CONF-8909221--6

BROOKHAVEN NATIONAL LABORATORY

December, 1989 BNL -43729

OG-2011

A Program of 'Quark-Gluon' Spectroscopy at BNL

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ABSTRACT

The current status and future prospects are given of the quark-gluon spectroscopy, and a multi-year experimental program at BNL is described, consisting of experiments E771, E818 and E852, which address the question of missing quarkonia in the $SU(3)$ family of mesons and the existence of exotic hadrons with gluonic degrees of freedom.

BNL--43729

DE90 005561

Invited talk at

the International Conference on Hadron Spectroscopy,

Ajaccio, Corsica, France, 23-27 September 1989.

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1. Introduction

This note is intended as a general overview of the status of the quark-gluon meson spectroscopy involving light quarks, and how a series of experimental programs at BNL is endeavoring to discover exotic hybrids, glueballs and missing quarkonia. Specifically, this note describes the BNL experiments, performed by a BNL-Florida State-Indiana-Rice-Southeastern Mass collaboration (E771[1]), being carried out by a BNL-Indiana-Kyungpook-Rice-Southeastern Mass collaboration (E818[2]) and being prepared by a BNL-Indiana-Louisville-Moscow State-Notre Dame-Rice-Southeastern Mass collaboration (E852[3]). All are designed to uncover the gluonic degrees of freedom in hadronic states and hunt for the missing quarkonia within the family of $SU(3)$ nonets. A key to future advances is that a comprehensive capability for both charged and neutral detection, embodied by E852, is precisely what is needed to fill out the missing nonets and simultaneously to uncover those characteristics of the hadronic states which lie outside the realm of quarkonia.

Much of the recent material in this field can be found in the Proceedings of the 1988 BNL Workshop on Glueballs, Hybrids and Exotic Hadrons[4]. The reader may consult additional relevant material in two recent reviews[5,6]. With regard to the characteristics of the missing nonet members and hybrids, the author has drawn heavily from two phenomenological papers[7,8].

The light-quark mesons listed in the Meson Summary Table[9] can be divided into two classes; the ones having ready placements in the ground-state (radial quantum number $n = 1$) nonets (Tables I, II and III) and those that appear to lie outside (Tables IV and V).

The S- and P-wave quarkonia, listed in Table I, are generally well established, but the $s\bar{s}$ states $h'(1380)$, $f'_0(1530)$ represent recent results from LASS[10]. The state $a_0(1300)$, seen as an S-wave structure in the $\pi\eta$ channel by the GAMS group[11], is a candidate for being the sought-after isovector $J^{PC} = 0^{++}$ resonance. In this scheme the $f_0(975)$ and the $a_0(980)$ may then be safely assigned to being the $K\bar{K}$ molecules[12].

The D- and F-wave quarkonia are given in Tables II and III. It is seen that many of the states are not yet established; only 6 states are listed in the Meson Summary Table, out of a total of 32 possible states. The masses and certain decay modes of the missing states correspond to the predictions given by Godfrey and Isgur (the GI model)[7].

Tables IV and V list the particles appearing in the Meson Summary Table but without ready placements in the $SU(3)$ family of mesons. The list includes the candidates for mesonic molecules, hybrids and glueballs, in addition to those belonging to the radial excitations.

Tables VI, VII and VIII contain J^{PC}-exotic states which are forbidden in the quarkonium family of mesons[8]. The notation is borrowed from that for quarkonia; the names are those which result if the C of the J^{PC} is flipped, and this operation is denoted with a 'tilde.' It should be noted that the 0^{--}-exotic hybrids are not allowed in the flux-tube model[13]. Discovery of such a state will necessitate, therefore, modification of the flux-tube model. Their masses are of course not predicted; they are arbitrarily assumed to be the same as those of other exotics in the table.

In this note, possible decay modes of a state are listed together with the particle, but it should be emphasized that no attempt has been made to be complete with all the possible decay modes. Instead, a few representative decays have been worked out using the final states which are readily identifiable experimentally. For a systematic study of meson decays in the flux-tube model, the reader is referred to a paper by R. Kokoski and N. Isgur[14].

2. E771 Experiment at BNL

This experiment was designed to study the *E/iota* phenomena at BNL energies; the data were taken in 1983, 1985, 1986 and 1987 with π^-, K^- and $\bar{p}$ beams at 6.6 or 8.0 GeV/c. The reactions of interest are

$$\begin{aligned}\pi^- p &\rightarrow K^+ K_S \pi^- n\\ K^- p &\rightarrow K^+ K_S \pi^- X^0\\ \bar{p} p &\rightarrow K^+ K_S \pi^- X^0\end{aligned}$$

where

$$K_S \rightarrow \pi^+\pi^-$$

Here missing neutrals are denoted by X^0. Table A shows a summary of the total flux attained and the numbers of events collected in each category. The $\bar{p}$ data from 1983 have a substantial background, because the fast forward protons were indistinguishable from K^+'s; this background has been eliminated with the use of a time-of-flight counter in 1987.

Table A: E771 Data on $K^+K_S\pi^-$ System

Year	Beam	Momentum (GeV/c)	Flux (ev/nb)	Recoil System	Events (K)
1983	π^-	8.0	290	n	15
1985	π^-	8.0	290	n	15
1986	π^-	8.0	440	n	23
			1020		53
1983	$\bar{p}$	6.6	49	X^0	12
1987	$\bar{p}$	8.0	86	X^0	6
			135		18
1985	K^-	8.0	13	X^0	1
1986	K^-	8.0	13	X^0	1
1987	K^-	8.0	68	X^0	6
			94		8

The experimental layout for the 1987 run is shown in Fig. 1. The MPS magnet energized to 5 kgauss was filled with 7 drift-chamber modules (DC1 through DC7) with 7 measuring planes each and a position resolution of $250 \mu m$, three proportional-wire chambers (P1, P2 and P3), a LH_2 target surrounded by a lead-scintillation sandwich veto counter (TB) to discriminate against soft pions and to enhance neutron recoils with π^- beams.

Downstream of the MPS magnet a high-pressure Cerenkov counter with η (threshold) = 10 was used to trigger on kaons or protons and was augmented with two planar scintillation counter hodoscopes (H1 and H2) and a precision time-of-flight (TOF) counter (T1) with a time resolution of 150 psec (rms). A key element in the trigger was a RAM system (128 x 128 x 128 elements) which allowed on-line identification of a K^+ or a proton with momentum greater than 1.5 GeV/c. The first two inputs to the RAM came from P2 and P3, while the third input was derived from $\mathrm{H1}\cdot\overline{\mathrm{C1}}$, $\mathrm{TOF}\cdot\overline{\mathrm{C1}}$ and H2. For K^-p data the TOF counter was indispensable in distinguishing a K^+ from a proton. The presence of a K_S decay was implemented in the trigger by requiring an increase in multiplicity by two from P1 to P2.

