EXPERIMENTAL MESON SPECTROSCOPY

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## I. Overview of Meson Spectroscopy

### Models

A classif ation of species, were it be of plants, animals, elements or hadrons, is one of the important scientific studies of our time. Proper classification often reveals the organization of the structure which forms these element. One typical example which is very close to our heart is the "Periodic Table o lements", which revealed a clear atomic structure to us. At the time, when the numbers of hadrons are rapidly increasing, it is natural for us physicists to search for a specific signature in these particles and start the game of the classification and to build the model by which these hadrons are formed.

Now let us review a history of these models briefly.

Extending an earlier model which showed that a pion, only known meson at that time is a combination of nucleons and antinucleons, the SAKATA model[1] was introduced in 1956. In this model the fundamental particles were assumed to be a triplet (p, n, Λ) and their antiparticles. Namely:

$$\pi^+ = p\bar{n} \quad , \quad \pi^- = \bar{p}n$$
$$K^+ = \bar{\Lambda}p \quad , \quad K^- = \Lambda\bar{p}$$
$$\Sigma^+ = \Lambda p\bar{n} \quad , \quad \Sigma^- = \Lambda\bar{p}n, \text{ etc.}$$

In 1958-60, a model based on a SU(3) representation using SAKATA triplet was introduced. In this model, a meson can be represented by a product of the 3 and $3^*$ representation of the triplet as $3 \times 3^* = 8 \pm 1$. Thus it was found that the mesons could be represented by an Octet (one triplet, two doublet and one singlet) and a singlet. For instance, in $0^-$ nonet, pseudoscaler mesons can be grouped into five sub-multiplets, i.e. a triplet ($\pi^+\pi^o\pi^-$), two doublets ($K^+$, $K^o$) and ($\bar{K}^o$, $K^-$), one singlet (η) and to a remaining isotropic signlet (η'). This early SU(3) representation, in spite of it seeming success for mesons, failed miserably for baryons. A baryon, in this model, is thought to be a composite of two fundamental baryon and one anti-baryon of SAKATA triplet. Corresponding SU(3) representation is $3 \times 3 \times 3^* = 15 + 6^* + 3 + 3$. The octet and decuplet which are thought to characterize the classification of baryons are obviously missing.



In their "eight-fold way", Ne'eman[2] and Gell-Mann,[3] independently, proposed that the symmetry group SU(3) was universally applicable to baryon as well, and invariance under SU(3) was of basic importance. Their argument was that, if we observe that both baryons and mesons were represented by the octet representation experimentally, then we should accept this as a fact and not be reluctant to use it, even if we could not see how to construct the baryon octet from the basic SAKATA triplet.

These considerations lead a way into "quark model".[3,4] In this model the SAKATA triplet was replaced by an imaginary fundamental triplet and its conjugate. The element of the triplet is named "quark", and has a very interesting characteristic of carrying a baryon number 1/3. The property of the fundamental triplet (quarks) and its conjugate (anti-quarks) are shown in Table I-1. In this representation mesons are constructed by quark-antiquark pairs, similarly to early SU(3) representation using SAKATA triplet, as

$$3 \times 3^* = 8 + 1.$$

Baryon, however, can be constructed using three quarks, leading to a representation

$$3 \times 3 \times 3 = 10 + 8 + 8 + 1$$

which contain two octets, one decaplet and one singlet. Success of the quark model, with SU(3) representation, as one of the ways to explain the hadron spectroscopy as well as the hadron dynamics gained the popularity since. However, acknowledgement of quarks as a constituent of hadron did not come until the discovery of J/ψ particle and so-called November Revolution.

Soon after the discovery of a new state J/ψ,[5] one at Brookhaven and the other at SLAC, a picture emerged such that the narrowness of the width of such high mass state is due to an existence of new fundamental entity who's strong decay into ordinary meson was suppressed by a need to annihilate these entities to create new fundamental entities (OZI Rule). This statement already implies the existence of such entity as a pseudo-physical constituent of a meson. The remarkable agreement between predictions[6] given to a family of states related to J/ψ on an assumption that they are bound states of massive quark and antiquark (charmonium) and discovery of narrow and higher mass state ψ', ψ", χ's in a good agreement with prediction[7] gave strong support for the notion of quark as a building block of these particles as well as other hadrons. The success of the charmonium spectroscopy, backed by the notion already existed for old mesons and baryons, and other accumulating experimental evidences[8] lead to our currently conventional view that a meson is a bound state of a quark and antiquark and a baryon is a bound state of three quarks.

A quark is spin 1/2 Fermion and is distinguished from one another by "flavor". At present, existence of five flavors (up, down, strange, charm and bottom) is known and the sixth (top) highly probable. As was the case with earlier "imaginary quarks" each of these quarks have 1/3 unit of baryon number. As far as we know, the quark is a massive point-like object whose mass depends on it's flavor. Some of the other characteristics of the quarks are listed in Table I-2. Quarks are thought to carry also a strong interaction charge called "color". There are three such colors, which we take as red, yellow and blue. An exchange of gluons which couple to color was introduced to explain quark-quark force. This coupling is necessary to explain experimental observation that the force between quark and quark in a baryon seems to have the same sign as between quark and antiquark in a meson. As a principle, it is assumed that the color is confined, i.e. only bound states which are colorless can be seen.

## Mesons

As discussed above, a meson is assumed to be a bound state of quark-antiquark pairs, each quark having spin 1/2. Coupling this to the orbital angular momentum L of the pair, total angular momentum of the system $\vec{J} = \vec{L} + \vec{S}$ can be formed. Leaving the bottom quark aside for a time being as it is so heavy and its observation is so new, four flavors of quarks and four flavors of antiquarks can form 16 combinations of quark-antiquark pairs for each L, S and J combination. Furthermore, additional sets of 16 can be found for radially excited states of each S, L and J combination. Since the quark and antiquark have opposite intrinsic parity, a meson thus formed has parity $p = (-1)^{L+1}$. For self conjugate meson states which are formed by $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$ and their linear combinations the charge conjugate quantum number $C = (-1)^{L+S}$.

As stated above four flavors of quarks give rise to 16 combinations. With fifth quark the combination becomes 25 and with sixth quark the combination becomes 36. If u and d quarks are degenerate in mass and have the same strong interaction, there is an SU(2) symmetry of strong interaction,



or isotopic spin invariance. Similarly, to the extent that u, d and s quarks may be regarded as degenerate and have the same strong interaction, one sees SU(3) symmetry. Thus, 16 states formed by a combination of four flavors of quarks and antiquarks may be represented by multiplets corresponding to the irreducible representations of these groups as shown in Table 3.

## Quark Configuration in Mesons

For the sake of this discussion, we will first consider the classical mesons which are formed by original three quarks (u, d, s) and then expand it to "charm" mesons. In the first case, only the octet and one of the singlet in Talbe 3 can be occupied, forming a series of nonets of given L, S, J and P assignment. In what follows, we try to assign the mesons we know to two well known nonet.

## The Pseudoscaler Nonet ($0^{-+}$, ground state)

L=0, S=0, J=0, P= -1, i.e. $^1S_o$ state. The quark contents and some of the properties are listed below for conventional mesons.

| Mesons | Mass (MeV/$c^2$) | I | $I_z$ | S | quark combination |
|---|---|---|---|---|---|
| $\pi^+$ | 140 | 1 | 1 | 0 | $\bar{d}u$ |
| $\pi^o$ | 135 | 1 | 0 | 0 | $(\bar{u}u-\bar{d}d)/\sqrt{2}$ |
| $\pi^-$ | 140 | 1 | -1 | 0 | $d\bar{u}$ |
| $K^+$ | 494 | 1/2 | 1/2 | 1 | $\bar{s}u$ |
| $K^o$ | 498 | 1/2 | -1/2 | 1 | $\bar{s}d$ |
| $\bar{K}^o$ | 498 | 1/2 | 1/2 | -1 | $s\bar{d}$ |
| $K^-$ | 494 | 1/2 | -1/2 | -1 | $s\bar{u}$ |
| $\eta$ | 549 | 0 | 0 | 0 | $(\bar{u}u+\bar{d}d-2\bar{s}s)/\sqrt{6}$ |
| $\eta'$ | 958 | 0 | 0 | 0 | $(\bar{u}u+\bar{d}d+\bar{s}s)/\sqrt{3}$ |

Extending the list of pseudoscaler to charm member, we can add the following assignments:

| Mesons | Mass ($MeV/c^2$) | I | $I_z$ | S | C | quark combinations |
|---|---|---|---|---|---|---|
| $D^+$ | 1868 | 1/2 | 1/2 | 0 | 1 | $\bar{d}c$ |
| $D^o$ | 1868 | 1/2 | -1/2 | 0 | 1 | $\bar{u}c$ |
| $F^+$ | (?) | 0 | 0 | 1 | 1 | $\bar{s}c$ |
| $\bar{D}^o$ | 1868 | 1/2 | 1/2 | 0 | -1 | $d\bar{c}$ |
| $D^-$ | 1868 | 1/2 | -1/2 | 0 | -1 | $u\bar{c}$ |
| $F^-$ | (?) | 0 | 0 | -1 | -1 | $s\bar{c}$ |
| $\eta_c$ | $\sim$3000 (?) | 0 | 0 | 0 | 0 | $c\bar{c}$ (?) |

As can be seen from the listings above, $0^-$ meson group is quite complete except for $\eta_c$ which has been predicted to have a mass of $\sim$ 3 GeV. Two more states in this group, $F^+$ and $F^-$ are also not found to date.

The Vector Mesons ($1^{--}$ states)

I=0, S=1, J=1, P= -1, i.e. $^3S_1$ state. The quark contents and some property are listed below for the conventional vector mesons.

| Mesons | Mass($MeV/c^2$) | I | $I_z$ | S | quark content |
|---|---|---|---|---|---|
| $\rho^+$ | 770 | 1 | 1 | 0 | $u\bar{d}$ |
| $\rho^o$ | 770 | 1 | 0 | 0 | $(u\bar{u}-d\bar{d})/\sqrt{2}$ |
| $\rho^-$ | 770 | 1 | -1 | 0 | $d\bar{u}$ |
| $K^{*+}$ | 892 | 1/2 | 1/2 | 1 | $u\bar{s}$ |
| $K^{*o}$ | 892 | 1/2 | -1/2 | 1 | $d\bar{s}$ |
| $\bar{K}^{*o}$ | 892 | 1/2 | 1/2 | -1 | $s\bar{d}$ |
| $\bar{K}^{*-}$ | 892 | 1/2 | -1/2 | -1 | $s\bar{u}$ |
| $\omega$ | 783 | 0 | 0 | 0 | $(u\bar{u}+d\bar{d})/\sqrt{2}$ |
| $\phi$ | 1019 | 0 | 0 | 0 | $s\bar{s}$ |



An assignment of $s\bar{s}$ to $\phi$ is to explain $\phi$ properties like $\phi \rightarrow K\bar{K}$ being the dominant decay mode (84%). In view of the fact that the next largest decay mode is $\pi^+\pi^-\pi^o$ (14%), $\phi$ is thought to have a small amount of $(u\bar{u})$ and $(d\bar{d})$ components mixed in it. Extending this list further to include charmed particles, we get:

| Mesons | Mass ($GeV/c^2$) | I | $I_z$ | S | C | quark combination |
|---|---|---|---|---|---|---|
| $D^{*+}$ | 2008 | 1/2 | 1/2 | 0 | 1 | $\bar{d}c$ |
| $D^{*o}$ | 2006 | 1/2 | -1/2 | 0 | 1 | $\bar{u}c$ |
| $F^{*+}$ | (?) | 0 | 0 | 1 | 1 | $\bar{s}c$ |
| $\bar{D}^{*o}$ | 2006 | 1/2 | 1/2 | 0 | -1 | $d\bar{c}$ |
| $D^{*-}$ | 2008 | 1/2 | -1/2 | 0 | -1 | $u\bar{c}$ |
| $F^{*-}$ | (?) | 0 | 0 | -1 | -1 | $s\bar{c}$ |
| $J/\psi$ | 3097 | 0 | 0 | 0 | 0 | $c\bar{c}$ |

From the known mass of various mesons and assigned quark combinations for them, and with a certain simplistic assumption on the binding energy between quark and antiquark pairs, one can estimate the so-called "constituent masses" for each quark flavor. They are:

$$M_u = M_d \sim 385\ MeV/c^2$$
$$M_s \sim 500\ MeV/c^2$$
$$M_c \sim 1550\ MeV/c^2$$
$$M_b \sim 5000\ MeV/c^2$$

A simple example of mass relationship can be verified.

$$M_{K^*} - M_\rho = M_s - M_d = 122\ MeV/c^2$$
$$M_\omega - M_\rho = M_d - M_d = 12\ MeV/c^2$$
$$M_\phi - M_\rho = 2M_s - 2M_d = 249\ MeV/c^2$$
$$M_\phi = 2M_s = 1019\ MeV/c^2$$
$$M_{J/\psi} = 2M_c = 3097\ MeV/c^2$$

These simple mass relationships work very well for the vector mesons. Regretably, however, it does not work well for the pseudoscaler mesons.

