How to complete light meson spectroscopy to $M = 2410$ MeV/c^2

D V Bugg [1]
Physics Department, Queen Mary, University of London, London E1 4NS, UK

Abstract

A measurement of transverse polarisation in $\bar{p}p \to$ all-neutral final states would almost certainly determine a complete set of partial wave amplitudes over the mass range 1910 to 2410 MeV. This should identify all resonances in this mass range. The experiment is technically straightforward and cheap by present standards.

One simple experiment has an excellent chance of completing spectroscopy of light mesons up to a mass of 2410 MeV. It requires a measurement of transverse polarisation in reactions

$$\begin{aligned}
\bar{p}p \quad &\to \quad \pi^0\eta,\ 3\pi^0 \text{ and } \pi^0\eta\eta, \qquad \eta \to \gamma\gamma \qquad &(1)\\
&\to \quad \omega\pi^0 \text{ and } \omega\pi^0\eta, \qquad \omega \to \pi^0\gamma \qquad &(2)\\
&\to \quad \omega\eta \text{ and } \omega\pi^0\pi^0, \qquad \omega \to \pi^0\gamma \qquad &(3)
\end{aligned}$$

This is a formation experiment of the form $\bar{p}p \to$ resonance $\to A + B$, where A and B are decay channels.

Data for differential cross sections already exist from the Crystal Barrel experiment at LEAR at eight beam momentum from 900 to 1940 MeV/c. Results and technical details are reviewed in Ref. [1]. There are also extensive measurements of polarisation in $\bar{p}p \to \pi^+\pi^-$ from two earlier CERN experiments [2] [3]. The importance of the polarisation data are illustrated vividly by the fact that a unique set of partial wave amplitudes is found for $I = 0$ and $C = +1$. Simulations from existing data show that reaction (1) would likewise give a unique set of amplitudes for $I = 1$ $C = +1$; reactions (2) and (3) would do the same for both $C = -1$ states. There would also be high statistics for $\bar{p}p \to \pi^0\pi^0$, $\eta\eta$ and $\eta\pi^0\pi^0$; polarisation data for these channels would check the present partial wave analysis for $I = 0$, $C = +1$.

The $\bar{p}p$ system contains singlet S and triplet T spin configurations; $d\sigma/d\Omega = |S|^2 + |T|^2$. The formula for $P_Y d\sigma/d\Omega$ is $Tr(A^*\sigma_Y A)$, where σ is the Pauli matrix and A the amplitude. For polarisation normal to the production plane, $Pd\sigma/d\Omega$ determines the imaginary part of interferences; for sideways spin (in the plane of scattering), it determines the real part of exactly the same interferences. Sideways polarisation P_S is zero for 2-body final states because momentum conservation demands that initial and final states lie in a plane. But for 3-body final states it is non-zero; it depends on $\sin\phi$, where ϕ is the azimuthal angle between the plane of polarisation and the decay plane of the 3-body final state.

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[1]email: d.bugg@rl.ac.uk

A major virtue of polarisation data is that they are phase sensitive. Without polarisation data, there are always twofold ambiguities in relative phases between amplitudes. The constraint of analyticity removes some of these ambiguities, but not all. With polarisation, they are eliminated; Argand diagrams for amplitudes can be traced unambiguously as a function of beam momentum. The phase sensitivity of polarisation data reduces errors on measured masses and widths by typically a factor 2. A further important point is that there are interferences between singlet and triplet states. It is already clear there are large amplitudes from $f_4(2050)$, $f_4(2300)$, $\rho_3(1982)$, $a_4(2005)$, $a_4(2255)$, $\rho_3(1982)$ and $\rho_3(2260)$. These serve as powerful interferometers for the determination of small partial waves. With the aid of dispersion relations or analytic functions fitting the data, the partial wave amplitudes are unique without further measurement of A or R parameters, as in πN scattering.

A further crucial point is that triplet states such as $^3P_2$ and $^3F_2$ have orthogonal combinations of Clebsch-Gordan coefficients; they are cleanly separated by polarisation data and $d\sigma/d\Omega$. This separation is presently vital missing information for all of reactions (1)-(3).

A frozen-spin target is required with the cryostat along the beam direction. Existing technology is perfectly adequate. A Monte Carlo simulation based on existing data shows that backgrounds from heavy nuclei are $\sim 10\%$; experience in Ref. [3] and experiments at LAMPF [4] confirm this. A modest beam intensity of $\sim 6 \times 10^4$ $\bar{p}$/s and a 3cm target of NH_3 gives ~ 100 good events/s. Statistics of $\sim 50K$ events per channel are required; this is hardest to achieve in the channel $\omega\eta$, but is possible with a running time of ~ 10 days/momentum (assuming 70% running efficiency). Twelve beam momenta are required.

Angular coverage of 98% of 4π is vital, because of partial waves up to $L = 5$ in the initial $\bar{p}p$ state. The existing Crystal Barrel detector needs to complete its present series of experiments on photoproduction first, but would then be ideal for the required measurements on meson spectroscopy.