Fig. 2 shows the K_S and missing mass spectra for the π^-p data (full sample). It is seen that the K_S mass is measured with an accuracy of 3.4 MeV (rms), while the missing mass spectrum shows that the neutron is detected with a resolution of 0.15 GeV^2 (rms). They demonstrate that our data are exceptionally clean, being consistent with better than 95% $K^+K_S\pi^-n$ exclusive events. The $K^+K_S\pi^-$ spectrum is given in Fig. 3, in which two prominent peaks are seen at 1.28 GeV and 1.42 GeV, respectively, and a 'blip' around 1.51 GeV. A fit of three S-wave Breit-Wigner forms over a polynomial background gives:

Mass (MeV)	Width (MeV)	Number of Events
1285 ± 1	22 ± 2	4750 ± 100
1419 ± 1	66 ± 2	8800 ± 200
1512 ± 4	35 ± 15	600 ± 200

A full partial-wave analysis (PWA) has been performed on this data and the results reported at a number of international conferences[15] and also published[16] in 1988. The results of the latest PWA on this data were presented at the BNL Workshop in 1988 by D. Zieminska[15].

The major conclusions of this analysis are that there exist two $J^{PG} = 0^{-+}$ states around 1.40 to 1.48 GeV. As shown in Fig. 5, the phase motion of the $0^{-+}\,(a_0\pi)$ with respect to the $1^{++}\,\left(K^*\bar{K}\right)\,0^+$ wave (the 0^+ here refers to $m = 0$ and reflectivity[17]=+1) exhibits a steep rise, consistent with the hypothesis that the $0^{-+}\,(a_0\pi)$ state is genuinely resonant. The $0^{-+}\,\left(K^*\bar{K}\right)$ wave, on the other hand, does not show a similar phase motion because of its low degree of coherence with the $1^{++}\,\left(K^*\bar{K}\right)$ wave. It can be argued, nevertheless, that this wave is also resonant since it is a P-wave state at the $K^*\bar{K}$ threshold.

The case for existence of two 0^{-+} states is summarized in Fig. 6. First, the two partial waves $0^{-+}\,(a_0\pi)$ and $0^{-+}\,\left(K^*\bar{K}\right)$ show different mass dependence (see Figs. 6a and 6b), in particular as a function of $-t$ (not shown), and second, the coherence between the two waves (see Fig. 6c) goes through a rapid variation above 1.45 GeV, indicating a different admixture of spin-flip and non-spin-flip amplitudes at the nucleon vertex. As a consequence, the coherence of the $0^{-+}\,(a_0\pi)$ with the 1^{++} wave is markedly different from that of the $0^{-+}\,\left(K^*\bar{K}\right)$. These observations strongly suggest there exist two 0^{-+} states at around 1.40 and 1.48 GeV, respectively.

The $K^+K_S\pi^-$ spectra from the data of the inclusive reactions with K^- and $\bar{p}$ beams (1987 data alone) is given Fig. 7, along with the π^- data on the same scale for comparison. All three data samples show a prominent structure in the 1.42 GeV region, but the 1.28 GeV peak is largely absent in the K^- data. This indicates that the 1.28 GeV structure is not primarily an $s\bar{s}$ state. The general drop-off of events in the mass region above 1.4 GeV is largely due to the falling acceptance of the E771 aparatus. Nevertheless, the 1.6-GeV region for the π^- data is clearly enhanced compared to those of the K^- and $\bar{p}$ data; the results of the PWA indicate that this broad enhancement is mostly due to the $J^{PG} = 1^{-+}$ state and confined to a low $-t$ region, i.e. the $\rho(1700)$ is being produced in the π^-p interactions. Note also that the 'blip' at 1.51 GeV seen in the π^- data is more strongly produced in the K^- data, indicating that this object has a substantial $s\bar{s}$ component.

The results of the PWA on the K^- and $\bar{p}$ data should be forthcoming in the near future.

3. E818 Experiment at BNL

The main purpose of this experiment is to look for a $J^{PC} = 1^{-+}$ (exotic) hybrid in the final state $\pi f_1\,(1285)$. Thus, the reaction of interest is

$$\begin{aligned} \pi^- p &\rightarrow \tilde{\rho}_1^-\,(1900)\, p \quad \text{at 18 GeV/c}, \\ \tilde{\rho}_1^-\,(1900) &\rightarrow f_1\,(1285)\,\pi^-, \\ f_1\,(1285) &\rightarrow K^+ K_S \pi^- \end{aligned}$$

where

$$K_S \rightarrow \pi^+\pi^-$$

According to the flux-tube model introduced by Isgur, Kokoski and Paton[8], the total width of the $\tilde{\rho}_1\,(1900)$ is 180 MeV, and its branching ratio into πf_1 is 28% with the rest going into πb_1. Note that both S and D orbital angular momenta are allowed for these decay modes; the ratio $S/(S{+}D)$ for the πf_1 decay is 60% according to the model, while the same ratio for the πb_1 decay is 77%.

The experimental setup[18] is similar to that of E771, with the veto box (TB) replaced by a 4-layer cylindrical drift-chamber module (each layer with a ϕ resolution better than 0.3°) to detect recoil protons and a new lead-scintillation sandwich veto counter surrounding the cylindrical module. The experiment is scheduled to run early in 1990 at the MPS.

In an 800-hr data-taking run at the AGS, one can anticipate a total flux of 950 ev/nb with a π^- beam at 1.5×10^6/spill and 1.2×10^3 spills/hr impinging on a 30cm LH_2 target, including a contingency factor of 50%. The acceptance for the final state of interest is 14.3% for an 18 GeV/c π^- beam. Thus the visible sensitivity is 135 ev/nb, meaning that a state with its σB of 1nb will show up as a 135-event bump.

This experiment aims to look for a 1^{-+} object from the πf_1 threshold up to 2.0 GeV. Of particular interest is the $M\,(1406)$ seen in the $\pi\eta$ decay mode; according to the flux-tube model, it is expected to have a substantial coupling to the πf_1 decay channel, appearing as a threshold enhancement.

4. E852 Experiment at BNL

This experiment represents an ambitious effort to systematically explore both neutral and charged decays of mesons, hybrids and other exotic hadrons in the mass range 1 to 2.5 GeV. It is in this mass region where the bulk of the missing D- and F-wave quarkonia, exotic hybrids and glueballs are expected to be discovered.

The experimental setup is given in Figs. 8a and 8b. At the downstream end of the MPS is a lead-glass detector (LGD) consisting of approximately 3000 blocks (3.8 x 3.8 x 45cm each). In front of the LGD is an atmospheric-pressure Cerenkov counter (C8) with η(threshold) = 20 for K^+ (K^-) or $p\,(\bar{p})$ identification. There are in addition four MPS drift-chamber modules and four proportional-wire chambers (TPX1 through TPX4) situated downstream of the target region. At the center of the MPS magnet is a 30-cm LH_2 target surrounded by a 180-element array of CsI crystals and a downstream lead-scintillation window-frame counter, where both systems are to be used to veto on soft photons outside of the cone covered by the LGD. The target assembly is further fitted with a Cerenkov-light detector designed to locate the production vertex for all-neutral triggers with a position resolution better than 5cm along the beam.