In the examples above, we saw the relatively simple and orderly classification of mesons which are attributed to the s-wave quark-antiquark system. The quark, being a spin 1/2 Fermion, these combinations can be extended to P-wave (L=1, $J^{PC}=2^{++}$, $1^{++}$, $0^{++}$ and $1^{+-}$), D-wave (L=2, $J^{PC}$ = $3^{--}$, $2^{--}$, $1^{--}$ and $2^{-+}$), and so on, as is the case in the atomic spectroscopy. As it will be discussed later, P state is in a reasonably good shape except for the $0^{++}$ nonet. There are many states yet to be found for D state.

Likewise, one would expect radially excited states which are states with same $J^{PC}$ but in general with higher mass. The clearest example of the radial excitation can be seen in a series of ψ's discovered by the $e^+e^-$ collision at SPEAR detector. They observed a narrow state ψ'(3684) which clearly is a radial excitation of J/ψ(3100). Two other states ψ(4030) and ψ(4415) which were observed in $e^+e^-$ experiment also were considered to be the radially excited state of J/ψ(3100). In the case of "old" mesons, the situation is more confused because of a large width which usually is common to high mass state. There, however, is reasonably convincing examples, of radial excitation making us to believe that the radial excitation does exist in the spectrum of the mesons. Assuming a certain potential for quark-antiquark interactions (taking a simple harmonic oscillator for now) the energy level of the states (or mass of mesons) is expected to follow the relationship

$$E \propto (2n + L)m = Nm$$

where n is a radial excitation quantum number.

Figure I-1 shows the energy levels of the $q\bar{q}$ mesons.



TABLE I-1

"Quark" and "Antiquark" Properties

| Name | $q_1$=p | $q_2$=n | $q_3$=λ | $\bar{q}_1=\bar{p}$ | $\bar{q}_2=\bar{n}$ | $\bar{q}_3=\bar{\lambda}$ |
|---|---|---|---|---|---|---|
| I | 1/2 | 1/2 | 0 | 1/2 | 1/2 | 0 |
| $I_z$ | 1/2 | -1/2 | 0 | -1/2 | 1/2 | 0 |
| B | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 |
| Q | 2/3 | -1/3 | -1/3 | -2/3 | 1/3 | 1/3 |
| J | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 |
| S | 0 | 0 | -1 | 0 | 0 | +1 |

TABLE I-2

Known Fractionally Charged Quarks

They all have baryon number 1/3 and spin $1/2^+$

| Flavor | u | d | s | c | b |
|---|---|---|---|---|---|
| old name | p | n | λ | - | - |
| B | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 |
| $J^P$ | $1/2^+$ | $1/2^+$ | $1/2^+$ | $1/2^+$ | $1/2^+$ |
| I | 1/2 | 1/2 | 0 | 0 | |
| $I_z$ | 1/2 | -1/2 | 0 | 0 | |
| Q | +2/3 | -1/3 | -1/3 | +2/3 | -1/3 |
| S (strangeness) | 0 | 0 | -1 | 0 | 0 |
| C (charm) | 0 | 0 | 0 | 1 | 0 |
| b (bottomness) | 0 | 0 | 0 | 0 | 1 |

TABLE I-3

Quark Antiquark Pairs and SU(2) and SU(3) Multiplet

| Flavor Combinations | | | SU(2) | SU(3) |
|---|---|---|---|---|
| $\bar{d}u$ | $(\bar{u}u-\bar{d}d)/\sqrt{2}$ | $d\bar{u}$ | 3 | 8 |
| $\bar{s}u$ | $\bar{s}d$ | | 2 | |
| | $s\bar{d}$ | $s\bar{u}$ | 2 | |
| | $(\bar{u}u+\bar{d}d-2\bar{s}s)/\sqrt{6}$ | | 1 | |
| $\bar{d}c$ | $\bar{u}c$ | | 2 | 3 |
| $\bar{s}c$ | | | 1 | |
| | $u\bar{c}$ | $d\bar{c}$ | 2 | 3 |
| | | $s\bar{c}$ | 1 | |
| | $(\bar{u}u+\bar{d}d+\bar{s}s)/\sqrt{3}$ | | 1 | 1 |
| | $\bar{c}c$ | | 1 | 1 |



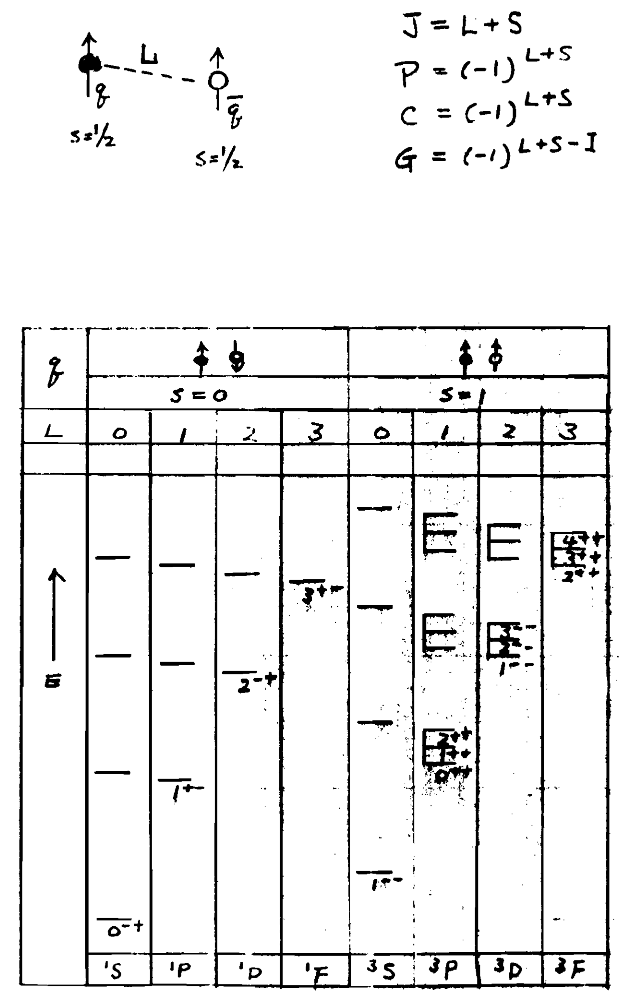


Fig I-1

## II. Current Status of the Meson Spectroscopy (light quarks)

The current situation on the classification of mesons is shown in Fig. II-1. In this figure, mesons are arranged according to their principle quantum number $N = (2n + L)$ where n is radial excitation, and L orbital angular momentum of quark-antiquark system. In this representation, energy of the level (or mass) should show an increase as N and L increases. A resultant large box is divided into 4 x 4 matrix by $J^{PC}$ of the nonet and isospin of the multiplets which should occupy small boxes.

States with N=0

They are the ground state of L=0 states. As discussed in detail in Chapter I, mesons in both $0^{-+}$ and $1^{--}$ nonets are well known and classification is well established.

States with N=1

These states include the lowest state of L=1 levels.

[$2^{++}$ nonet] This is another nonet in which the mesons are well established and classification well understood. From the $K\bar{K}$ decay which dominates f' decay branching ratio, f' is considered to be $\phi$ like object.

[$1^{++}$ nonet] Situation on this nonet had not been clear for some time with rather ambiguous experimental situation with $A_1$, $Q_1$ and $Q_2$. Earlier experimental studies of these mesons were in the diffractive channel with high Deck type background. With recent high statistics experiments and studies in the non-diffractive channel with smaller background, the situation has improved.

$A_1$: A number of analyses of diffractively produced $\rho\pi$ final state required a resonance in the mass region 1.2 $\sim$ 1.4 GeV with a width of 300 MeV.[9] However, there has been no agreement in its mass value among the experiments. In addition, these analyses failed to observe a change of the phase which is typical of most of resonance production. Recent high statistics bubble chamber experiment[10] on $K^-p \to \Sigma^-(3\pi)^+$ has observed a $3\pi$ enhancement in the backward direction with $J^P = 1^+$. With a resonance interpretation, the mass and the width was determined to be 1.04 GeV and 230 MeV respectively. Decay of $\tau^-$ ($\tau^- \to \nu\pi^-\pi^+\pi^-$)[11] gave further evidence on this evasive $A_1$. This $3\pi$ system is predominantly in the $J^P = 1^+$ $\pi\rho$ state and Breit Wigner resonance fit gives mass of 1.1 GeV and width 400 MeV. In summary, evidence for the existence of $A_1$ is now strong. Only problem is that its mass and width is



yet to be determined. The most recent report at Geneva Conference on the result of phase shift analysis on 600,000 events on the reaction $\pi^-p \to (3\pi)p$ put its mass value at 1.28 GeV and P $\sim$ 300 MeV.

$Q_A$: Recent analyses[12] of data on $K\rho$ and $K^*\pi$ resonances showed that the observed $K\rho$ resonance at $\sim$ 1280 MeV ($Q_1$) and $K^*\pi$ resonance at $\sim$ 1400 MeV ($Q_2$) were indeed a mixture of the SU(3) state $Q_A$ - $Q_B$. Namely,

$$|Q_1\rangle = \cos\theta_Q|Q_A\rangle + \sin\theta_Q|Q_B\rangle$$
$$|Q_2\rangle = \sin\theta_Q|Q_A\rangle + \cos\theta_Q|Q_B\rangle$$

These SU(3) analyses of the decay coupling of $Q_1$ and $Q_2$ present a coherent picture. In a recent partial wave analysis, a clear resonant peak for $Q_2$ was observed in $J^P = 1^+$ $K^*\pi$ partial wave (see section III-7)

D: This relatively narrow enhancement has been observed in $K\bar{K}$ and $\eta\pi^+\pi^-$ decay modes.[13] A recent partial wave analysis of the data from $\pi^-p \to \pi^+\pi^-\eta n$ showed a prominent peaking of the amplitude and phase variation in I=0 $J^P = 1^+$ $\rho\pi$ wave confirming this assignment.

E: Recent experiment[14] on $\pi^-p \to K^\pm K^o_s\pi^\mp n$ at 3.9 GeV/c showed a clear E signal at the mass of 1431 ± 3 MeV and a width of 26 ± 8 MeV, establishing the existence of this resonance well. However, a determination of its spin-parity is still to be done before a definite assignment of this meson to this multiplet can be made. The width observed is rather narrow when it is compared with SU(3) prediction for that of $1^{++}$ state. The narrowness of the width may be due to the fact that this resonance lies very close to $KK^*$ threshold and if so, the narrowness is not necessarily an evidence against the assignment of $J^{PC} = 1^{++}$.

[$1^{+-}$ nonet] In this nonet, B is relatively well established by early bubble chamber experiments. B is also observed in the backward production from $K^-p$ interactions in the $\pi^+\omega$ spectrum.[15] $Q_B$, which is an SU(3) state of $Q_1$ and $Q_2$ is also become clear from analyses of $K\rho$ and $K^*\pi$ data.[12] However, two singlet states are completely missing.

[$0^{++}$ nonet] The assignment of mesons with $J^{PC} = 0^{++}$ is not clear yet, although recent experiments shed some light on this nonet. Problem is that many of these states are wide and the production cross section are generally small. Therefore, the experiment is very difficult and in addition the results of the analysis depends critically on the specific parameterization used. The multiplet assignment of these mesons are of extreme importance since we might expect first evidence of glueballs (a color singlet pair of vector gluons) or multiquark exotic mesons.[16]

Rather well-known states in this nonet are δ(980) I=1, which is seen in ηπ and $K\bar{K}$ decay and $S^*(980)$ I=0 which is seen in $K^o_sK^o_s$ decay. ε(1300) I=0 is also quoted to be seen according to the Particle Data Table. Recent analysis on $K^-K^o_s$ system[17] indicates a broad enhancement in s-wave amplitude indicating possible I=1 resonance at ∿ 1300 MeV. Another analysis[18] on $K^o_sK^o_s$ found enhancement in the same mass region. Authors of this analysis seems to favor I=1 for this enhancement, but on somewhat weak ground. From an amplitude analysis of $\pi^-p \to K^-K^+n$ and $\pi^+n \to K^-K^+p$, I=0 and I=1 amplitude can in principle be separated. However, due to an ambiguity, there are eight solutions. A solution[19] of these eight, which is most favored by the authors, contains I=0 s-wave enhancement at 1300 MeV. The author claims that the $S^*(1300)$ which is seen in $K^+K^-$ channel is not the same as ε(1300) which, according to SU(3) consideration, should predominantly decay into $\pi^+\pi^-$ and negligible in $K\bar{K}$.

