Parity Doubling and highly excited mesons

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Abstract

Glozman has proposed that highly excited mesons and baryons fall into parity doublets, and that the \( f_4(2050) \) on the leading Regge trajectory should have a nearly degenerate \( J^{PC} = 4^{-+} \) partner. A re-analysis of Crystal Barrel data does not support this idea. A likely explanation is that centrifugal barriers on the leading trajectory allow formation of the \( L = J - 1 \) states, but are too strong to allow \( L = J \) states. Two new polarisation experiments have the potential for major progress in meson spectroscopy.

PACS: 14.40.-n, 11.30.Qc

Keywords: mesons, resonances

There are two objectives in this Letter. The first is to report a search for parity doubling on the leading Regge trajectory for \( I = 0, \ C = +1 \) mesons and relate the negative result to the centrifugal barrier. The second objective is to draw attention to the simplicity of formation experiments compared to production experiments, and point out that two polarisation measurements have the potential for major improvements in spectroscopy of light mesons.

Iachello first drew attention to parity doubling in baryon spectra, i.e. the fact that states with a given \( J \) are approximately degenerate between negative and positive parity [1]. Glozman pointed out in 2002 that many mesons observed above 1900 MeV by Crystal Barrel show similar approximate parity doubling [2]. He relates this to restoration of chiral symmetry at high excitations. Glozman and Swanson [3] predicted \( J^{PC} = 3^{++} \) mesons roughly degenerate with \( \rho_3(1690) \), likewise \( 4^{-+} \) degenerate with \( f_4(2050) \). Swanson extended this prediction to include \( 3^{++} \) states near 1700 MeV.

Observed states do not presently agree with parity doubling on the leading (highest) Regge trajectory, though approximate parity doubling is observed for many states on daughter trajectories. The well known \( \rho_3(1690) \) appears strongly in many sets of data, but there is no known \( 3^{+-} \) or \( 3^{++} \) partner with isospin \( I = 0 \) or 1 near 1700 MeV. The high spins of these states should make them conspicuous; all four appear strongly from 2025 to 2048 MeV, but not at 1700 MeV. The \( a_2(1320) \) is not accompanied by a nearby \( 2^{-+} \) state; instead, the \( \pi_2(1670) \) appears prominently in many channels as the lowest \( I = 1 \) \( J^{PC} = 2^{-+} \) state. In Crystal Barrel data, the \( f_4(2050) \) appears prominently, but the lowest observed \( 4^{-+} \) state is at 2328 \( \pm \) 38 MeV [4]. Afonin points out similarities of the observed spectrum to that of the hydrogen atom [5].

The \( \pi, \eta \) and \( K \) are abnormally light, whereas their excitations are not, so there is clearly some degree of chiral symmetry restoration at high mass, though precisely how this works is not yet agreed. Before plunging into detail, let us clarify how the partial wave analysis treats orbital angular momentum \( L \), since Glozman argues it is not a good quantum number. Glozman argues that the \( f_4(2050) \), for example, involves relativistic quarks obeying the Dirac equation and coupling equally to \( ^3F_4 \) and \( ^3H_4 \). However, decays of mesons involve final states which are not highly relativistic. As one example, \( \bar{p}p \rightarrow f_4(2050) \rightarrow a_2(1320)\pi \), where the \( a_2 \) has \( \beta = 0.43 \). Decay amplitudes of mesons are written in terms of Lorentz invariant tensors. It is necessary to
introduce Blatt-Weisskopf centrifugal barriers which depend on $L$ [6]; explicit formulae for $L=1$ to 5 are given at the end of Section 2.1 of Ref. [7]. The orbital angular momenta are expressed in terms of 3 or 5 powers of beam momentum, constructed so that tensors for different $L$ are orthogonal. A decay amplitude with orbital angular momentum $\ell = 3$ in the final state is constructed likewise in terms of the centre of mass momentum in the decay and the usual spin 2 tensor for $a_2 \rightarrow \eta \pi$. The treatment of orbital angular momentum is fully relativistic, though initial and final states are not highly relativistic. Decay widths of mesons depend on $L$ and are suppressed for high $L$.