The rms energy resolution of the LGD is expected to be

$$\frac{\sigma_E}{E} = 1.1\% + \frac{5.3\%}{\sqrt{E(GeV)}}$$

and a spatial resolution of 1 to 2mm at the front face of the LGD. A study of the all-neutral reaction

$$\pi^- p \rightarrow M^0(1406)\,n \rightarrow \pi^0 \eta n \rightarrow 4\gamma n$$

at 21 GeV/c, for example, shows that one should achieve the following rms mass resolutions:

$$\delta M\,(\eta) = 16 \text{ MeV}, \qquad \delta M\,(\pi^0) = 5 \text{ MeV},$$
$$\delta M\,(\pi^0\eta) = 21 \text{ MeV}, \qquad \delta MM^2 = 0.7\ (\text{GeV})^2,$$

If one assumes an AGS run of 1000 hours, one can accumulate a total flux of 1.56 ev/pb with a π^- beam at 2×10^6/spill and 1.2×10^3 spills/hr on a 30cm LH_2 target, including a contingency factor of 50%. Extrapolating from the GAMS data at 100 GeV/c beam with the cross section dependence of P_{LAB}^{-2}, one obtains for the $M^0(1406) \rightarrow 4\gamma$ a σB of (79±18)nb. The acceptance of our apparatus for this final state is estimated to be 57%, so that one may expect an $M^0(1406)$ yield of $(70 \pm 16) \times 10^3$. This is to be compared to 1.2×10^3 events attributable to $M^0(1406)$ in the GAMS-4000 data at CERN. The crucial difference between these two experiments is that the cross section is over 20 times larger at 21 GeV/c than at 100 GeV/c.

E852 has additional advantages over GAMS, in that E852 aims to detect most, if not all, charged decay modes as well. For example, the decay $\eta \rightarrow \pi^+\pi^-\pi^0$ is accessible to E852; so is the charged meson of interest, i.e. $M^-(1406) \rightarrow \pi^-\eta$ recoiling off a proton.

The E852 collaboration is hoping to fabricate all the necessary apparatus by the end of 1992 and be ready for data-taking in 1993. The collaboration regards this as the beginning of a long series of experiments to explore all the ramifications of the light-quark hadron spectroscopy. In particular, this apparatus can be exposed to a K^- beam to explore strange quarkonia and strangeonia. This avenue becomes particularly attractive with the Booster at the AGS[19] and an RF-separated K^- beam, in which case the flux becomes comparable to that of the currently available π^- beam.

With this experimental setup there exists a certain class of 'practical' particles which are easily accessible. They are listed in Table B along with their decay modes and branching ratios.

The listed decay channels show that they can be observed either by an electromagnetic calorimeter or by a strange-particle detector with both a Cerenkov counter and a V^0 detector. In addition, the listed particles are either abundantly produced in hadronic interactions or have distinct experimental signatures with generally narrow widths.

The experiment is to be performed with a π^- beam impinging on a LH_2 target. It is therefore assumed that E852 will be most sensitive to non-strange quarkonia $n\bar{n}$, multi-quarks $n\bar{n}n\bar{n}$ or hybrids $n\bar{n} + g$. For example, the $a_0(980)$ is seen in π^-p interactions, but it is thought to be a $K\bar{K}$ molecule; the $\iota/\eta(1450)$, a hybrid candidate, is again observed in π^-p interactions.

Table B: 'Practical Particles' for E852

Particle	Decay Modes	Branching Ratio(%)
π^0	$\gamma\gamma$	98.8
η	$\gamma\gamma$	38.9
$\omega\,(783)$	$\pi^0\gamma$	8.0
$b_1\,(1235)$	$\pi\omega$	Dominant
$f_1\,(1285)$	$\pi\pi\eta$	49
	$K\bar{K}\pi$	11
$a_2\,(1320)$	$\pi\eta$	14.5
	$K\bar{K}$	4.9
$f_2\,(1270)$	$K\bar{K}$	4.2

If hybrids are produced in hadronic interactions, then surely the J^{PC}-exotic hybrids should also be observed in these processes. The $M/\tilde{\rho}_1\,(1406)$, seen in a $\pi\eta$ channel, is currently the most promising candidate for an exotic hybrid. Since it is produced in the partial-wave P_0 in $\pi^- p$ interactions, the $b_1\,(1235)$ is the only allowed exchanged particle. Therefore, the M must also decay into the channel πb_1. According to Isgur et al[8], this decay mode should indeed be the dominant one. Note that the GAMS group, with an all-neutral detector only, could not have observed the πb_1 channel because the M is an isovector.

It is helpful to recapitulate a plethora of particles which the channels πb_1 and πa_2 can couple to. It is summarized in Tables C and D.

Note that, ignoring $I = 2$, a channel with a net charge can couple only to an isovector, while that with two neutral particles communicates only with an isoscalar. The subscripts, as before, denote orbital angular momenta (L). Whenever allowed, up to two L values are given as subscripts.

It should be emphasized that the decay modes considered in this note are those that are kinematically allowed; no consideration is given to possible dynamical variations in the coupling constants.

Table C: Decay channels $\pi b_1\,(1235)$ and $\pi a_2\,(1320)$ for quarkonia

Particle	Decay Modes	Particle	Decay Modes
$\pi_2\,(1670)$	$[\pi b_1]^{\pm}_{D}$	$\eta_2\,(1680)$	$[\pi^0 a_2^0]_{S,D}$
$\rho_1\,(1660)$	$[\pi a_2]^{\pm}_{D}$	$\omega_1\,(1660)$	$[\pi^0 b_1^0]_{S,D}$
$\rho_2\,(1700)$	$[\pi a_2]^{\pm}_{S,D}$	$\omega_2\,(1660)$	$[\pi^0 b_1^0]_{D}$
$\rho_3\,(1700)$	$[\pi a_2]^{\pm}_{D,G}$	$\omega_3\,(1660)$	$[\pi^0 b_1^0]_{D,G}$
$b_3\,(2030)$	$[\pi a_2]^{\pm}_{P,F}$	$h_3\,(2030)$	$[\pi^0 b_1^0]_{F}$
$a_2\,(2050)$	$[\pi b_1]^{\pm}_{P,F}$	$f_2\,(2050)$	$[\pi^0 a_2^0]_{P,F}$
$a_3\,(2050)$	$[\pi b_1]^{\pm}_{F}$	$f_3\,(2050)$	$[\pi^0 a_2^0]_{P,F}$
$a_4\,(2010)$	$[\pi b_1]^{\pm}_{F,H}$	$f_4\,(2050)$	$[\pi^0 a_2^0]_{F,H}$

Table D: Decay channels $\pi b_1\,(1235)$ and $\pi a_2\,(1320)$ for exotic hybrids

Particle	Decay Modes	Particle	Decay Modes
$\tilde{a}_0\,(1900)$		$\bar{f}_0\,(1900)$	$[\pi^0 b_1^0]_{P}$
$\bar{\pi}_0\,(1900)$	$[\pi a_2]^{\pm}_{D}$	$\bar{\eta}_0\,(1900)$	
$\bar{\rho}_1\,(1900)$	$[\pi b_1]^{\pm}_{S,D}$	$\bar{\omega}_1\,(1900)$	$[\pi^0 a_2^0]_{S,D}$
$\bar{a}_2\,(1900)$	$[\pi a_2]^{\pm}_{P,F}$	$\bar{f}_2\,(1900)$	$[\pi^0 b_1^0]_{P,F}$
$\bar{\rho}_3\,(1900)$	$[\pi b_1]^{\pm}_{D,G}$	$\bar{\omega}_3\,(1900)$	$[\pi^0 a_2^0]_{D,G}$
$\bar{a}_4\,(1900)$	$[\pi a_2]^{\pm}_{F,H}$	$\bar{f}_4\,(1900)$	$[\pi^0 b_1^0]_{F,H}$

5. Conclusions

In this note a survey of the current status of the quark-gluon spectroscopy is given and a series of three experiments at BNL designed to attack the unsolved problems is described.