Additional contributions to the confusing state of $0^{++}$ mesons came from the partial wave analysis of ππ and Kπ data done recently. One of the analyses on $\pi^+\pi^-$ system[20] allows a broad ε(1200), a narrow $S^*(993)$ and ε(800) resonances. Another analysis[21] on ππ, πK and KK data favors ε(800), $S^*(1005)$ and ε'(1540) and allows δ(980) and possibly δ'(1300) as candidates of 4 quark bound states. This analysis allows, in addition, one and only one I = 1/2 state K(1510).

Summarizing the above, we have the following candidates to fill the nonet boxes.

| | | | |
|---|---|---|---|
| I=1 | δ(980) | M = 980 MeV | Γ ∿50 MeV |
| | δ'(1300) | M ∿1300 MeV | broad |
| I=1/2 | K(1510) | M ∿1500 MeV | Γ ∿260 MeV |
| I=0 | ε(800) | M ∿800 MeV | Γ ∿1000 MeV |
| | $S^*(980)$ | M ∿980 MeV | Γ ∿40 MeV |
| | ε(1300) | M ∿1300 MeV | Γ ∿200-400 MeV |
| | $S^*(1300)$ | M ∿1300 MeV | broad |
| | ε'(1540) | M ∿1540 MeV | Γ ∿250 MeV |



Here, one should note that ε(1300) and $S^*(1300)$ could be the same state in spite of the statement above on their distinction by the decay mode. Due to its enormous width, ε(800) is also doubtful. As it can be seen above, there are more candidates to fill the multiplet box than we can accommodate except for I = 1/2. One assignment which can be made is δ, K, ε(800), $S^*(980)$ for triplet, doublet and two singlets. This assignment, however, gives some difficulty of a very large mass difference between K(1540) and δ(980) compared to the other nonets. Another difficulty is that the ratio $g_{KK}/g_{\pi\pi}$ for $S^*$ is ∿ 2 instead of $\sqrt{2/3}$ expected of SU(3) singlet assignment. A notion of two $0^{++}$ nonets, one of $q\bar{q}$ bound state and the other of $qq\bar{q}\bar{q}$ bound state was offered by Jaffe.[22] This assignment classifies the $0^{++}$ meson as follows:

| Multiplet | Name | Candidate | Major Quark Content |
|---|---|---|---|
| I=1 | δ(980) | δ(980) | $u\bar{d}s\bar{s}$ |
| I=1/2 | K(800-1100) | Not found | $u\bar{s}d\bar{d}$ |
| I=0 | ε(700) | ε(800) | $u\bar{u}d\bar{d}$ |
| I=0 | $S^*(993)$ | $S^*(980)$ | $s\bar{s}(u\bar{u}-d\bar{d})/\sqrt{2}$ |
| I=1 | δ'(1270) | δ'(1300) | $u\bar{d}$ |
| I=1/2 | K'(1400) | K(1510) | $u\bar{s}$ |
| I=0 | ε(1300) | ε(1300) | $(u\bar{u}+d\bar{d})/\sqrt{2}$ |
| I=0 | S'( ? ) | $S^*(1300)$? | $s\bar{s}$ |

Trouble with these assignments, however, is that there is no known K state in the mass range 800-1100 MeV and that the mass of $q\bar{q}$ mesons in $0^{++}$ nonet becomes somewhat higher than those of $2^{++}$ and $1^{++}$ nonet which is hard to accept in the quark-antiquark context. In summary, there is a lot to be understood for $0^{++}$ nonet and further experiments are being awaited.

<u>States with N=2</u>

$J^{PC} = 3^{--}$, $2^{--}$ and $2^{-+}$ mesons in this group naturally belong to nonets with L=2, whereas mesons with $J^{PC} = 0^{-+}$ belong to the radial excitation state of L=0. Mesons with $J^{PC} = 1^{--}$ can be assigned to either L=0 or L=2.

[$3^{--}$ nonet] There are three well established mesons; i.e. g(1680), $K^*(1780)$[23] and ω(1670) all have $J^{PC} = 3^{--}$ and belong to this nonet.

[$2^{--}$ nonet] There are no mesons known to fall in this category.

[$2^{-+}$ nonet] Although not well established, there is an evidence for $A_3$ with $J^{PC}$ assignment of $2^{-+}$ seen as a 300 MeV wide bump of $f\pi$ s-wave system in the diffractive process $\pi N \rightarrow (3\pi)N$. Like $A_1$, $A_3$ is rather evasive resonance. Although resonant behavior is seen in many analyses,[24] the resonance-like change of phase is missing in most of them. To date, there is no other meson found for this nonet.*

[$1^{--}$ nonet] There are collections of experiments which claim K resonances with natural spin-parity in the mass region of 1700 MeV. If any one of these resonances become well established with $J^P$ assignment of $1^-$, it can be assigned either L=0 or L=2. Recent partial wave analysis on the data from an MPS experiment on $K^-p \rightarrow K^o\pi^+\pi^-n$ at 6 GeV(39) shows an enhancement at $\sim$ 1500 MeV and $\sim$ 1800 MeV both in $1^{--}$ state. Recently a broad enhancement of I=1 was observed in $e^+e^- \rightarrow 4\pi^\pm$ state centered around 1550 MeV.[25] For I=0 state, $e^+e^-$ experiment found two narrow resonances, one with 3 standard deviation at 1660 MeV ($\Gamma \sim$ 40 MeV) in $3\pi$ and $5\pi$ final state and the other with 5 standard deviation at 1770 MeV ($\Gamma \sim$ 50 MeV) in $5\pi$ final state.[25] Latter does not show preference to K decay, indicating it to be $\omega$ like state though the width may be too narrow for it. Confirmation of these states are badly needed as these mesons and many others are called for to fill $1^{--}$ nonet for both L=2 and radial excitation state of L=0.

[$0^{-+}$ nonet] A partial wave analysis of data on $K\pi\pi$ indicate $0^{-+}$ K resonance at $\sim$ 1400 MeV hidden under large $2^+$ K(1430) peak.[26] Another partial wave analysis of the $\pi\pi\eta$ data from reaction $\pi^-p \rightarrow \eta\pi^+\pi^-n$ show a tentative evidence of $0^{-+}$ resonance in $\pi\delta$ mode at $\sim$ 1260 MeV ($\Gamma \sim$ 100 MeV).[13] These evidences need a confirmation and, if confirmed, can be placed in this radial excitation state of $0^{-+}$ nonet.

States with N $\geqq$ 3

In these groups, I=0 meson h(2040) with $J^{PC}$ assignment of $4^{++}$ is well established. I=1 resonance at 1.95 GeV, $\Gamma \sim$ 200 MeV, is also reported in the reaction $\pi^+p \rightarrow K^+K^o_sp$(27) but high statistics confirmation is desired. This experiment confirms earlier observation of similar state in the reaction $\pi^-p \rightarrow K^-K^o_sp$,[28] confirming the existence of I=1, $J^P=4^+$ state. Still higher mass resonance was reported in $K^+K^-$ system[29] at the mass of 2.216 $\pm$ .11 GeV, $\Gamma = 281^{+200}_{-100}$ MeV. This experiment also observed a clear enhancement

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* G. Otter et al. [Nucl. Phys. B147, 42 (1979)] report observation of $2^-$ $K^*(890)\pi$ resonance at the mass of 1.58 GeV with width 110 MeV.



of $K^+K^-$ spectrum at 1.982 $\pm$ 0.09 GeV, $\Gamma$ = 118 $\pm$ 40 MeV, presumably $J^P = 4^+$ and possibly a mixture of I=1 and I=0 states. Unfortunately, no reliable spin-parity assignment is given to this state. A yet higher spin object at a mass of 2.3 GeV is reported by ACCMOR collaboration in the reaction $\pi^-p \rightarrow K^+K^-n$.[30] From recurrence of the mesons, this object is thought to be I=1 $J^{PC} = 5^{--}$ state, which is N=4, L-4 in terms of quark-antiquark picture. It is highly likely these two experiments are observing the same states.

A description of meson spectroscopy cannot be complete without a discussion on the current status of the baryonium. In 1966, an experiment[31] on $\pi^-p \rightarrow pX^-$ with CERN missing mass spectrometer observed a series of narrow peaks in the missing mass spectrum, S(1929), T(2195) and U(2382). Recently an experiment at CERN Omega spectrometer[32] which studied the reaction $\pi^-p \rightarrow (\pi^-p_f)\bar{p}p$ observed two narrow resonances in $\bar{p}p$ system when $\pi^-p_f$ formed $\Delta^o$ or N* and came out in the forward direction. One of these resonances were at the mass of 2020 MeV and the other at 2204 MeV (T). Another evidence of narrow $\bar{p}p$ resonance came from an observation of structure in $\bar{p}p$ total cross section[33] measured in 1974 at BNL. Corresponding mass of the resonance from this formation process is 1936 MeV (S). There were several other experiments, particularly the measurement of total cross sections[34] which observed one or the other of these narrow states, giving a credence to the existence of high mass narrow state which couple strongly to nucleon-antinucleon system. There, however, was a number of experiments which did not observe such narrow enhancement, creating a vivid controversy. Such high mass narrow state is not in the ordinary picture of mesons as a bound state of quark-antiquark pairs. Therefore, discovery of these states created excitement and many speculations within the high energy physics community. Included is a speculation that these baryonium states are exotic four quark or six quark states.

The experimental situation in baryonium, however, has changed within the last year. Not finding any structure in the $\bar{p}p$ charge exchange process and elastic scattering cross section, $\bar{p}p$ total cross section measurements was repeated in the energy range in question but with more suitable setup. The new experiment,[35] to everyone's surprise, failed to observe any structure in the cross section, casting a very serious doubt on the believability of earlier experiments and existence of S meson at 1935 MeV. Another experiment at MPS[36] investigated the backward production of baryonium using the reaction $\pi^+ p \to (\pi^+ p)p\bar{p}$. This process is similar to the reaction studied by the Omega spectrometer experiment except that the upper vertex of the exchange diagram shows $\pi^+ \to \Delta^{++}$ with p or $\Delta^+$ exchange instead of $\pi^- \to \Delta^o$ with p or $\Delta^+$ exchange. Data from this experiment is now being analyzed, but preview of the results show no significant structure in $\bar{p}p$ mass spectrum in the mass region of 2.0 - 2.3 GeV. With these two experiments, the existence of narrow baryonium state is currently very much questioned.

As it is clear from Fig. II-1 and the description above, lower mass mesons are in good shape in terms of a picture based on mesons being bound states of quark and antiquark. Situation that there are more $0^{++}$ mesons than number of boxes available may mean one or more of the following:

a. There indeed are more than one N=1 nonet; one for $q\bar{q}$ and the other for $qq\bar{q}\bar{q}$ state.[16]

b. Some of seen $0^{++}$ state may well be glueballs.[16]

c. $0^{++}$ mass difference between N=1 states and N=3 states is much smaller than we think and some of the $0^{++}$ mesons belong to N=3 $0^{++}$ nonet.[37] This however is rather unlikely.

d. Some of the experiments and their interpretations are wrong.