The partial wave analysis includes coupling constants $g$ of $4^+$ states with $L = 3$ and 5 using a fitted ratio $r_{J=4} = g_{L=5}/g_{L=3}$. In principle this ratio can have both magnitude and phase. However, relative phases are $< 20^\circ$ in well determined cases for all $J$. The natural interpretation is that a resonance has a unique phase because of multiple scattering, but the same phase for all decay channels. Since phases are consistent with zero, they are set to zero so as to minimise the number of fitted parameters.

Above a mass of 1900 MeV, there are two complete towers of $I = 0$, $C = +1$, $2s+1L_J$ resonances in eight sets of $\bar{p}p$ data, which are fitted with consistent parameters in all channels [4]. That analysis was done fitting Crystal Barrel data for $\bar{p}p \rightarrow \eta\pi^0\pi^0$, $\pi^0\pi^0$, $\eta\eta$ and $\eta'\eta'$ at nine beam momenta; it included extensive measurements of both differential cross sections and polarisations for $\bar{p}p \rightarrow \pi^+\pi^-$ from two experiments [8] and [9]. That analysis also fixed the mass and width of $\eta_2(2267)$ from Crystal Barrel data on $\bar{p}p \rightarrow \eta'\pi^0\pi^0$ [10]. Later data on $\bar{p}p \rightarrow 3\eta$ provided a clear peak for $\eta(2320)$ [11]. The present analysis is made to all of these data, fixing masses and widths of resonances at values from Table 2 of Ref. [4], except for the $\eta(2320)$.

The polarisation data continue to play a vital role. They determine imaginary parts of interferences between triplet partial waves, while differential cross sections determine real parts of interferences. This phase sensitivity identifies all $3H$, $3F$ and $3P$ amplitudes unambiguously, whatever their phases and traces out Argand diagrams. Polarisation also separates $3F_2$ and $3P_2$ mesons cleanly, because they have orthogonal Clebsch-Gordan coefficients for spin dependent amplitudes.

This combined analysis has now been rerun, trying to force in a $4^{-+}$ resonance near 2060 MeV and $5^{++}$ near 2310 MeV. These are called $\eta_1$ and $h_5$ in the notation of the Particle Data Group [12]. Formulae are identical to those of Ref. [4]; a more expansive presentation of formulae is given in my review paper [13]. Breit-Wigner resonances of constant width are fitted to each of 21 $I = 0$ resonances and 6 $I = 1$ resonances, (plus tails of two resonances below the mass range, playing only a small role as backgrounds). Each resonance requires a complex coupling constant fitted to each channel of data. A further detail is that $\pi^0\pi^0$, $\eta\eta$ and $\eta'\eta'$ data are fitted to SU(3) formulae [13], where $s\bar{s}$ components turn out to be small.

There is definite evidence for $\eta_4(2328)$ in $\bar{p}p \rightarrow \eta\pi^0\pi^0$ data in decays to $[a_0(980)\pi]_{\ell=4}$, $[a_2(1320)\pi]_{\ell=2}$ and $[f_2(1275)\eta]_{\ell=2}$. Their branching ratios are 1.0:0.28:0.05. In present data, the $1G_4$ partial wave interferes only with $\bar{p}p$ singlet states, since $\bar{p}p \rightarrow \pi\pi$ polarisation involves only triplet states ($G$ parity $= +1$ for $\pi\pi$). Two well identified resonances $\eta_2(2267)$ and $\eta(2320)$ interfere with $\eta_4(2328)$ and require that it has resonant phase variation. The $\eta_2(2267)$ is one of the most prominent resonances, appearing as a clear peak in $f_2(1270)\eta'$ [10] and also in $[f_2(1270)\eta]_{\ell=2}$, $[a_0(980)\pi]_{\ell=2}$ and $[f_0(1500)\eta]_{\ell=2}$. The $\eta(2320)$ appears as a strong peak in $\bar{p}p \rightarrow 3\eta$ in the $f_0(1500)\eta$ channel [11] and also in $\eta\pi^0\pi^0$ data. The $\eta_4(2328)$ contributes a highly significant improvement of 558 in log likelihood to the combined analysis. Log likelihood
Figure 1: Intensities fitted to (a) $\eta_4(2328)$ alone (full curve) and the coherent sum of $\eta_4(2328)$ and $\eta_4(2060)$ (dashed curve), (b) likewise for $h_5(2500)$ and $h_5(2310)$, (c) $f_4(2050)$ (full curve) and $f_4(2300)$ (dashed).

is defined so that a change of 0.5 is equal to a change in $\chi^2$ of 1 for the high statistics available. In assessing the significance level of changes in log likelihood, it is necessary to use formulae for $\chi^2$ allowing for the number of degrees of freedom for each resonance.