The results of E771 show the existence two 0^{-+} $K\bar{K}\pi$ states in the 1.40 to 1.48 GeV region. The data of J/ψ radiative decays are also consistent with this interpretation[20].

At least one of the two is likely to be either a glueball or a hybrid. The glueball mass calculations with the Lattice Gauge Theory generally put $M\left(0^{-+}\right)$ at or near $M\left(2^{++}\right)$ which lies about 1.5 times higher in mass than $M\left(0^{++}\right)$[21,22,23]. Thus, if the $G\,(1590)$ is the 0^{++} glueball, then the 2^{++} and the 0^{-+} glueballs lie well above 2.0 GeV. In this scenario, one of the two 0^{-+} states seen below 1.5 GeV is likely to be a hybrid. Since a hybrid has both valence gluon and quarks, it may be produced abundantly both in J/ψ radiative decays and in hadronic interactions.

The E818 experiment is designed to look at the $\pi f_1\,(1285)$ channel, where a hybrid is expected to be seen at around 1.9 GeV according to the flux tube model. This experiment will also collect events satisfying the E771 trigger; the chief aim here is to study the energy dependence of the two 0^{-+} states in 1.4 to 1.5 GeV region.

The E852 experiment is conceived as a definitive treatment of the mesons produced at BNL energies. This experiment, one hopes, will settle all the missing links in the $D-$ and $F-$wave quarkonia. In addition, the glueballs and hybrids up to 2.4 GeV can be looked for systematically. This endeavor will continue well into the era of the upgraded AGS with the Booster, probably until the advent of the RHIC.

Acknowledgement

The author is grateful to the organizers of the 3rd International Conference on Hadron Spectroscopy at Ajaccio, Corsica, France during 23-27 September 1989. The meeting was a great success, thanks to the Conference organizers as well as the local authorities of Corsica. He is also indebted to W. Kern, S. D. Protopopescu, H. J. Willutzki and D. Zieminska for their careful reading of a preliminary draft of this note. Finally, he acknowledges with pleasure several valuable conversations he has had with N. Isgur and S. Godfrey.

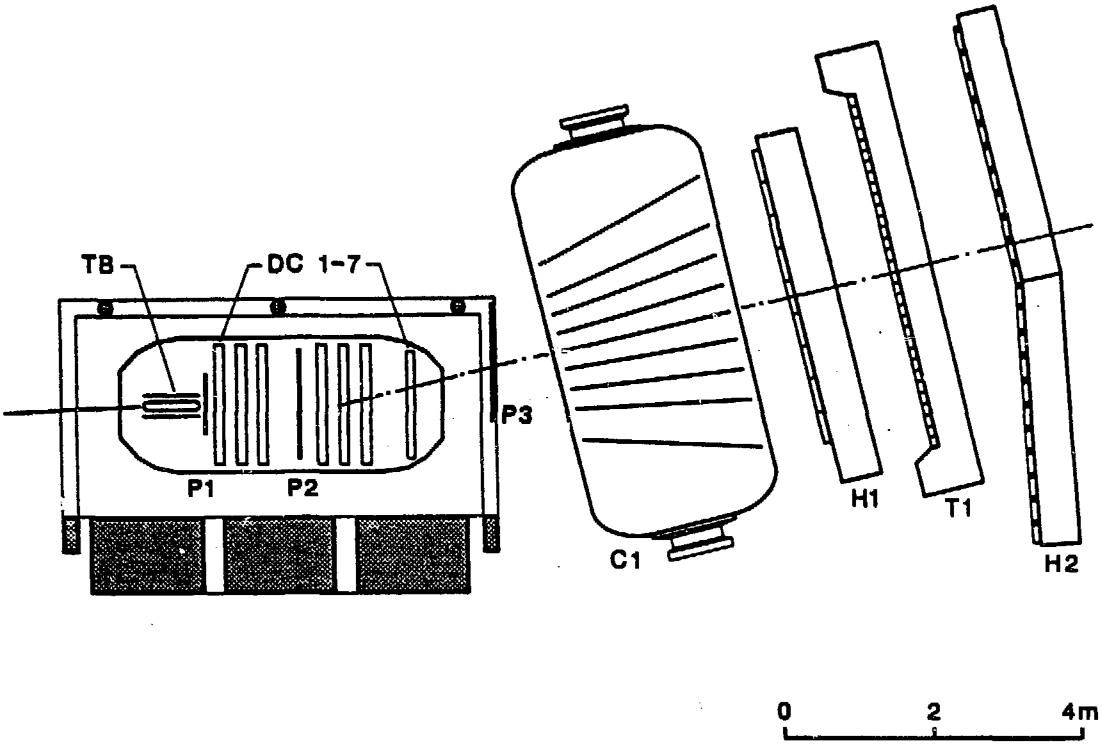

Figure 1: E771 layout. See text for explanations.