For the high mass levels, situation clearly is far from ideal. At present, the difficulty is not in the assignment of mesons to boxes. Instead, we still find that many more mesons are needed to fill the available boxes. A search and study of these mesons, however, is very difficult for the following obvious reasons:

a. Most of low mass meson spectroscopy was done using bubble chambers at low energy where production cross section for these mesons were relatively high and background was low. Also, at low energies, the number of waves involved in the analysis is relatively small and therefore a good analysis can be made with relatively low statistics data. For high mass mesons, production cross section is relatively low. In addition, the analysis requires a large number of waves in general, requiring a set of data with high statistics. This makes the bubble chamber almost useless for the study of high mass mesons.

b. In order to overcome the deficiency of bubble chambers above, a large solid angle spectrometer with electronic readout such as Omega Spectrometer of CERN and MPS of Brookhaven was developed. Although these

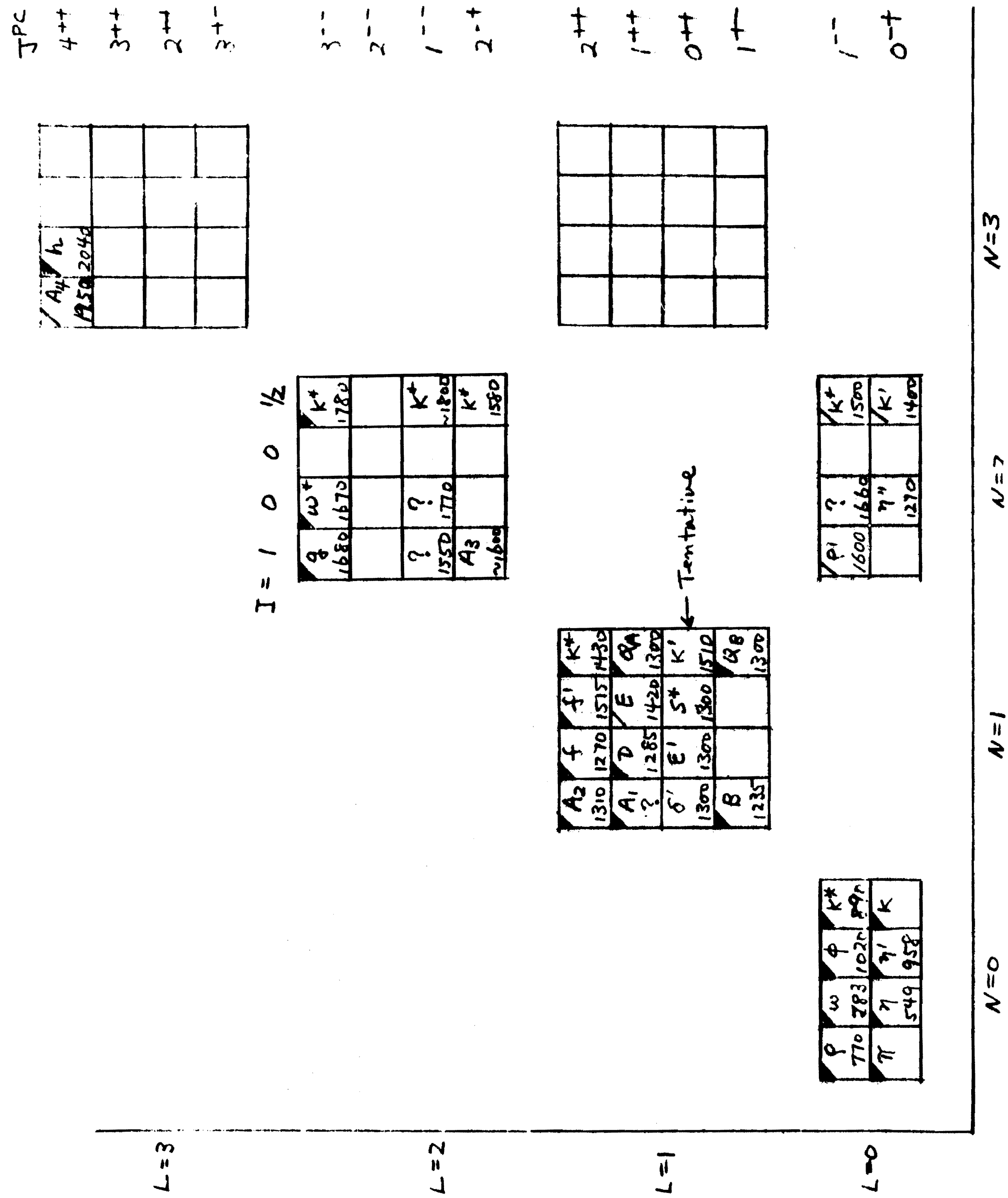


spectrometers provide more than one order of magnitude improvement over the bubble chamber, they present another problem; namely, in spite of the intention to cover a large solid angle ($\sim 4\pi$) for the reaction products, the coverage over the angular distribution is never uniform. This difficulty is more enhanced for a study of high mass objects due to a large opening angle in the decay. This unfortunately will add further complication on the analysis of the data.

c. Although these spectrometers have been in operation during the past several years, the attention of physicists who used them has been directed toward more glamorous field of charm.

d. In terms of physics involved, these high mass states, in general, are wide and have many decay modes. In addition, there are many of them overlapping each other. This requires more complex multichannel analysis of the data.

In spite of these difficulties, importance and interest of physicist are there to study the high mass state. I have no doubts that new high mass states would be discovered and studied.



$J^{PC}$
L=3
L=2
L=1
L=0
N=0
N=1
N=2
N=3
I = 1 0 0 ½
Tentative

III. MPS and Experiments at the Spectrometer Facility

As an example of detectors used for the study of meson spectroscopy, I will discuss the MPS (Multiparticle Spectrometer) at BNL and its experimental program with it. The MPS, in brief, is a large aperture spectrometer to detect the particles in the final state of an interaction with close to $4\pi$ solid angle, allowing us to reconstruct the entire event. In this sense, some people call this kind of device as an electronic version of bubble chambers. The bubble chambers, as we know, made numerous early contributions to the study of meson spectroscopy. The MPS has an additional advantage. That is, the detectors in this device has short resolving time (or memory time) compared to the bubble chamber. Furthermore, these electronic detectors are triggerable, allowing us to selectively detect and analyze only those events which we consider to be a candidate for further study. Therefore, we can handle large numbers of interactions in a short time giving us much higher sensitivity in the study of phenomena than was possible with bubble chambers. For instance, early bubble chambers studied the phenomena with $\sim$ μb cross sections. Present spectrometer can reach to $\sim$ 10 nb.

A schematic layout of the spectrometer which is located in the northwest corner of the AGS experimental area, is shown in Fig. III-1. The main part of the spectrometer is a 700 ton C-magnet with a large field volume (1.82m x 4.55m poles with a 1.21m gap), which is equipped with a set of wire spark chambers giving a good multiparticle handling capability for particle trajectory detection. It also includes a number of proportional chambers and counter hodoscopes to generate a trigger. With a target which is placed in this magnet gap and with a set of target area detectors, a large solid angle coverage ($\sim 4\pi$) to the reaction products can be obtained for an investigation of complex multiparticle final states. The main spectrometer is followed by a set of large spark chambers, scintillation counter hodoscopes and Cerenkov counter hodoscopes for improved momentum resolution and particle identification of those particles which emerge from the MPS magnet. In addition to the basic detectors, the MPS is outfitted with special electronics for trigger logic (RAM), detector readout electronics, data acquisition and recording devices and the on-line computer (PDP10).



The MPS is, at present, serviced by two beams; the MESB from B target station and the HEUB from A target station. The MESB is a medium energy separated beam with a maximum momenta of 10 GeV/c. A good $K/\pi$ separation can be obtained up to 6 GeV/c and $\bar{p}/\pi$ separation up to the maximum momentum. The HEUB is a high intensity unseparated beam with a maximum momenta of 28.5 GeV/c. The magnet can be rotated around its pivot by ± 15°. This accommodates MESB and HEUB lines which come from different directions, but also optimizes the detector geometry for some experiments.

At present there are 48 main spark chambers placed in the magnet gap downstream of the target. They are grouped in 8 each of two types of modules, one type being made up of one X, one U, one V, and one X measuring chambers where U and V are ± 15° from the X coordinate, and the other of two Y's. As they are installed in a modular form, the configuration can be altered with relative ease. Both high voltage and ground planes are read out by magnetostrictive lines to give better readout accuracy. The scaler system which encodes these readouts can handle up to 15 sparks for each readout.

The resolving time of the spark chamber system is $\sim$ 2 μsec. This limits the maximum beam flux to $\sim 10^5$/sec. The dead time of the system for clean operation is $\sim$30 msec, thus creating 50% dead time with 15 triggers per AGS pulse. If one takes $3 \times 10^5$ particles per AGS pulse incident on 60 cm long hydrogen target, and the trigger rate of $10^{-4}$, simple arithmetic gives an attainable sensitivity of 0.4 events/μb/pulse, or 0.5 events/nb/hour. The resolutions of the forward detector system is as follows:

momentum $\quad \frac{\Delta p}{p} \approx \sqrt{(.0025)^2 + (.0012p)^2}$

angular $\quad \Delta\theta_x \approx \frac{3.5 \text{ mr}}{p}$ up to $p \sim 7$ GeV/c.

Typical effective mass resolutions are:

| | |
|---|---|
| $K^0$ | 4-5 MeV for 0.5 $\sim$ 15 GeV/c |
| $K^0\pi\pi$ or $K^0_sK^0_s$ | 20 MeV for 4 GeV mass. |

Detector configuration which surrounds the target is expected to be very much experiment-dependent. In fact, with this in mind, the system has been designed to have a maximum flexibility in the area. Currently, two types of detector assembly are available as described below. However, this is the area where the user's imagination and ingenuity will play an important role.

The MPS has been in operation for the high energy physics research program at the AGS since late 1974. To date it has run five experiments in the MESB beam line and four experiments in the HEUB beam line. The experimental program includes the studies of conventional hadron spectroscopy, the measurement of very small cross section phenomena and the search of new narrow states such as an exotic baryonium state and the charmed particles. This demonstrates the effectiveness and the versatility of the MPS.

In what follows I will discuss some of the experiments which were run in the recent past.

1. AGS Experiment 679 (BNL/CCNY)

Limited, but still high data handling capability of the MPS was used to investigate very small cross section phenomena. The reaction studied was:

$$\pi^- p \to \underbrace{K^+K^-}_{\phi} + \underbrace{K^+K^-}_{\phi} + n \quad \text{at } 23 \text{ GeV/c}$$

The experiment was run in August-September of 1977 and the preliminary data were published.[38] A principal motivation of this experiment was to study the spectroscopy of the $\phi\phi$ system. Possible states which may be found in this system are isoscaler bosons which are even under charge conjugation of any spin and parity. Such states as strangeonium ($s\bar{s}$ state) are of particular interest. Another motivation was a search for $\eta_c$ through its possible decay into $\phi\phi$ final state which is expected to present a low conventional physical background.



Figure III-1 shows the way MPS was equipped for this experiment. The trigger was designed to select events with three or more charged kaons produced in a 60-cm-long liquid-hydrogen target. The K-meson signature was a track emerging from the target with a momentum between 4 and 12 GeV/c, as measured by the proportional wire chambers TPX2 and TPX3 and the counter hodoscope H5, with no signal from the corresponding cell in C6, a Freon 114 threshold-Cerenkov-counter hodoscope. The threshold of C6 for pions was 2.8 GeV/c, and the efficiency was measured to be 99.3% for momenta above 4 GeV/c. Thus, the contamination of pions in the sample is small, although, of course, the counter does not distinguish between kaons and protons. The above selection criteria were achieved using a special trigger system, designed and built at BNL. The system used a fast random-access memory (RAM) with two million bits in a 128 x 128 x 128 three-dimensional array. Each dimension represented one of the three trigger detector elements (TPX2, TPX3, and H5 $\cdot$ $\bar{C}6$). The memory is preloaded to contain "ones" at all three-dimensional points satisfying the chosen criteria. The detector outputs are strobed into a fast register which serves to address the RAM's. 180 nsec later the overall OR tree is strobed to see if any of the addressed combination contains logical "ones".

The hardware is arranged so that the outputs in one dimension are added linearly to give a signal proportional to the number of combinations satisfying the trigger criteria. For this experiment we chose to use H5 $\cdot$ $\bar{C}6$ as this dimension, since at that point the spatial separation between kaons of positive and negative charge is almost complete; by dividing the memory into two sections, we were able to determine the number of particles of each charge. We triggered the spark chambers on events with three or more "kaons" with at least one of each charge. The trigger requirements were satisfied for one in approximately 45,000 incident particles; we recorded 1.3 million triggers. As can be seen in the scatter plot (Fig. III-2) of the effective mass of a pair of $K^+K^-$ vs. the other pair of 4-kaon final state, there is a surprisingly clear enhancement of $\phi\phi$ production. The integral of the $\phi\phi$ mass spectra shown in Fig. III-3 gives a cross section of 23 ± 2 nb (30% systematic error).

The spectrum shows marked enhancement in the low effective mass region but without a clear indication of structure. The upper limit on the $\sigma \cdot$ BR for $\eta_c$, if the mass is $\sim 2.8$ GeV, is $\sim 2$ nb.

