quark model) of the 1400-MeV, $\frac{1}{2}^+$ resonance is in doubt. This resonance seems not to be photoproduced from hydrogen, but it could be photoproduced from deuterium according to some assignments.

The knowledge we now have is enough to stimulate a dynamical model which will, in turn, stimulate more experiments. Walecka[10] has tried a simple model which yields the excited states at the right masses and predicts the longitudinal (Coulomb) form factors. This model treats the pion cloud as a classical field and searches for normal-mode oscillations, similar to the collective model in nuclear physics. This model is crude, but it brings out the major features of the electromagnetic excitation of these resonances and relates them to the nucleon size.

This note is restricted to the excited states of the nucleon although there exist many excited hyperons. Less is known in detail about these states; we do not have a phase-shift analysis as we do for πN scattering, so we have probably missed many resonances. Indeed $SU3$ predicts hyperon resonances to match the nucleon resonances. The study of the excited states of the nucleon is likely to continue to be more intensive simply because of the relative ease of study. Although it appears often that there is much that is unknown about the excited states of the nucleon, the progress so far attained is impressive in view of the complexity of the problem.

RICHARD WILSON

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