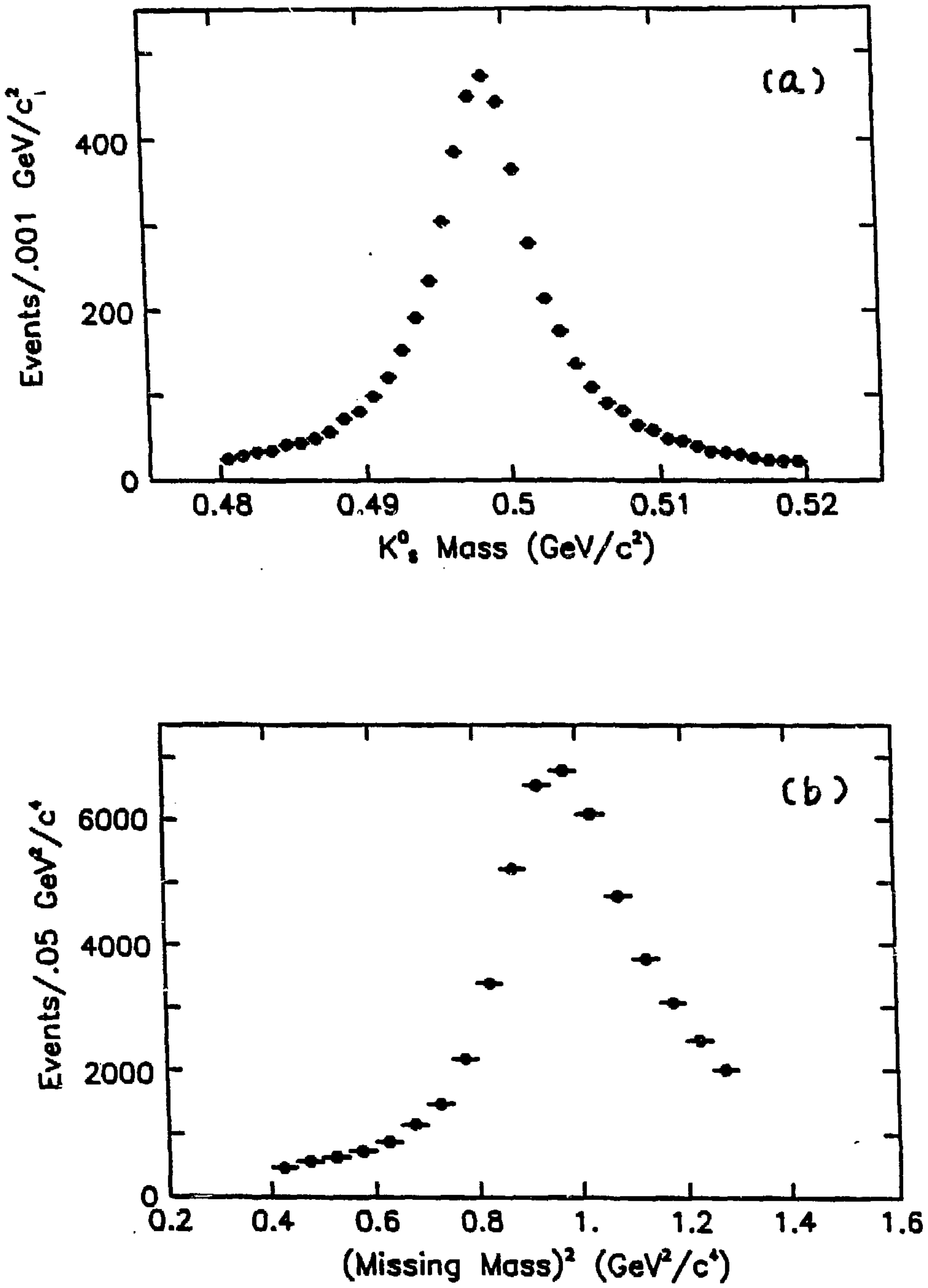

Figure 2: Characterisitics of the $\pi^- p$ data: (a) K_S mass spectrum. (b) (Missing Mass)^2 spectrum.

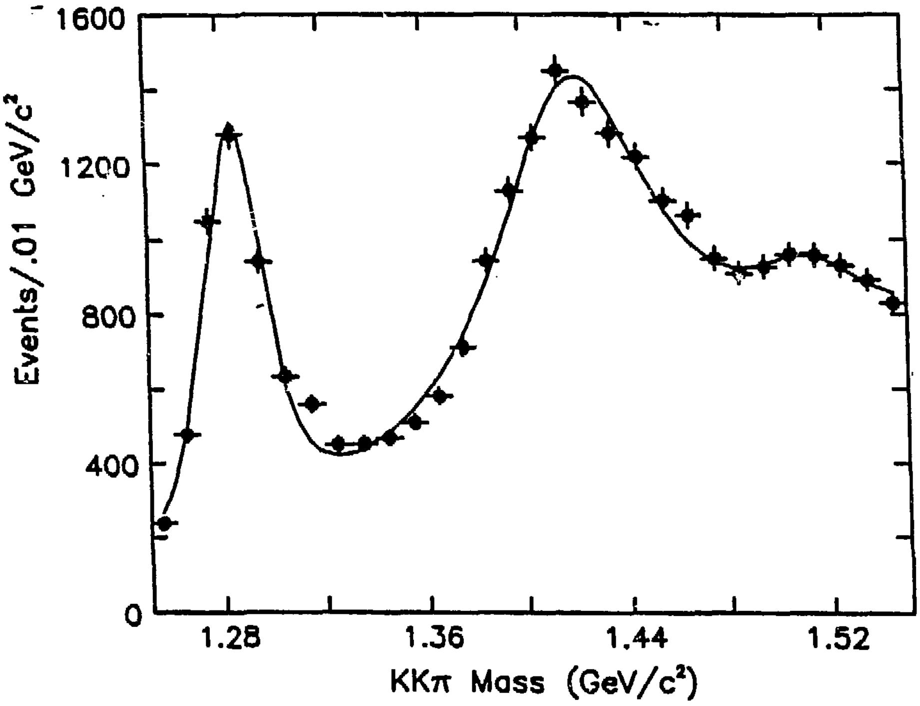

Figure 3: $K^+K_S\pi^-$ mass spectrum for the π^-p data. See text for an explanation of the curve.