One thing which is remarkable in our data is a strong enhancement of $\phi\phi$ production which is expected to be OZI suppressed. A comparison of integrated $\phi\phi$ production cross section with OZI allowed $\phi KK$ production, give a ratio of $\lesssim 10$ (not $\sim 100$ as one might expect). The other observation made was the enhancement of $K^+K^-$ mass spectra at $\phi$ mass over background. The degree of the $\phi$ signal enhancement when the remaining $K^+K^-$ pair is in the $\phi$ mass band (Fig. III-4a) is similar to, if not stronger than that when it is not in the $\phi$ mass band (Fig. III-4b). This certainly is not the behavior one would expect if the $\phi\phi$ production is suppressed by the OZI rule. We therefore have the unusual situation that the "forbidden" reaction produces a higher $\phi$ enhancement over $K^+K^-$ background than the allowed reaction, although equal enhancements cannot be ruled out because of the possible contamination of the data with $p\bar{p}$ pairs.

The MPS has been active in the searches of exotic states and charmed particles. Three experiments (E686, E688 and E682) were run recently searching for the associated production of charmed particles. (E682 is also investigating the baryonium states as well as charmed particle production.) As the analysis of data from these experiments is now in progress, and the results are not yet available; I can only present how these experiements were run and what one might expect in the results.

2. AGS E686 (Brandeis, BNL, U. Penn., SUNY, Syracuse)

$\pi^- p \to D^- \quad C^+$
  $D^- \to e^-$ + anything,  $C^+ \to$ all charged

A pair of transition radiation detectors, which were developed at BNL and located in the MPS gap downstream of the target was used, in conjunction with a shower detector which was located at the downstream exit of the MPS gap for electron identification. The overall hadron rejection ratio of this combination was 1/30K. A good trigger rate of 1/100K was obtained using the electron detectors above and a juditious use of the RAM trigger system mentioned above. Their anticipated sensitivity is such that 20-30 events are expected if the associated production cross section is $\sim 100$ nb. This assumes the branching ratio for $D^-$ and $C^+$ to be $\sim 10\%$ each.



This experiment also collected extensive data on $\pi^- p \to e^+e^- + X$. The $e^+e^-$ effective mass spectrum which is measured down to the mass of 20 MeV with an excellent mass resolution inherent to the MPS should prove very significant. They also have data on $e^+e^-\gamma$ to investigate the Dalitz decay of $\eta$.

3. AGS E688 (Brandeis, BNL, Cincinnati, Syracuse)

$\pi^- p \to D^- \quad C^+$
  $D^- \to K^0\mu^-\nu$,  $C^+ \to$ all charged

The identification of $\mu^-$ was doen using two Cu absorbers with total thickness of $\sim 30''$ placed in the MPS magnet. The increase in the multiplicity gave $K^0$ signature. The sensitivity of the experiment is said to be 1 ev/nb ($\sigma \cdot B$). Therefore, if the $K^0\mu^-\nu$ branching ratio is 10% and $C^+ \to$ all charged branching ratio is 10$\sim$30%, 100 $\mu$b associated production cross section should yield $\sim$ 1-3 events.

4. AGS E682 (Brandeis, BNL, CCNY, U. Mass, SMU)

This is an experiment currently in progress at MPS. One objective of this experiment is to investigate the baryonium production and the other is to search for the charmed particles.

The reactions used for the baryonium study and the expected sensitivities of the experiment are:

$\pi^- p \to \Delta^0 + \bar{p}p$  $\sim$ 30 ev/nb
  $\Delta^0 \to p\pi^-$  (forward p trigger)

$\pi^- p \to \Delta^0(p\bar{p}\pi^0)$
  $\to \Delta^0 \quad (p\bar{n}\pi^-)$  $\sim$ 2 ev/nb
  $\Delta^0 \to p\pi^-$ (forward p trigger)  $\to$ (side p trigger)

For the charm experiment, the reaction and sensitivity are:

$\pi^- p \to D^{*-} \quad C^+$
  $D^{*-} \to D^0\pi^-$  $\sim$ 20 ev/nb $(\sigma \cdot B)$
  $D^0 \to K^+\pi^-$  (forward $K^+$ trigger)

5. E716 (Carnegie-Mellon, Southeastern Massachusetts University, BNL)

Motivated by the observation of narrow $\bar{p}p$ state at CERN,[32] and encouraged by seeing a possible candidate for this state in their earlier $\bar{p}p$ experiment, this group undertook a search of the exotic baryonium states. The reactions used were:

$\pi^+p \to \Delta^o + X^{++}$ (1) — $\Delta^o \to p\pi^-$; $X^{++}$ reconstructed

$\to \Delta^{++} + X^o$ (2) — $\Delta^{++} \to p\pi^+$; $X^o \to \bar{p}p$

$\to \Lambda^o + S^{++}$ (3) — $\Lambda^o \to p\pi^-$

Reactions (1)–(3): forward p trigger

$\pi^+p \to X^o + \Delta^{++}$ (4) — $X^o \to \bar{p}p$

$\to \bar{p} + (?)$ (5) — (?) reconstructed

Reactions (4)–(5): forward $\bar{p}$ trigger

Again the RAM trigger was used to improve the trigger ratio, thus gaining a high sensitivity of the experiment. A post run estimation of the sensitivities of this experiment are:

| | |
|---|---|
| for $\pi^+p \to p_{fwd}$ + one or more prongs | ∿ 18 ev/nb |
| for $\pi^+p \to p_{fwd}$ + 3 or more prongs | ∿ 30 ev/nb |
| for $\pi^+p \to \bar{p}_{fwd}$ + one or more prongs | ∿ 40 ev/nb. |

Reactions (1) and (3) are of particular interest. If a narrow resonance peak is observed in the spectrum, it must mean that a manifestingly exotic state exists which cannot be accommodated by a simple $q\bar{q}$ meson.

The results of a preliminary analysis of the $\Delta^o$ forward data shows a striking lack of peak in the missing mass $X^{++}$.[36] This result, together with the disappearance of S(1920) in the new measurement of $\bar{p}p$ total cross section[35] cast great doubt on the existence of narrow nucleon-antinucleon state, so far called baryonium.

In the area of more conventional meson spectroscopy, the MPS program includes the following experiments.

6. AGS E705 (BNL, CCNY, Michigan State, Tufts, Vanderbilt)

Another experiment which utilizes the capability of the MPS at its best is the high sensitivity study of the reaction

$$\pi^-p \to V^oV^o + \text{neutrals at 23 GeV/c.}$$



This experiment searches for $0^+$, $2^+$ ... state decay into $K^o_sK^o_s$ and I = 0 state decaying into $\Lambda\bar{\Lambda}$. With anticipated 50 ev/nb sensitivity up to the effective mass of 4 GeV, we expect new interesting features in the mass spectrum which may lead us to an observation of new resonances. A trial run of this experiment was done in conjunction with E679 above. The main run is expected to take place in the Fall of 1979.

7. AGS E594 (BNL, CCNY)

In this experiment, a study was made of the reaction:

$$K^-p \to K^o_s\pi^+\pi^- + n$$

using 6 GeV/c $K^-$ beam from MESB to search for strange meson resonances. Unlike the/$(K^-\pi^+)$ two-body final states, $K^o_s\pi^+\pi^-$ state can be fed by natural as well as unnatural spin parity resonances. Also charge exchange reaction suppressed a large Deck type background common to the diffractive processes. The $K^*$ mass spectrum, however, is very complex in the mass range studied due to the fact that it is populated by a large number of wide and narrow overlapping resonances. We therefore have to perform a partial wave analysis of the data using isobar model. The results[39] shown in Fig.III-5, a,b,c, shows a clear peak for $2^+$ $K^*$(1430) resonance and strongest evidence to date of the $1^+$ $Q_2$ (1400) resonance. Although $Q_2$ was seen in diffractive processes, interpretation was not clear due to a presence of large Deck background. We also find a convincing evidence for a new $1^-$ state at around 1450 MeV. In the high mass region, the experiment is short of statistics. However, we see a clear peak in $3^-$ wave at $K^*$(1800) through its major decay mode and not strong but promisable enhancement in $1^-$ wave at ∿ 1800 MeV.

8. AGS E557 (BNL, Brandeis, CCNY, U. Mass., U. Penn.)

In this experiment[23] a production of high mass $K^*$ was studied with high statistics using a reaction

$$K^-p \to K^-\pi^+n \text{ at 6 GeV/c.}$$

$K^-\pi^+$ mass spectrum is shown in Fig. II-6 and the results of the moment analysis is shown in Fig.III-7. From these results, it was concluded that this experiment showed the best $K^*$(1780) signal to date in $K^-\pi^-$ mass spectrum and that there exists a $K^*$ state with mass 1786 ± 8 MeV, width 95 ± 31 MeV and $J^P = 3^-$ (or higher) which is produced predominantly, but not entirely, in the diffractive dissociation region at this energy.