The full curve of Fig. 1(a) shows the line-shape of $\eta_4(2328)$ normalised to 1 at its peak, which lies at $\sim 2375$ MeV because of the centrifugal barrier for production from $\bar{p}p$. In searching for the parity partner of $f_4(2050)$, the $\eta_2(2030)$ and $\eta_2(2010)$ likewise act as interferometers. The $\eta_2(2030)$ is visible by eye in Crystal Barrel data on $\bar{p}p \rightarrow \eta 3\pi^0$ [14] and is also required by $\eta\pi^0\pi^0$ data [15]. The $\eta(2010)$ of Crystal Barrel is observed in three decays and is also conspicuous in BES 2 data on $J/\Psi \rightarrow \gamma pp$ [16] with a slightly lower mass of 1970 MeV.

If a hypothetical $\eta_4(2060)$ is added to the analysis with $\Gamma = 250$ MeV, decays to $[a_0(980)\pi]_{\ell=4}$ and $[a_2(1320)\pi]_{\ell=2}$ give small improvements $< 40$ in log likelihood; decays to $[f_2(1275)\eta]_{\ell=2}$ are negligible. There is no optimum when the mass and width of $\eta_4(2060)$ are scanned and it improves log likelihood only by a total of 58. An improvement $> 40$ is normally required for any amplitude to be regarded as definitive. The origin of this choice is that there are always some correlations between $\bar{p}p$ singlet amplitudes with $J^{PC} = 0^{-+}, 2^{-+}$ and $4^{-+}$. In differential cross-sections, the presence of $4^{-+}$ depends on terms like $\cos^6 \theta$ and $\cos^8 \theta$, where $\theta$ is the decay angle of the resonance in its rest frame. However, there is further confusion from triplet final states with high spins, which contribute terms in the differential cross section up to $\cos^8 \theta$. An extensive simulation shows that a clean identification of an amplitude requires a change in $\ln L > 40$. Table 2 of Ref. [4] quotes changes in $\ln L$ for all observed resonances in $\eta\pi^0\pi^0$ data; the $2^+$ states listed there have much higher log likelihood changes in $\bar{p}p \rightarrow \pi^+\pi^-$. The dashed curve on Fig. 1(a) shows what happens: interferences of $\eta_4(2060)$ with $\eta_4(2328)$ enhance the intensity slightly, but with no significant structure near 2060 MeV. The likely explanation of the enhancement is that the centrifugal barriers are slightly wrong. The Blatt-Weisskopf formula is derived by approximating it with an equivalent square barrier. That gives too sharp a rise of the barrier with momentum. What is desirable is a barrier corresponding to the Coulomb part of the confining potential with a short-range cut-off or Gaussian smearing. However, no simple recipe suitable for fitting data exists. Adding $\eta_4(2060)$ can improve the detailed line-shape of $\eta_4(2328)$. Presently, all decays of all resonances are fitted with the same
barrier radius 0.83 ± 0.03 fm. The barrier radius for the \( \bar{p}p \) channel is larger, 1.11 ± 0.10 fm, probably due to the 3 quarks in each nucleon. If the barrier radii for \( J^P = 4^- \) are set free, the fit with \( \eta(2060) \) alone is midway between full and dashed curves.

A similar test has been made including a hypothetical \( ^1H_5 \) state \( h_5(2310) \). The logic behind this test is that parity doubling predicts a \( 5^+ \) partner for \( \rho_5(2350) \) which has \( J^{PC} = 5-- \). The small mass difference between \( u \) and \( d \) quarks then predicts a \( 5^{++} \) state nearly degenerate with \( 5^{+} \). For \( ^1H_5 \), the situation is less well defined experimentally. Fig. 1(b) shows as the full curve a fitted \( h_5(2500) \) with \( \Gamma = 370 \text{ MeV} \). However, this mass is well above the highest experimental data at 2410 MeV, so the ‘resonance’ is simply a parametrisation of the required \( H \) wave. The dashed curve shows the effect of adding a \( h_5(2310) \) with \( \Gamma = 250 \text{ MeV} \). Again, constructive interference enhances the fitted signal, but there is no peak below 2410 MeV where data stop. Fig. 1(c) shows the line-shapes of \( f_4(2050) \) and \( f_4(2310) \), which are observed clearly in \( \bar{p}p \to a_2\pi \) and \( f_2\eta \) \[13\]. Note that the \( f_4(2050) \) actually has a mass of 2018 ± 11 MeV in the Particle Data Tables. It peaks at 2080 MeV in present data because of centrifugal barriers.