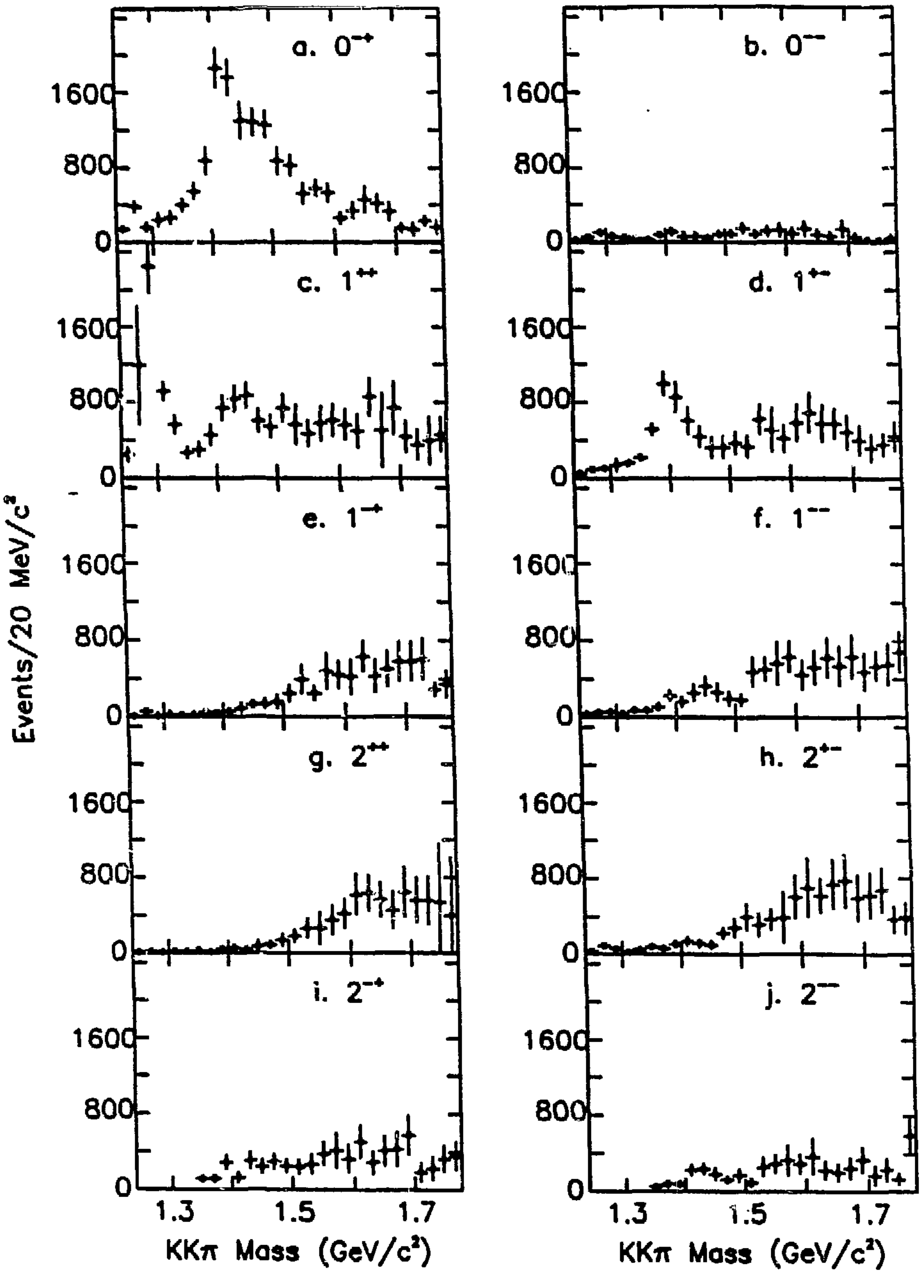

Figure 4: Results of the PWA on the $\pi^- p$ data, showing decomposition into various J^{PG} waves. The analysis was done on three separate $-t$ bins, 0–0.14, 0.14–0.40 and 0.40–1.40 $(\mathrm{GeV}/c)^2$, and the resulting waves have been recombined.

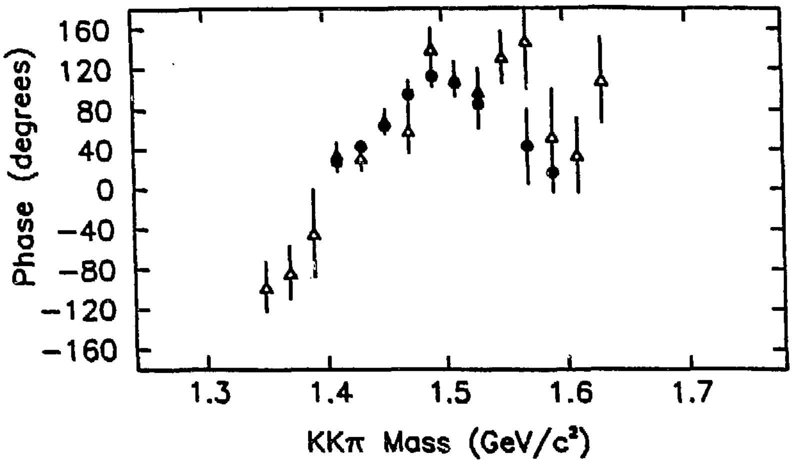

Figure 5: Phase of $0^{-+}\,(a_0\pi)$ with respect to $1^{++}\,(K^*\bar{K})\,0^+$ for $0.14 \leq -t < 0.40\,(\mathrm{GeV/c})^2$(closed circles) and for $0.40 \leq -t < 1.40\,(\mathrm{GeV/c})^2$(open triangles).

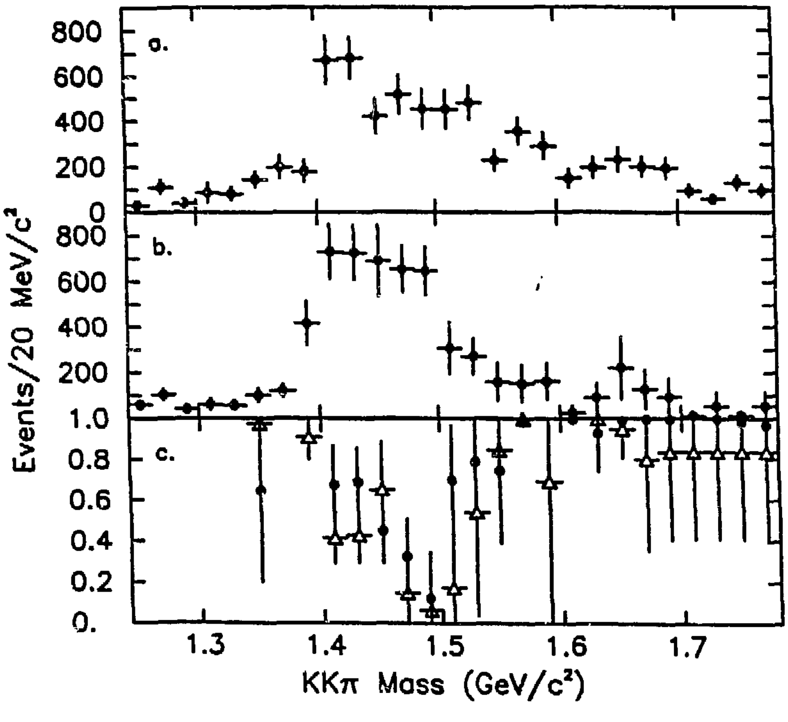

Figure 6: Study of the $J^{PG} = 0^{-+}$ wave. (a) $0^{-+}\,(a_0\pi)$; (b) $0^{-+}\,(K^*\bar{K})$; (c) Coherence between the two waves.