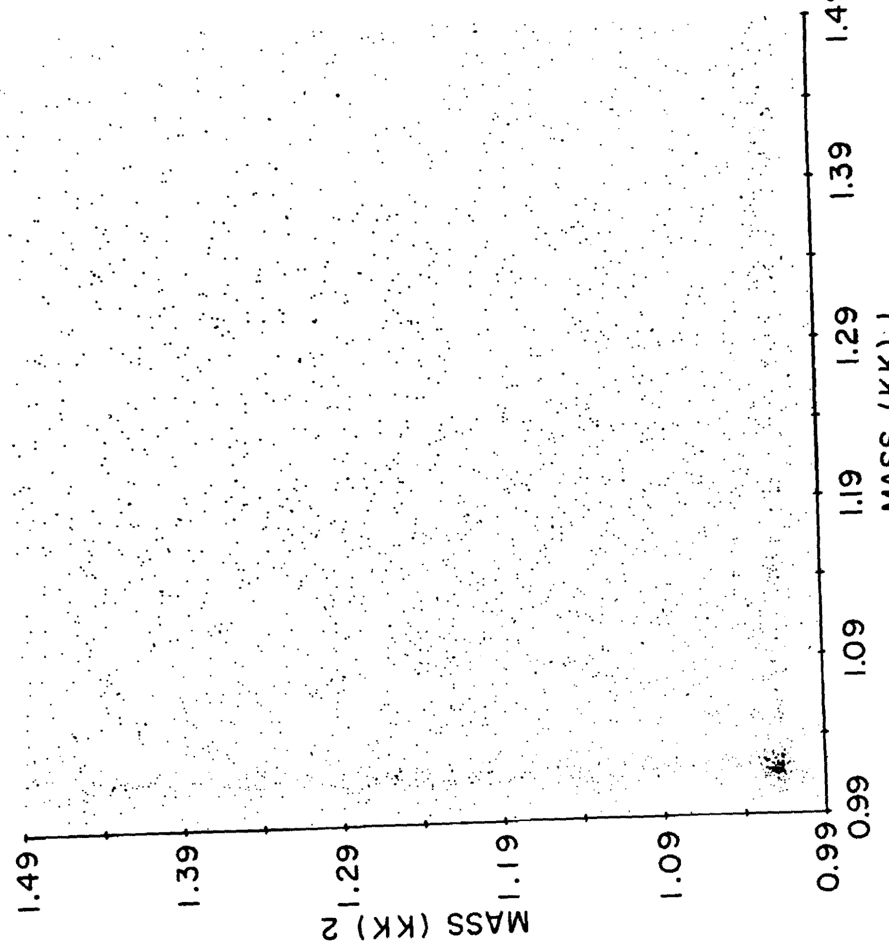



Figure 2



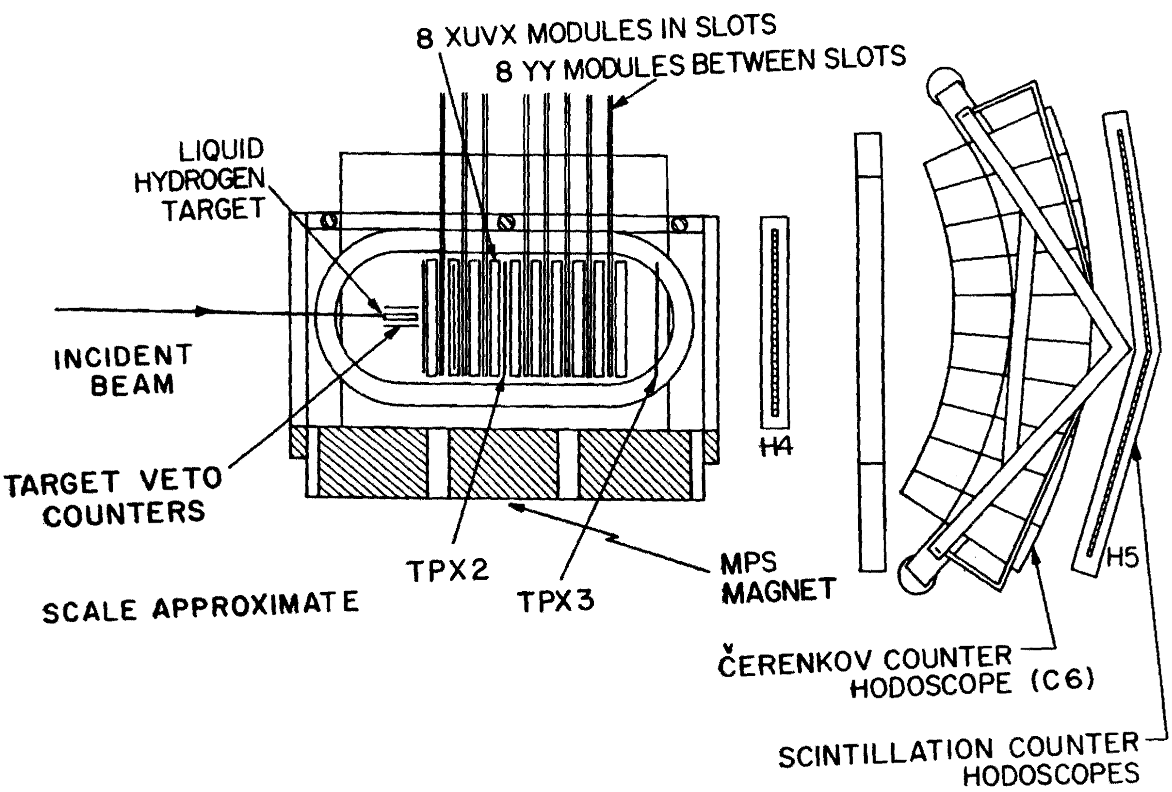



Figure 1

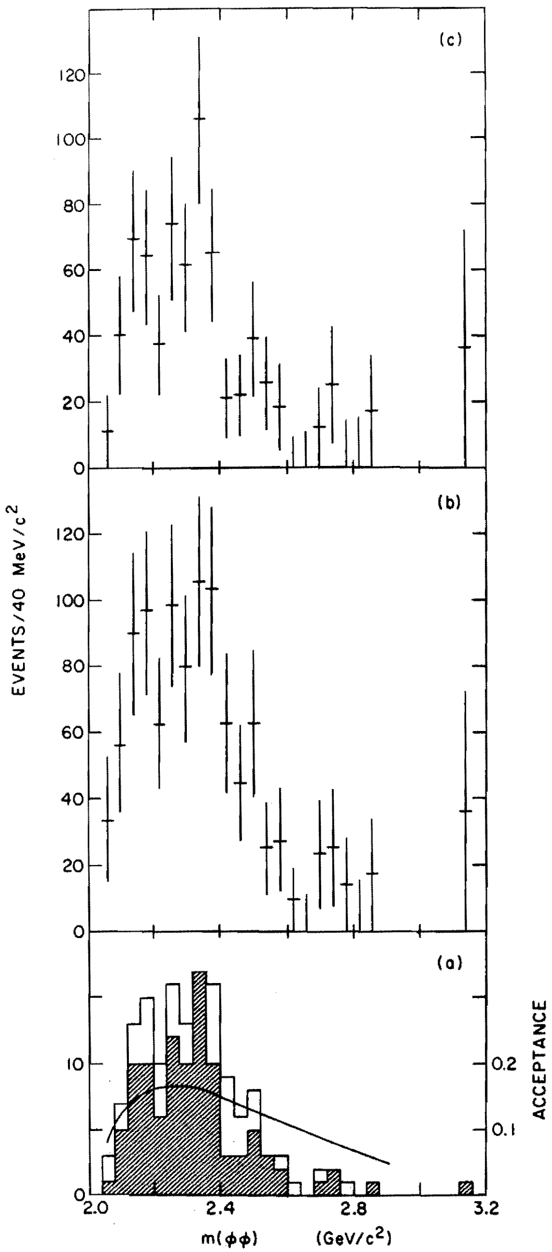



Figure 3



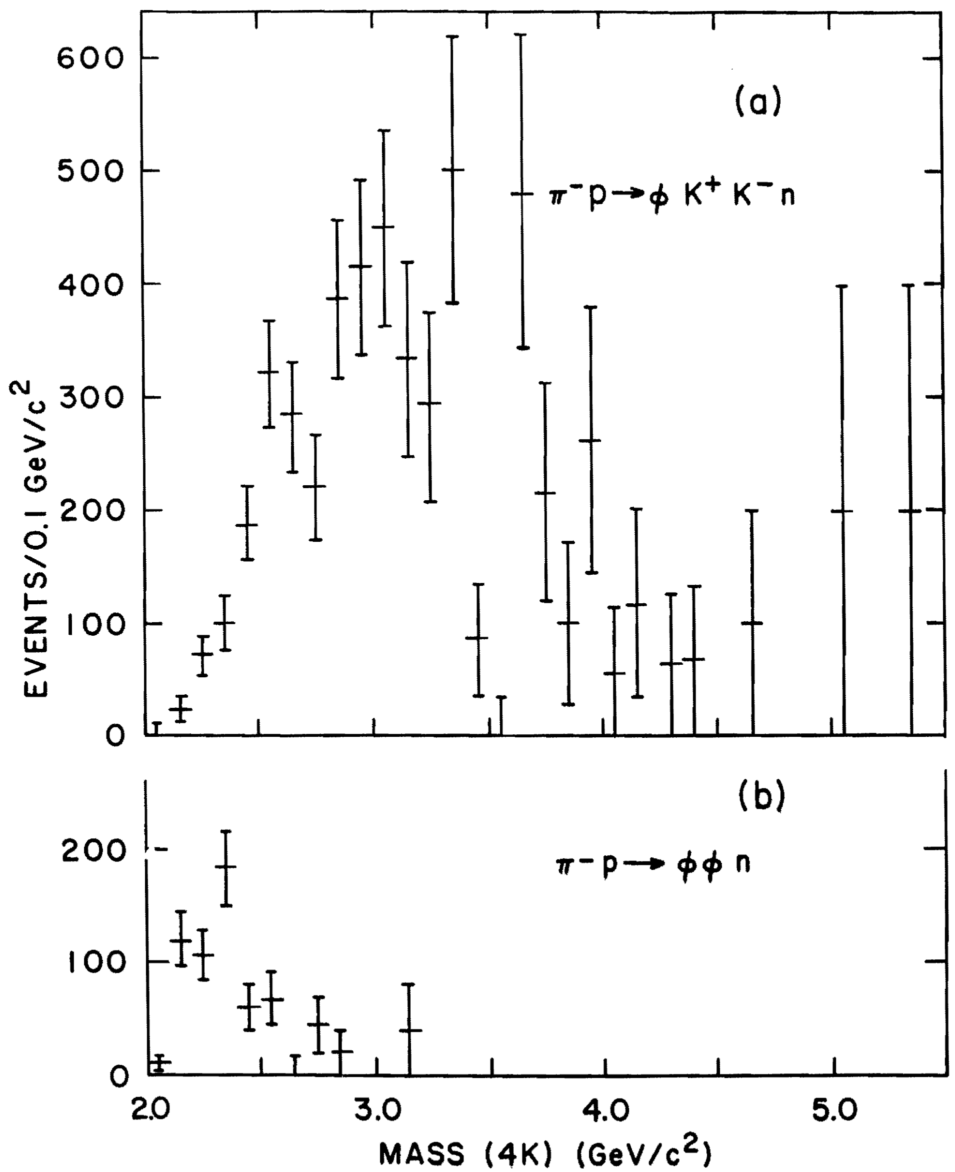



Figure 4

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# Meson Table

April 1978

In addition to the entries in the Meson Table, the Meson Data Card Listings contain all substantial claims for meson resonances. See Contents of Meson Data Card Listings below.

*Quantities in italics are new or have changed by more than one (old) standard deviation since April 1976.*

| Name | $I^G(J^P)C_n$ estab. | Mass M (MeV) | Full Width Γ (MeV) | $M^2$ $\pm\Gamma M$[a] $(GeV)^2$ | Partial decay mode: Mode | Fraction (%) [Upper limits are 1σ (%)] | | p or $p_{max}$[b] (MeV/c) |
|---|---|---|---|---|---|---|---|---|
| $\pi^\pm$ | $1^-(0^-)+$ | 139.57 | 0.0 | 0.019479 | See Stable Particle Table | | | |
| $\pi^0$ | | 134.96 | 7.95 eV ±.55 eV | 0.018215 | | | | |
| η | $0^+(0^-)+$ | 548.8 ±0.6 | 0.85 keV ±.12 keV | 0.301 ±.000 | Neutral | 71.0 | See Stable Particle Table | |
| | | | | | Charged | 29.0 | | |
| ρ(770) | $1^+(1^-)-$ | 776[¶] ±3[§] | 155[¶] ±3[§] | 0.602 ±.120 | ππ | ≈ 100 | | 362 |
| | | | | | πγ | 0.024 ±.007 | | 375 |
| | | | | | $e^+e^-$ | 0.0043±.0005 (d) | | 388 |
| | | | | | $\mu^+\mu^-$ | 0.0067±.0012 (d) | | 373 |
| | | | | | ηγ | *seen*[¶] | | 194 |
| M and Γ from neutral mode. | | | | | For upper limits, see footnote (e) | | | |
| ω(783) | $0^-(1^-)-$ | 782.6 ±0.3 S=1.3* | 10.1 ±.3 | 0.612 ±.008 | $\pi^+\pi^-\pi^0$ | 89.9±0.6 | S=1.2* | 327 |
| | | | | | $\pi^+\pi^-$ | 1.3±0.3 | S=1.5* | 366 |
| | | | | | $\pi^0\gamma$ | 8.8±0.5 | | 380 |
| | | | | | $e^+e^-$ | 0.0076±.0017[¶] | S=1.9* | 391 |
| | | | | | ηγ | *seen*[¶] | | 199 |
| | | | | | For upper limits, see footnote (f) | | | |
| η′(958) | $0^+(0^-)+$[¶] | 957.6 ±0.3 | < 1 | 0.917 <.001 | ηππ | 66.2±1.7 | | 231 |
| | | | | | $\rho^0\gamma$ | 29.8±1.7 | S=1.1* | 165 |
| | | | | | ωγ | *3.1±0.4* | | 159 |
| | | | | | γγ | 2.0±0.3 | | 479 |
| | | | | | For upper limits, see footnote (g) | | | |
| δ(980) | $1^-(0^+)+$ | 980[(h)] ±5[§] | 50[(h)] ±10[§] | 0.960 ±.049 | ηπ | seen | | 318 |
| | | | | | $K\bar{K}$ | *seen*[¶] | | |
| S*(980) | $0^+(0^+)+$ | ∿ *980*[(c)§] *±10*[§] | 40[(c)§] ±10[§] | 0.960 ±.039 | $K\bar{K}$ | seen[¶] | | |
| | | | | | ππ | seen | | 470 |
| See note on ππ and $K\bar{K}$ S wave[¶]. | | | | | | | | |
| Φ(1020) | $0^-(1^-)-$ | 1019.6 ±0.2 S=1.5* | *4.1* ±.2 | 1.040 ±.004 | $K^+K^-$ | 48.6±1.2 | S=1.3* | 128 |
| | | | | | $K_LK_S$ | 35.1±1.2 | S=1.5* | 111 |
| | | | | | $\pi^+\pi^-\pi^0$ (incl. ρπ) | *14.7±0.7* | S=1.2* | 462 |
| | | | | | ηγ | 1.6±0.2 | | 362 |
| | | | | | $\pi^0\gamma$ | 0.14±0.05 | | 501 |
| | | | | | $e^+e^-$ | .031±.001 | S=1.1* | 510 |
| | | | | | $\mu^+\mu^-$ | .025±.003 | | 499 |
| | | | | | For upper limits, see footnote (i) | | | |
| ‡ $A_1$(1100) | $1^-(1^+)+$ | ∿ 1100[¶] | ∿ 300[¶] | 1.21 ±.33 | ρπ | ∿ 100 | | 249 |
| B(1235) | $1^+(1^+)-$ | 1231 ±10[§] | 128 ±10[§] | 1.52 ±.16 | ωπ | only mode seen | | 347 |
| | | | | | [D/S amplitude ratio = .29±.05] | | | |
| | | | | | For upper limits, see footnote (j) | | | |
| f(1270) | $0^+(2^+)+$ | 1271 ±5[§] | 180 ±20[§] | 1.62 ±.23 | ππ | 80.3±0.3 | | 620 |
| | | | | | $2\pi^+2\pi^-$ | 2.8±0.3 | S = 1.1* | 557 |
| | | | | | $K\bar{K}$ | 3.1±0.4 | S = 1.3* | 395 |
| | | | | | $\pi^+\pi^-2\pi^0$ | seen | | 560 |
| | | | | | For upper limits, see footnote (ℓ) | | | |
| D(1285) | $0^+(1^+)+$ | 1282 ±5[§] | 25 *±10*[§] | 1.64 ±.03 | $K\bar{K}\pi$ | seen | | 301 |
| | | | | | ηππ | seen | | 481 |
| | | | | | †[δπ | seen] | | 238 |
| | | | | | $2\pi^+2\pi^-$ (prob. $\rho^0\pi^+\pi^-$) | seen | | 563 |
| ε(1300) | $0^+(0^+)+$ | ∿ *1300* | *200–400* | | ππ | seen | | |
| | | | | | $K\bar{K}$ | *seen* | | |
| See note on ππ and $K\bar{K}$ S wave[¶]. | | | | | | | | |