Analysis of the mass range 1910 to 2050 MeV requires further measurements of $d\sigma/d\Omega$ at ~ 360 MeV/c (the lowest beam momentum without stopping $\bar{p}$ in the target), ~ 470, 600 and 750 MeV/c; these data were scheduled to be taken at LEAR, but the machine closed just 2 weeks before the data could be taken. Measurements from a polarised gas-jet target are unrealistic since $d\sigma/d\Omega$ must be normalised accurately between momenta; also the geometry of the detector would pose serious problems. Therefore an extracted beam such as those which existed at LEAR is necessary, but is technically not difficult. Modifications to the existing Crystal Barrel detector and polarised target would be minor, so this is not an expensive experiment.

A detail which is clear from existing Crystal Barrel data is that $\bar{p}p$ interactions produce $s\bar{s}$ states only very weakly. Data on $\bar{p}p \to \pi^0\pi^0$, $\eta\eta$ and $\eta\eta'$ determine mixing angles of states observed in these channels between $n\bar{n}$ and $s\bar{s}$ [5]; they are mostly zero within experimental errors. Even the prominent $f_2(1525)$ is hard to detect in $\bar{p}p$ interactions.

It is already known that high mass states have strong decays to final states such as $\pi\omega(1650)$ and $\pi\omega_3(1670)$. There is therefore a hope that similar decays would reveal the states presently missing in the mass range 1600-1900 MeV, but no guarantee. There are missing $^3D_2$ and $^1S_0$ states for both isospins and also the exotic $I = 0$ $J^{PC} = 1^{-+}$ state. A general remark is that production experiments of the form $\pi N \to X + N$ have the

serious disadvantage that the exchanged meson can have non-zero spin, necessitating the determination of both the exchanged spin and the spin of X. Generally this is impossible or at best guesswork, hence explaining why experiments of this type have not been able to observe most of the states above 1900 MeV.
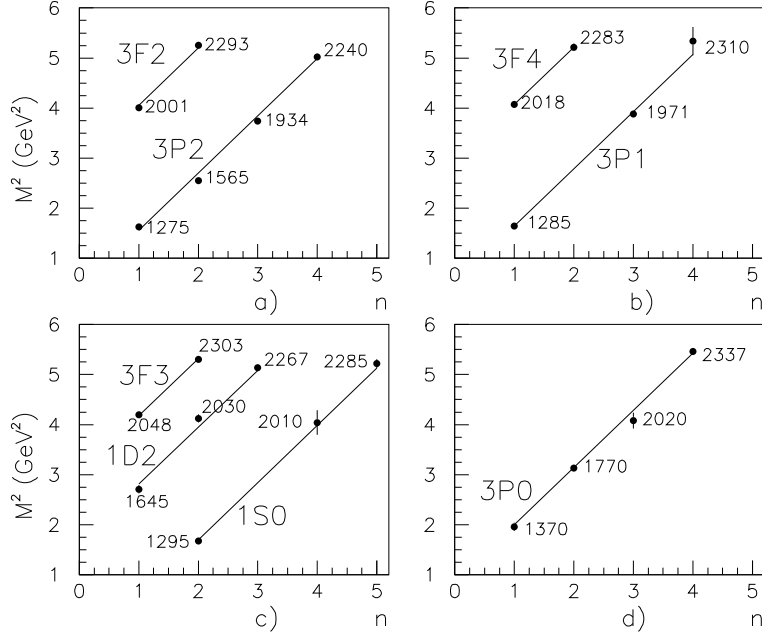

Figure 1: Trajectories of $I = 0$, $C = +1$ mesons; n is the radial excitation number; masses are shown in MeV.

Confinement is one of the fundamental phase transitions of physics. Completing the spectroscopy of light mesons and baryons should therefore be a fundamental priority. It is already clear that Chiral Symmetry Breaking plays a decisive role at low masses. At high masses, there is a striking regularity of observed states illustrated in Fig. 1 for $I = 0$ $C = +1$ states. All of these states except the $^3P_0$ state (and one $^1G_4$ state, not shown) have been observed in at least three channels of data, see Ref. [1] for details. They are listed by the Particle Data Group under 'Other Light Mesons' [6] with the remark that they have been observed only by a single group and thus need confirmation. Confirmation is indeed needed, and could be achieved in the proposed experiment. Several of the states in the regular listings have also been identified only by one group and likewise need confirmation.

Existing states fall close to parity doubling, e.g. $J^{PC} = 2^{-+}$ and 2^{++}, so an understanding of the extent of Chiral Symmetry restoration at high masses is imporant. Glozman [7] argues in favour of full restoration, on the basis that quarks are highly relativistic at such momenta, so J should be a good quantum number. However, present data show definite mass shifts of ~ 80 MeV between F and P states and ~ 40 MeV between F and D states. This leads Afonin [8] to argue that orbital angular momentum L is a better label, as in the hydrogen atom. The physical explanation may be that L is carried by the rotating flux-tube, which breaks above a certain value of L. More precise determinations of masses and widths would clarify the experimental situation greatly.

In summary, this is a straightforward experiment and the technology exists. It should be done.

References

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