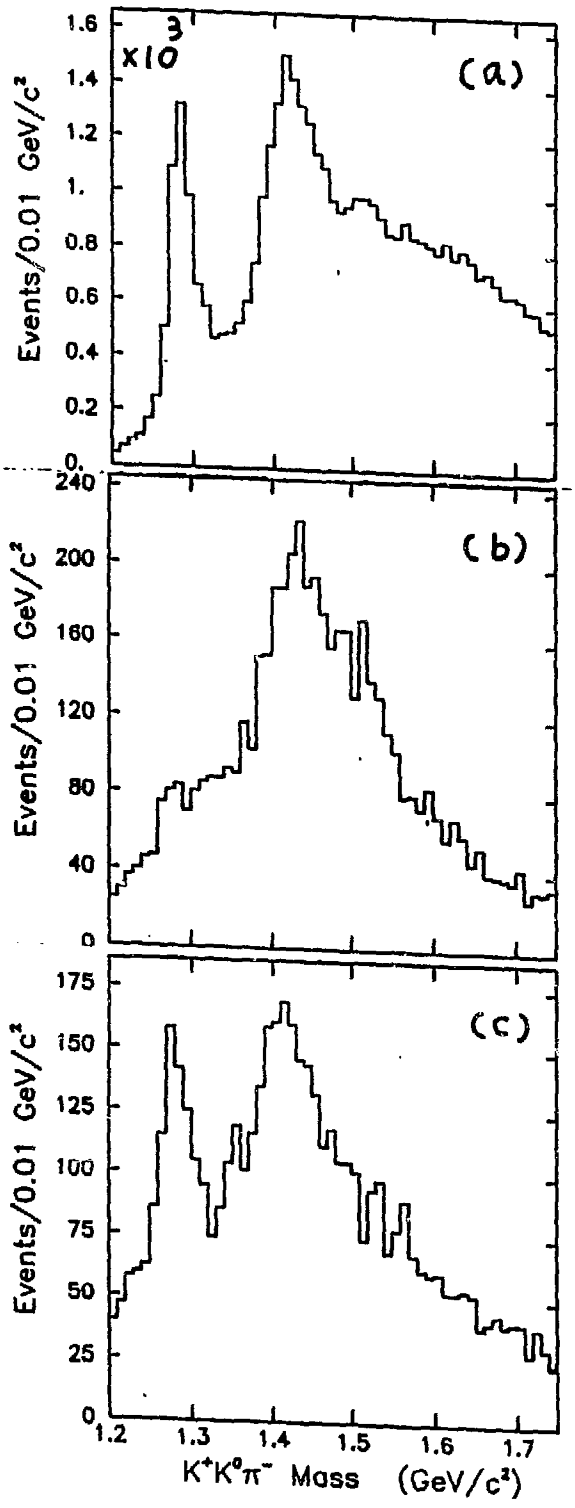

Figure 7: $K\bar{K}\pi$ Spectra from the E771 data. (a) $\pi^- p$ data; (b) $K^- p$ data; (c) $\bar{p}p$ data.

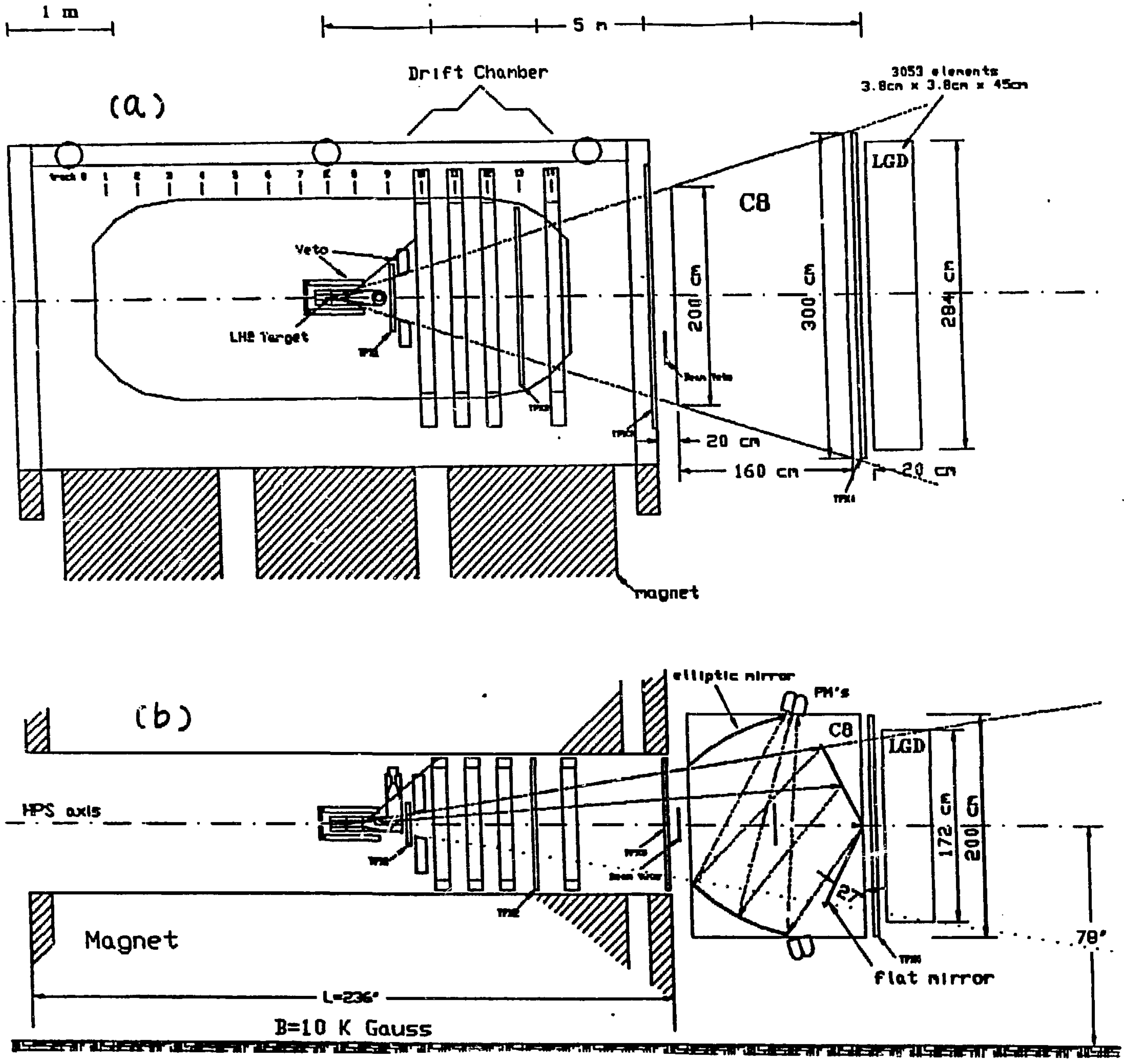

Figure 8: E852 layout. See text for explanations. (a) Plan view; (b) Side view.

Table I: Ground-state quarkonia [a]

$^{2S+1}L_J$	J^{PC}	$I=1\,(n\bar{n})$ Decay Modes [b],[c]	$I=0\,(n\bar{n})$ Decay Modes [b],[c]	$I=0\,(s\bar{s})$ Decay Modes [b],[c]	$I=1/2\,(s\bar{n})$ Decay Modes [b],[c]
$^1S_0$	0^{-+}	π[d]	$\eta'\,(958)$[d],[e] $\pi\pi\eta$	η[d],[e]	K[d]
$^3S_1$	1^{--}	$\rho\,(770)$[d] $\pi\pi$	$\omega\,(783)$[d] $\pi\pi\pi$	$\phi\,(1020)$[d] $K\bar{K}$	$K^*\,(892)$[d] $K\pi$
$^1P_1$	1^{+-}	$b_1\,(1235)$[d] $[\pi\omega]_S$	$h_1\,(1170)$[d] $[\pi^0\rho^0]_S$	$h'\,(1380)$[f] $K\bar{K}\pi$	$K_{1b}\,(1300)$[g] $K\pi\pi$
$^3P_0$	0^{++}	$a_0\,(1300)$[h] $\pi\eta$	$f_0\,(1400)$[d] $\pi^0\pi^0$	$f_0'\,(1530)$[f] $K\bar{K}$	$K_0^*\,(1430)$[d] $K\pi$
$^3P_1$	1^{++}	$a_1\,(1260)$[d] $[\pi\rho]_S$	$f_1\,(1285)$[d] $\pi^0a_0^0\,(980)$ $\pi\pi\rho$	$f_1'\,(1530)$[d] $[K^*\bar{K}]_S$	$K_{1a}\,(1390)$[g] $K\pi\pi$
$^3P_2$	2^{++}	$a_2\,(1320)$[d] $[\pi\rho]_D$ $\pi\eta$ $K\bar{K}$	$f_2\,(1270)$[d] $\pi^0\pi^0$ $\pi^+\pi^-2\pi^0$ $K\bar{K}$	$f_2'\,(1525)$[d] $K\bar{K}$	$K_2^*\,(1430)$[d] $K\pi$ $[K^*\pi]_D$

[a] n stands for u and d.