Table 1 summarises the prominent \( ^3F_i, ^3D_3 \) and \( ^3P_2 \) states. Spin-splitting is mostly tensor and agrees within errors with that predicted by perturbative QCD; spin-orbit splitting is small. The \( ^3D_3 \) state at 1982 MeV is particularly prominent in polarisation data, and is clearly lower than the \( F \) states. The \( ^3P_2 \) state is lower still; this is the \( f_2(1910) \) of the Particle Data group \[12\]. This pattern is repeated near 2270 MeV. Splitting between \( F, D \) and \( P \) mesons is consistent with a stronger centrifugal barrier in \( F \) states, which therefore resonate higher in mass. A linear extrapolation through \( ^3P_2, ^3D_3 \) and the centroid of \( F \) states predicts a hypothetical \( G \) state at 2067 ± 10 MeV. This is rounded down to 2060 MeV to maximise effects of centrifugal barriers and \( ^1H_5 \) is likewise taken at 2310 MeV.

| \( ^{2S+1}L_J \) | Mass (MeV) | Mass (MeV) |
|-----------------|------------|------------|
| \( f_4 \equiv ^3 F_4 \) | 2018 ± 6   | 2283 ± 17  |
| \( f_3 \equiv ^3 F_3 \) | 2048 ± 8   | 2303 ± 15  |
| \( f_2 \equiv ^3 F_2 \) | 2001 ± 10  | 2293 ± 13  |
| \( h_3 \equiv ^1 F_3 \) | 2025 ± 20  | 2275 ± 25  |
| \( \rho_3 \equiv ^3 D_3 \) | 1982 ± 14  | 2260 ± 20  |
| \( f_2 \equiv ^3 P_2 \) | 1934 ± 20  | 2240 ± 15  |

Table 1: Masses of some \( I = 0, C = +1 \) states from combined Crystal Barrel and PS172 data.

Could the \( \eta(2060) \) and \( h_5(2310) \) both be invisible because they are attenuated by centrifugal barriers? It is instructive to compare the hypothetical \( \eta(2060) \) and the \( f_4(2050) \), which is clearly visible with an intensity 10% of \( \eta\pi^0\pi^0 \) data. It is necessary to fold the line-shapes of both resonances with the effects of centrifugal barriers for both \( \bar{p}p \) and decays. The result is that the \( f_4(2050) \) (with mass 2018 MeV) peaks at 2080 MeV and the \( \eta(2060) \) would peak at 2150 MeV. The intensity of a Breit-Wigner resonance is

\[
I(s) = \frac{\Gamma_{\bar{p}p}(s)\Gamma_{\text{decay}}(s)}{|M^2 - s|^2 + |MT_{\text{total}}(s)|^2}
\]

(1)

and \( \Gamma_{\bar{p}p} \) is proportional to the centrifugal barrier. The ratio \( \Gamma_{\bar{p}p}(4^-)/\Gamma_{\bar{p}p}(J^P = 4^+) \) at their peaks is 0.48. Conversely, the effect of decay centrifugal barriers is to enhance the ratio...
Figure 2: Regge trajectories of some of the $I = 0$, $C = +1$ states.

$\Gamma_{\text{decay}}(4^-)/\Gamma_{\text{decay}}(4^+)$ to $2.4$ for $[a_2\pi^0]_{\ell=2}$ at their peaks and to $1.9$ for $[f_2\pi^0]_{\ell=2}$. For decays of $\eta_4(2060)$ to $[a_0(980)\pi^0]_{\ell=4}$, the lower mass of $a_0(980)$ compared with $a_2(1320)$ almost exactly cancels the difference between them due to decay barriers. The net effect of centrifugal barriers is to reduce the intensity of $\eta_4(2060)$ by a factor $0.6$. This is significant but not disastrous. If one makes the assumption that $\eta_4(2060)$ has the same branching fractions as $\eta_4(2328)$, it should be detectable with an improvement in log likelihood $> 40$ if its central mass is as low as 1980 MeV. Experimentally, its intensity is no larger than 4\% of $f_4(2050)$.