# Meson Table *(cont'd)*

| Name | $I^G(J^P)C_n$ (estab.) | Mass M (MeV) | Full Width Γ (MeV) | $M^2 \pm \Gamma M$[a] $(GeV)^2$ | Partial decay mode: Mode | Fraction (%) [Upper limits are 1σ (%)] | p or $p_{max}$[b] (MeV/c) |
|---|---|---|---|---|---|---|---|
| $A_2(1310)$ | $1^-(2^+)+$ | 1312[§] ±5[§] | 102 ±5[§] | 1.72 ±.13 | $\rho\pi$ | 70.3±2.1 | 411 |
| | | | | | $\eta\pi$ | 14.4±0.9 | 531 |
| | | | | | $\omega\pi\pi$ | 10.6±2.5 | 356 |
| | | | | | $\bar{K}K$ | 4.7±0.5 | 430 |
| | | | | | $\eta'\pi$ | <1 | 281 |
| | | | | | $\pi\gamma$ | *0.45±0.11* | 649 |
| ·E(1420) | $0^+(A\ )+$ | 1416 ±10[§] | 60 ±20[§] | 2.01 ±.08 | $K\bar{K}\pi$ | seen | 421 |
| | | | | | †[$K^*\bar{K} + \bar{K}^*K$ | seen] | 130 |
| | | | | | $\eta\pi\pi$ | seen | 564 |
| | | | | | †[$\delta\pi$ | possibly seen] | 349 |
| Not a well established resonance. | | | | | | | |
| $f'(1515)$ | $0^+(2^+)+$ | 1516 ±10[§] | *65* ±10[§] | 2.30 ±.10 | $K\bar{K}$ | dominant | 572 |
| | | | | | $\pi\pi$ | *seen* | 745 |
| | | | | | For upper limits, see footnote (k) | | |
| $\rho'(1600)$ | $1^+(1^-)-$ | ∼ 1600[¶] | ∼ *300*[¶] | 2.56 ±.48 | $4\pi$ | *75*[§]*±10*[§] | 738 |
| | | | | | †[$\rho\pi^+\pi^-$ | seen with $\pi^+\pi^-$ in S-wave] | 572 |
| | | | | | $\pi\pi$ | *25*[§]*±10*[§] | 788 |
| $A_3(1640)$ | $1^-(2^-)+$ | ∼ 1640 | ∼ 300 | 2.69 ±.49 | $f\pi$ | dominant | 304 |
| Not a well established resonance.[¶] | | | | | | | |
| $\omega(1670)$ | $0^-(3^-)-$ | 1668 ±10[§] | 160 ±15[§] | 2.78 ±.27 | $\rho\pi$ | seen | 645 |
| | | | | | $3\pi$ | possibly seen | 806 |
| | | | | | $5\pi$ | possibly seen | 740 |
| | | | | | †[$\omega\pi\pi$ | possibly seen] | 615 |
| $g(1680)$[¶] | $1^+(3^-)-$ | 1688 ±20[§] | 180 ±30[§] | 2.85 ±.30 | $2\pi$ | 24±5[§] | 832 |
| | | | | | $4\pi$ (incl. $\pi\pi\rho, \rho\rho, A_2\pi, \omega\pi$) | large | 786 |
| | | | | | $K\bar{K}$ | small | 682 |
| $J^P$, M and Γ from the 2π mode. | | | | | $K\bar{K}\pi$ (incl. $K^*\bar{K}$) | small | 623 |
| $S(1935)$[¶] J < 4 | | *1935* ±2[§] | *9* ±4[§] | 3.74 ±.02 | $N\bar{N}$ | *dominant* | 236 |
| $h(2040)$ | $0^+(4^+)+$ | 2040 ±20 | 193 ±50 | 4.16 ±.39 | $\pi\pi$ | seen | 1010 |
| | | | | | $K\bar{K}$ | seen | 890 |
| $T(2190)$[¶] | $1^+(3^-)-$ | *2192* ±10[§] | *150*[§] ±50[§] | 4.80 ±.33 | $N\bar{N}$ | *dominant* | 564 |
| | | | | | $\pi\pi$ | *seen* | 1086 |
| $U(2350)$[¶] | $0^+(4^+)+$ | *2350*[§] ±25[§] | ∼ *200*[§] | 5.52 ±.47 | $N\bar{N}$ | *dominant* | 707 |
| | | | | | $\pi\pi$ | *seen* | 1167 |
| $\psi(3100)$ or J | $0^-(1^-)-$ | 3097±2 | 0.067±0.012 | 9.598 ±.000 | $e^+e^-$ | 7±1 | 1549 |
| | | | | | $\mu^+\mu^-$ | 7±1 | 1545 |
| | | | | | hadrons | 86±2 | |
| | | | | | †[$2(\pi^+\pi^-)\pi^0$ | *3.7±0.5* | 1496 |
| | | | | | $3(\pi^+\pi^-)\pi^0$ | *2.9±0.7* | 1433 |
| | | | | | $\pi^+\pi^-\pi^0K^+K^-$ | *1.2±0.3* | 1369 |
| | | | | | $\rho\pi$ | *1.1±0.2* | 1448 |
| | | | | | $4(\pi^+\pi^-)\pi^0$ | *0.9±0.3* | 1345 |
| | | | | | $K^{*0}(890)\ \bar{K}^{*0}(1430)$ | *0.67±0.26* | 1007 |
| | | | | | $K\bar{K}^*$ | *0.61±0.08* | 1373 |
| | | | | | $p\bar{p}\pi^+\pi^-$ | *0.41±0.08* | 1108 |
| | | | | | $2(\pi^+\pi^-)$ | *0.4±0.1* | 1517 |
| | | | | | $3(\pi^+\pi^-)$ | *0.4±0.2* | 1466 |
| | | | | | $p\bar{n}\pi^-$ | *0.38±0.08* | 1174 |
| | | | | | $2(\pi^+\pi^-)K^+K^-$ | *0.31±0.13* | 1320 |
| | | | | | $K^0K^{+-}\pi^{-+}$ | *0.26±0.07* | 1440 |
| | | | | | $\phi\pi^+\pi^-$ | *0.21±0.09* | 1365 |
| | | | | | $p\bar{p}$ | *0.21±0.02* | 1232 |
| | | | | | $p\bar{p}\eta$ | *0.19±0.04* | 948 |
| | | | | | $\phi K\bar{K}$ | *0.18±0.08* | 1176 |
| | | | | | $\Lambda\bar{\Lambda}$ | *0.16±0.08* | 1075 |
| | | | | | $p\bar{p}\pi^+\pi^-\pi^0$ | *0.11±0.04* | 1033 |
| | | | | | $p\bar{p}\pi^0$ | *0.10±0.02* | 1175 |
| | | | | | $\phi\eta$ | *0.10±0.06*] | 1320 |
| | | | | | †[$\gamma\eta'$ | *0.25±0.06* | 1401 |
| | | | | | $\gamma f$ | *0.20±0.07* | 1288 |
| | | | | | $\gamma X(2830) \to 3\gamma$ | *0.14±0.04*] | 256 |
| | | | | | For smaller branching ratios, upper limits, and resonance subchannels of the above modes, see listing.[¶] | | |

# Meson Table *(cont'd)*

| Name | $I^G(J^P)C_n$ estab. | Mass M (MeV) | Full Width Γ (MeV) | $M^2 \pm \Gamma M^{(a)}$ $(GeV)^2$ | Partial decay mode: Mode | Fraction (%) [Upper limits are 1σ (%)] | | p or $p_{max}$[b] (MeV/c) |
|---|---|---|---|---|---|---|---|---|
| χ(3415) | $0^+(0^+)+$ | 3413±5 | | 11.649 | $2(\pi^+\pi^-)$ (incl. $\pi\pi\rho$) | *4.4±0.8* | | 1678 |
| | | | | | $\pi^+\pi^-K^+K^-$ (incl. $\pi K\bar{K}^*$) | *3.7±1.0* | | 1579 |
| | | | | | $\gamma J/\psi(3100)$ | *3.3±1.0* | | 300 |
| | | | | | $3(\pi^+\pi^-)$ | *1.9±0.7* | | 1632 |
| | | | | | $\pi^+\pi^-$ | *1.0±0.3* | | 1701 |
| | | | | | $K^+K^-$ | *1.0±0.3* | | 1634 |
| | | | | | $p\bar{p}\pi^+\pi^-$ | *0.5±0.2* | | 1319 |
| $P_c$ or χ(3510) | $0^+(A)\pm$ | 3508±4 | | 12.306 | $\gamma J/\psi(3100)$ | *23.4±0.8* | S = *2.4** | 388 |
| | | | | | $3(\pi^+\pi^-)$ | *2.4±0.8* | | 1682 |
| | | | | | $2(\pi^+\pi^-)$ (incl. $\pi\pi\rho$) | *1.5±0.6* | | 1727 |
| | | | | | $\pi^+\pi^-K^+K^-$ (incl. $\pi K\bar{K}^*$) | *0.9±0.4* | | 1632 |
| $J^P = 1^+$ preferred. | | | | | $\pi^+\pi^-p\bar{p}$ | *0.14±0.11* | | 1381 |
| χ(3555) | $0^+(N)\pm$ | 3554±5 | | 12.631 | $\gamma J/\psi(3100)$ | *16±3* | S = *1.3** | 427 |
| | | | | | $\pi^+\pi^-K^+K^-$ (incl. $\pi K\bar{K}^*$) | *2.0±0.6* | | 1655 |
| | | | | | $3(\pi^+\pi^-)$ | *1.1±0.7* | | 1706 |
| | | | | | $\pi^+\pi^-$ and $K^+K^-$ | *0.29±0.15* | | |
| | | | | | $\pi^+\pi^-p\bar{p}$ | *0.29±0.14* | | 1408 |
| $J^P = 2^+$ preferred. | | | | | $2(\pi^+\pi^-)$ (incl. $\pi\pi\rho$) | *0.23±0.06* | | 1750 |
| ψ(3685) | $0^-(1^-)-$ | 3686±3 | 0.228±0.056 | 13.587 ±.001 | $e^+e^-$ | 0.9±0.1 | | 1842 |
| | | | | | $\mu^+\mu^-$ | 0.8±0.2 | | 1839 |
| | | | | | hadrons | 98.1±0.3 | | |
| | | | | | †[$J/\psi\ \pi^+\pi^-$ | 33±3] | | 474 |
| $m_{\psi(3685)} - m_{\psi(3100)} = 588.6\pm0.8$ | | | | | †[$J/\psi\ \pi^0\pi^0$ | 17±2] | | 478 |
| | | | | | †[$J/\psi\ \eta$ | 4.2±0.7] | | 189 |
| | | | | | †[$2(\pi^+\pi^-)\pi^0$ | *0.4±0.2*] | | 1798 |
| | | | | | †[$\pi^+\pi^-K^+K^-$ | *0.14±0.04*] | | 1725 |
| | | | | | †[$2(\pi^+\pi^-)$ | *0.08±0.08*] | | 1816 |
| | | | | | †[$\gamma\ \chi(3415)$ | 7±2] | | 261 |
| | | | | | †[$\gamma\ \chi(3510)$ | 7±2] | | 172 |
| | | | | | †[$\gamma\ \chi(3555)$ | 7±2] | | 128 |
| ψ(3770) | $(1^-)-$ | *3772 ±6* | *28 ±5* | 14.228 ±.106 | $e^+e^-$ | *0.0013±0.0008* | | 1885 |
| | | | | | $D\bar{D}$ | *dominant* | | 184 |
| ψ(4415) | $(1^-)-$ | 4414±7 | 33±10 | 19.483 ±.146 | $e^+e^-$ | 0.0013±0.0003 | | 2207 |
| | | | | | hadrons | dominant | | |
| Υ(9500) | $(1^-)-$ | ∿ *9500* | | 90.25 | $\mu^+\mu^-$ | *seen* | | 4750 |
| | | | | | $e^+e^-$ | *seen* | | 4750 |
| Seen split into two peaks $m_1$ = 9410±13, $m_2$=10060±30. Additional structure may be present¶. | | | | | | | | |
| $K^+$ | $1/2(0^-)$ | 493.67 | | 0.244 | See Stable Particle Table | | | |
| $K^0$ | | 497.67 | | 0.248 | | | | |
| $K^*(892)$ | $1/2(1^-)$ | 892.2 ±0.4 | 49.5 ±1.5 | 0.796 ±.044 | $K\pi$ | ≈ 100 | | 288 |
| | | | | | $K\pi\pi$ | < 0.2 | | 216 |
| | | | | | $K\gamma$ | 0.15±0.07 | | 309 |
| M and Γ from charged mode; $m^0 - m^\pm$ = 4.1±0.6 MeV. | | | | | | | | |
| $Q_1(1280)$ | $1/2(1^+)$ | ∿ *1280* | ∿ *120* | 1.64 ±.19 | $K\pi\pi$ | *dominant* | | 501 |
| | | | | | †[$K\rho$ | *large*] | | 62 |
| | | | | | †[$K^*\pi$ | *possibly seen*] | | 307 |
| Existence of a second resonance, $Q_2(1400)$, decaying mainly into $K^*\pi$, not well established¶. | | | | | $K\omega$ | *possibly seen* | | |
| κ(1400) | $1/2(0^+)$ | *1400–1450* | *200–300* | | $K\pi$ | seen | | |
| See note on Kπ S wave¶. | | | | | | | | |
| $K^*(1430)$ | $1/2(2^+)$ | *1434*§ *±5*§ | 100§ ±10§ | 2.06 ±.14 | $K\pi$ | *49.1±1.6* | | 623 |
| | | | | | $K^*\pi$ | *27.0±2.2* | | 424 |
| | | | | | $K^*\pi\pi$ | *11.8±2.5* | | 374 |
| | | | | | $K\rho$ | 6.6±1.5 | | 327 |
| | | | | | $K\omega$ | 3.7±1.6 | | 320 |
| | | | | | $K\eta$ | 2.5±2.5 | | 492 |