It is of course possible to argue that decay widths may be fortuitously too weak for these hypothetical states to be detectable. However, experience for other $J^P$ is that the lowest states usually appear strongly. The $f_2(2001)$ (mostly $^3F_2$ in $\bar{p}p$) and $f_3(2048)$ each contribute 10\% in intensity to $\bar{p}p \to \eta\pi^0\pi^0$; $h_3(2025) \equiv 1^1 F_3$ is $5\%$ of $\bar{p}p \to \omega\eta$. The $\rho_3(1690)$ and $\pi_2(1670)$ appear prominently in many channels. However, it is puzzling that the $\eta_4(2328)$ contributes only 2.1\% of $\eta\pi^0\pi^0$ data, while its isospin 1 partner $\pi_4(2230)$ contributes a huge 59\% of all $\bar{p}p \to \omega\pi^0$ data. For both $\pi_4(2230)$ and $\eta_4(2328)$, dominant decays are with $L = 4$ to the lowest available final states $\omega\pi$ and $a_0(980)\pi$. This may be attributed to good overlap of wave functions at the impact parameter of $L = 4$ $\bar{p}p$ interactions. Then a likely decay mode for $\eta_4(2328)$ (and $\eta_4(2060)$) is to $[\pi\rho]_{\ell=4}$, but presently no data are available.

Suppose we take at face value the absence of parity partners for $f_2(1270)$, $\rho_3(1690)$, $f_4(2050)$ and $\rho_5(2330)$. The Regge trajectories of Fig. 2 show that it costs $\sim 250 - 300$ MeV for every step in $J$. The confining potential has a shallow minimum between the centrifugal barrier at small radius and attraction at long range. The inference from data is that this shallow minimum is insufficient to form an $\eta_4(2060)$ resonance with $L = 4$. Important further information from polarisation data is that the $f_4(2050)$ couples to $\bar{p}p$ with a ratio of $^3H_4$ and $^3F_4$ waves $r_4 = 0.00 \pm 0.08$; for $f_4(2300)$, $r_4$ rises to $2.7 \pm 0.5$. Still no second $^3H_4$ state appears near 2300 MeV; the first known H state is $f_6(^3H_6)$ at 2465 $\pm$ 50 MeV. Likewise $\rho_3(1982)(^3D_3)$ has $r_3 = 0.006 \pm 0.008$ and there is no evidence for a $^3G_3$ resonance until 2300 MeV. These results show that centrifugal barriers suppress states with $L = J + 1$, while allowing them for $L = J - 1$ on the leading trajectory.

If an additional $H$ state orthogonal to $f_4(2050)$ exists near a mass of 2.1 GeV, it is likely to be narrow. There is no evidence for narrow peaks in total cross sections, which have been
measured in small steps of mass \([17, 18]\).

A different line of argument is that an \(\bar{n}n\) meson may be modelled as a flux tube with quarks attached to the ends. Most of the angular momentum is carried by the flux tube, not the quarks; the angular momentum is then an observable, though relativistic. The spins of the quarks couple via the Dirac equation at the ends of the flux tube. However, to generate a \(4^-\) state still requires a flux tube with \(L = 4\) compared with \(L = 3\) for \(f_4(2050)\).

In principle a search can also be made for \(4^-\) states with \(I = 0\) and \(1\) near 2000 MeV. However, for \(C = -1\) states there are no polarisation data, making separation of \(2^-\) and \(1^-\) states difficult and hindering detection of \(4^-\) states severely near 2000 MeV. There is an obvious need for further polarisation data.

Let us now discuss further experiments. The formation process \(\bar{p}p \rightarrow \text{resonance} \rightarrow \text{decays}\) used by Crystal Barrel is much simpler than production reactions. The high quality polarisation data on \(\bar{p}p \rightarrow \pi^+\pi^-\) demonstrate that it is a practical proposition to find a complete spectrum of \(I = 0\) \(C = +1\) states from 1910 to 2400 MeV. The \(I = 1\) \(C = -1\) spectrum is almost complete, but \(3S_1\) and \(3D_1\) states are poorly identified. The phase sensitivity available from polarisation data is absent in production experiments; as a result, only strong resonances appearing as peaks or states interfering with well established resonances can be identified. Polarisation data are crucial, as in baryon spectroscopy.

Two key experiments are needed, each with a \(4\pi\) detector, good \(\gamma\) detection and transverse polarisation. At FLAIR, the \(\bar{p}\) ring under construction at GSI with momenta up to 2 GeV/c, measurement of polarisation from 360 to 1940 MeV/c for neutral final states would be straightforward in detectors like Belle, Babar and Cleo C, which are all now idle; the detector does not need a magnetic field. The low momenta are crucial in probing the lower sides of resonances clustered near 2000 MeV.

I have made a Monte Carlo simulation based on existing differential cross sections and the Crystal Barrel detector as an example [19]. It shows that polarisation data for \(\bar{p}p \rightarrow \omega\pi^0, \omega\eta\) and \(\omega\eta\pi^0\) (detecting \(\omega\) in \(\pi^0\gamma\) as in Crystal Barrel) could complete the \(I = 1\) \(C = -1\) and \(I = 0\) \(C = -1\) states; they would also allow checks on parity doubling of \(a_4(2040)\). Data for \(\eta\pi^0\) and \(\eta\eta\pi^0\) would probably complete the \(I = 1\) \(C = +1\) states, which already resemble \(I = 0\) \(C = +1\), but with one discrete ambiguity in the \(\eta\pi\) solution. They would allow tests for \(4^-\) states near \(f_4(2050)\). Polarisation for \(\bar{p}p \rightarrow \eta\pi^0\pi^0\) would check the present \(I = 0\) \(C = +1\) spectrum. They would provide interferences between singlet \(\bar{p}p\) states and known triplet states, hence improving the work presented here.

The technology of polarised targets is well developed and costs are modest. Background from nitrogen nuclei in an ammonia target are estimated by the Monte Carlo simulation to be \(\leq 10\%\) after kinematic fitting, and are of similar magnitude to cross-talk between final states. That has been demonstrated in an experiment at LAMPF using a polarised beam and polarised target to study \(pp \rightarrow pn\pi^+\) [20]. The Fermi momentum in the nucleus is \(\sim 120\) MeV/c along each of \(x\), \(y\) and \(z\) axes, compared with errors \(\leq 20\) MeV/c for reconstructed photons. Seven of the nine momenta used by Crystal Barrel with \(\bar{p}\) in flight were taken in 4 calendar months, so running time is quite reasonable for a high return of physics.

A related programme at VEPP2 [21] and VEPP4 [22] (Novosibirsk) using CMD2 and SND detectors and transversely polarised electrons could separate \(3S_1\) and \(3D_1\) amplitudes. Transverse polarisation is a linear combination of \(s_z = \pm 1\). For \(3D_1\) components, they produce highly distinctive azimuthal asymmetries of the form \(\cos \phi\) and \(\cos 2\phi\), where \(\phi\) is the azimuthal angle
between the final state and the plane defined by the initial polarisation and the beam. Clean identification of $J^P = 1^{--}$ states and the ratios of $^3D_1$ and $^3S_1$ amplitudes would provide quantitative information relevant to chiral symmetry restoration. If $1^{--}$ states follow the pattern of other $J^{PC}$, a $^3S_1$ state recurrence of the $\rho$ is expected near 1300 MeV and two states $^3S_1$ and $^3D_1$ near 1700 MeV. Above this the experimental situation is confused. Information on $I = 0$ and $s\bar{s}$ states is scanty. Such data above 1900 MeV would improve greatly the analysis of Crystal Barrel data with $C = -1$.

Those readers interested in the existing data should consult my review [13], where a full set of references and listings of all observed decay modes are given in Tables 2, 5, 7 and 8. Listings of the Particle Data Group do not include observed decay channels nor complete lists of the reactions studied. Only final combined analyses of all data are referenced. For $J = 1$, $C = +1$, tabulations are out of date (despite promptings) and the final combined analysis [23] is not referenced nor masses and widths determined there. The casual reader could be misled into believing that the listings of Crystal Barrel states are single observations of each resonance. In fact, the great majority have been observed in two or more decays and several in four or five decays and up to 8 sets of data.

Clarification of the spectroscopy of light mesons and baryons is crucial to a full understanding of QCD and confinement, which is one of the basic phase transitions of physics.

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