# Meson Table *(cont'd)*

| Name | $I^G(J^P)C_n$ estab. | Mass M (MeV) | Full Width $\Gamma$ (MeV) | $M^2$ $\pm\Gamma M$[a] $(GeV)^2$ | Partial decay mode: Mode | Fraction (%) [Upper limits are 1σ (%)] | $p$ or $p_{max}$[b] (MeV/c) |
|---|---|---|---|---|---|---|---|
| L(1770) | 1/2(A ) | 1765 ±10§ | 140 ±50§ | 3.11 ±.25 | $K\pi\pi$ | dominant | 788 |
| | | | | | $K\pi\pi\pi$ | seen | 757 |
| | | | | | †[$K^*(1430)\pi$ and other subreactions¶] | | |
| Not a well established resonance¶. | | | | | | | |
| $K^*(1780)$¶ | 1/2($3^-$) | 1784 ±10§ | 135 ±40§ | 3.19 ±.24 | $K\pi\pi$ | *large* | 798 |
| | | | | | †[$K\rho$ | *large*] | 619 |
| | | | | | †[$K^*\pi$ | *large*] | 660 |
| | | | | | $K\pi$ | *19±6*§ | 817 |
| ‡ | | | | | | | |
| $D^+$ | 1/2($0^-$) | 1868.3 | | 3.491 | See Stable Particle Table | | |
| $D^0$ | | 1863.3 | | 3.472 | | | |
| $D^{*+}(2010)$ | 1/2($1^-$) | 2008.6 ±1.0 | <2.0 | 4.034 | $D^0\pi^+$ | *60±16* | 39 |
| | | | | | $D^+\pi^0$ } | *40±16* | 37 |
| | $m_{D^{*+}} - m_{D^0} = 145.3 \pm 0.5$ MeV | | | | $D^+\gamma$ } | | 135 |
| $D^{*0}(2010)$ | 1/2($1^-$) | 2006 ±1.5 | < 5 | 4.024 | $D^0\pi^0$ | *55±16* | 45 |
| | | | | | $D^0\gamma$ | *45±16* | 138 |
| ‡ | | | | | | | |

## Contents of Meson Data Card Listings

| Non-strange (S = 0, C = 0) entry | $I^G(J^P)C_n$ | entry | $I^G(J^P)C_n$ | entry | $I^G(J^P)C_n$ | Strange (\|S\| = 1, C = 0) entry | $I(J^P)$ |
|---|---|---|---|---|---|---|---|
| $\pi$ | $1^-(0^-)+$ | $A_2$ (1310) | $1^-(2^+)+$ | → $e^+e^-$(1100-3100) | | K | 1/2($0^-$) |
| $\eta$ | $0^+(0^-)+$ | E (1420) | $0^+$(A )+ | → X (2830) | | $K^*$(892) | 1/2($1^-$) |
| $\rho$ (770) | $1^+(1^-)-$ | → X (1410-1440) | | $\psi$ (3100) or J | $0^-(1^-)-$ | $Q_1$(1280) | 1/2($1^+$) |
| $\omega$ (783) | $0^-(1^-)-$ | $f'$(1515) | $0^+(2^+)+$ | $\chi$ (3415) | $0^+(0^+)+$ | → $Q_2$(1400) | 1/2($1^+$) |
| → M (940-953) | | → $F_1$(1540) | 1 (A ) | → $\chi$ (3455) | | → $K'$(1400) | 1/2($0^-$) |
| $\eta'$ (958) | $0^+(0^-)+$ | $\rho'$(1600) | $1^+(1^-)-$ | $P_c$ or $\chi$(3510) | $0^+$(A )+ | $\kappa$ (1400) | 1/2($0^+$) |
| $\delta$ (980) | $1^-(0^+)+$ | $A_3$(1640) | $1^-(2^-)+$ | $\chi$ (3555) | $0^+$(N )+ | $K^*$(1430) | 1/2($2^+$) |
| $S^*$ (980) | $0^+(0^+)+$ | $\omega$ (1670) | $0^-(3^-)-$ | $\psi$ (3685) | $0^-(1^-)-$ | → $K_N$(1700) | 1/2 |
| → H (990) | | g (1680) | $1^+(3^-)-$ | $\psi$ (3770) | $(1^-)-$ | L (1770) | 1/2(A ) |
| $\phi$ (1020) | $0^-(1^-)-$ | → X (1690) | | → $\psi$ (4030) | $(1^-)-$ | $K^*$(1780) | 1/2($3^-$) |
| → M (1033-1040) | | → $A_4$(1900) | $1^-$ | $\psi$ (4415) | $(1^-)-$ | → $K^*$(2200) | |
| → $\eta_N$(1080) | $0^+$(N )+ | → X (1900) | $1^-(4^+)+$ | T (9500) | $(1^-)-$ | → I (2600) | |
| $A_1$(1100) | $1^-(1^+)+$ | S (1935) | 1 | → T (10060) | $(1^-)-$ | Charmed (\|C\| = 1) | |
| → M (1150-1170) | | h (2040) | $0^+(4^+)+$ | | | | |
| B (1235) | $1^+(1^+)-$ | T (2190) | $1^+(3^-)-$ | | | D (1870) | 1/2($0^-$) |
| → $\rho'$(1250) | $1^+(1^-)-$ | U (2350) | $0^+(4^+)+$ | | | $D^*$(2010) | 1/2($1^-$) |
| f (1270) | $0^+(2^+)+$ | → $\bar{N}N$(2360) | 1 | | | → F (2030) | |
| D (1285) | $0^+$(A )+ | → $\bar{N}N$(1400-3600) | | | | → $F^*$(2140) | |
| $\epsilon$ (1300) | $0^+(0^+)+$ | → X (1900-3600) | | | | → Exotics | |

# Meson Table *(cont'd)*

- • Indicates an entry in Meson Data Card Listings not entered in the Meson Table. We do not regard these as established resonances. All the entries in the Listings can be found in the Table of Contents of Meson Data Card Listings.
- ¶ See Meson Data Card Listings.
- * Quoted error includes scale factor $S = \sqrt{\chi^2/(N-1)}$. See footnote to Stable Particle Table.
- † Square brackets indicate a subreaction of the previous (unbracketed) decay mode(s).
- § This is only an educated guess; the error given is larger than the error of the average of the published values. (See Meson Data Card Listings for the latter.)

(a) $\Gamma M$ is approximately the half-width of the resonance when plotted against $M^2$.

(b) For decay modes into ≥ 3 particles, $p_{max}$ is the maximum momentum that any of the particles in the final state can have. The momenta have been calculated by using the averaged central mass values, without taking into account the widths of the resonances.

(c) From pole position $(M - i\Gamma/2)$.

(d) The $e^+e^-$ branching ratio is from $e^+e^- \to \pi^+\pi^-$ experiments only. The $\omega\rho$ interference is then due to $\omega\rho$ mixing only, and is expected to be small. See note in Meson Data Card Listings. The $\mu^+\mu^-$ branching ratio is compiled from 3 experiments; each possibly with substantial $\omega\rho$ interference. The error reflects this uncertainty; see notes in Meson Data Card Listings. If $e\mu$ universality holds, $\Gamma(\rho^0 \to \mu^+\mu^-) = \Gamma(\rho^0 \to e^+e^-) \times 0.99785$.

(e) Empirical limits on fractions for other decay modes of $\rho(770)$ are $\pi^\pm\eta < 0.8\%$, $\pi^+\pi^+\pi^-\pi^- < 0.15\%$, $\pi^\pm\pi^+\pi^-\pi^0 < 0.2\%$.

(f) Empirical limits on fractions for other decay modes of $\omega(783)$ are $\pi^+\pi^-\gamma < 5\%$, $\pi^0\pi^0\gamma < 1\%$, $\eta$ + neutral(s) < 1.5%, $\mu^+\mu^- < 0.02\%$, $\pi^0\mu^+\mu^- < 0.2\%$.

(g) Empirical limits on fractions for other decay modes of $\eta'(958)$: $\pi^+\pi^- < 2\%$, $\pi^+\pi^-\pi^0 < 5\%$, $\pi^+\pi^+\pi^-\pi^- < 1\%$, $\pi^+\pi^+\pi^-\pi^-\pi^0 < 1\%$, $6\pi < 1\%$, $\pi^+\pi^-e^+e^- < 0.6\%$, $\pi^0e^+e^- < 1.3\%$, $\eta e^+e^- < 1.1\%$, $\pi^0\rho^0 < 4\%$.

(h) The mass and width are from the $\eta\pi$ mode only. If the $K\bar{K}$ channel is strongly coupled, the width may be 300 MeV or more.

(i) Empirical limits on fractions for other decay modes of $\phi(1020)$ are $\pi^+\pi^- < 0.03\%$, $\pi^+\pi^-\gamma < 0.7\%$, $\omega\gamma < 5\%$, $\rho\gamma < 2\%$, $2\pi^+2\pi^-\pi^0 < 1\%$.

(j) Empirical limits on fractions for other decay modes of B(1235): $\pi\pi < 15\%$, $K\bar{K} < 2\%$, $4\pi < 50\%$, $\phi\pi < 1.5\%$, $\eta\pi < 25\%$, $(\bar{K}K)^\pm\pi^0 < 8\%$, $K_SK_S\pi^\pm < 2\%$, $K_SK_L\pi^\pm < 6\%$.

(k) Empirical limits on fractions for other decay modes of f'(1515) are $\eta\eta < 50\%$, $\eta\pi\pi < 30\%$, $K\bar{K}\pi + K^*\bar{K} < 35\%$, $2\pi^+2\pi^- < 32\%$.

(ℓ) Empirical limits on fractions for other decay modes of f(1270) are $\eta\pi\pi < 1\%$, $K^0K^-\pi^+$ + c.c. < 1%, $\eta\eta < 2\%$.

Established Nonets, and octet-singlet mixing angles from Appendix IIB, Eq. (2'). Of the two isosinglets, the "mainly octet" one is written first, followed by a semicolon.

| $(J^P)C_n$ | Nonet members | $\theta_{lin.}$ | $\theta_{quadr.}$ |
|---|---|---|---|
| $(0^-)+$ | $\pi$, K, $\eta$; $\eta'$ | $-24 \pm 1°$ | $-11 \pm 1°$ |
| $(1^-)-$ | $\rho$, $K^*$, $\phi$; $\omega$ | $38 \pm 1°$ | $40 \pm 1°$ |
| $(2^+)+$ | $A_2$, $K^*(1430)$, f'; f | $24 \pm 2°$ | $26 \pm 2°$ |