[b] All-neutral decay modes, where possible, are explicitly given.

[c] The lowest allowed orbital-angular momentum (≤ 3) is given as a subscript.

[d] Listed in the Meson Summary Table.

[e] η [$\eta'\,(958)$] is approximately an $SU\,(3)$ octet [singlet].

[f] LASS result

[g] Assumed ideally mixed combination of $K_1\,(1270)$ and $K_1\,(1400)$.

[h] GAMS result

Table II: Ground-state quarkonia[a]—cont'd

${}^{2S+1}L_J$	J^{PC}	$I=1\,(n\bar{n})$ Decay Modes [b],[c]	$I=0\,(n\bar{n})$ Decay Modes [b],[c]	$I=0\,(s\bar{s})$ Decay Modes [b],[c]	$I=1/2\,(s\bar{n})$ Decay Modes [b],[c]
${}^1D_2$	2^{-+}	$\pi_2\,(1670)$[d] $[\pi\rho]_P$ $[\pi f_2]_S$ $[\pi b_1]_D$ $[\pi f_1]_D$ $[\rho\omega]_P$	$\eta_2\,(1680)$[i] $[\pi^0 a_2^0]_S$ $[\omega\omega]_P$	$\eta_2'\,(1890)$[i] $[K^*\bar{K}]_P$ $[K_2^*\bar{K}]_S$	$K_2\,(1780)$[i] $[K\rho]_P$ $[K_2^*\pi]_S$ $[K^*\pi]_P$
${}^3D_1$	1^{--}	$\rho_1\,(1660)$[i] $\pi\pi$ $[\pi\omega]_P$ $[\eta\rho]_P$ $[\pi a_2]_D$	$\omega_1\,(1660)$[i] $[\pi^0\rho^0]_P$ $[\pi^0 b_1^0]_S$ $[\eta\omega]_P$	$\phi_1\,(1880)$[i] $K\bar{K}$ $[K^*\bar{K}]_P$	$K_1^*\,(1780)$[i] $K\pi$ $[K^*\pi]_P$ $[K\rho]_P$
${}^3D_2$	2^{--}	$\rho_2\,(1700)$[i] $[\pi\omega]_P$ $[\pi a_2]_S$ $[\eta\rho]_P$	$\omega_2\,(1700)$[i] $[\pi^0\rho^0]_P$ $[\eta\omega]_P$ $[\pi^0 b_1^0]_D$	$\phi_2\,(1910)$[i] $[K^*\bar{K}]_P$ $[K_2^*\bar{K}]_S$	$K_2^*\,(1810)$[i] $[K^*\pi]_P$ $[K_2^*\pi]_S$
${}^3D_3$	3^{--}	$\rho_3\,(1690)$[d] 4π $\pi\pi$ $[\pi a_2]_D$ $[\eta\rho]_F$	$\omega_3\,(1670)$[d] $\pi\pi\pi$ 5π $[\pi^0 b_1^0]_D$ $[\eta\omega]_F$	$\phi_3\,(1850)$[f] $K\bar{K}$ $[K^*\bar{K}]_F$ $[K_2^*\bar{K}]_D$	$K_3^*\,(1780)$[d] $K\pi\pi$ $K\pi$ $[K_2^*\pi]_D$

[i] Mass predicted by Godfrey and Isgur.

Table III: Ground-state quarkonia[a]—cont'd

${}^{2S+1}L_J$	J^{PC}	$I=1\,(n\bar{n})$ Decay Modes [b],[c]	$I=0\,(n\bar{n})$ Decay Modes [b],[c]	$I=0\,(s\bar{s})$ Decay Modes [b],[c]	$I=1/2\,(s\bar{n})$ Decay Modes [b],[c]
${}^1F_3$	3^{+-}	$b_3\,(2030)$[i] $[\pi\omega]_D$ $[\pi a_2]_P$ $[\rho b_1]_P$ $[\eta b_1]_F$	$h_3\,(2030)$[i] $[\pi^0\rho^0]_D$ $[\eta\omega]_D$ $[\omega f_2]_P$ $[\omega f_1]_P$ $[\pi b_1]_F$	$h_3'\,(2220)$[i] $K\bar{K}\pi$ $[K_2^*\bar{K}]_P$ $[K^*\bar{K}]_D$	$K_3\,(2120)$[i] $K\pi\pi$ $[K_2^*\pi]_P$ $[K^*\pi]_D$
${}^3F_2$	2^{++}	$a_2\,(2050)$[i] $[\pi f_2]_P$ $[\pi b_1]_P$ $[\rho\omega]_S$ $[\pi f_1]_P$	$f_2\,(2050)$[i] $[\omega\omega]_S$ $[\pi^0 a_2^0]_P$ $[\eta f_1]_P$ $[\rho^0 b_1^0]_P$	$f_2'\,(2240)$[f] $K\bar{K}$ $[K_2^*\bar{K}]_P$ $[K^*\bar{K}]_D$	$K_2^*\,(2150)$[i] $K\pi$ $[K_2^*\pi]_P$ $[K^*\pi]_D$
${}^3F_3$	3^{++}	$a_3\,(2050)$[i] $[\pi f_2]_P$ $[\pi b_1]_F$ $[\rho\omega]_D$ $[\eta a_2]_P$	$f_3\,(2050)$[i] $[\pi^0 a_2^0]_P$ $[\eta f_2]_P$ $[\omega\omega]_D$ $[\rho^0 b_1^0]_P$	$f_3'\,(2240)$[f] $K\bar{K}\pi$ $[K_2^*\bar{K}]_P$ $[K^*\bar{K}]_D$	$K_3^*\,(2150)$[i] $K\pi\pi$ $[K_2^*\pi]_P$ $[K^*\pi]_D$
${}^3F_4$	4^{++}	$a_4\,(2010)$[i] $\pi\pi\pi$ $[\rho\omega]_D$ $[\pi b_1]_F$ $[\pi f_2]_F$ $[\eta a_2]_F$	$f_4\,(2050)$[d] $\pi^0\pi^0$ $[\omega\omega]_D$ $[\pi^0 a_2^0]_F$ $[\eta f_1]_F$ $[\rho^0 b_1^0]_F$	$f_4'\,(2210)$[f] $K\bar{K}$ $[K_2^*\bar{K}]_F$ $[K^*\bar{K}]_D$	$K_4^*\,(2075)$[d] $K\pi$ $[K_2^*\pi]_F$ $[K^*\pi]_D$

[i] Mass predicted by Godfrey and Isgur.

Table IV: Mesons omitted from previous tables[a]

I^G	J^{PC}	Particle Decay Modes [b],[c]	Comments [d]
0^+	0^{++}	$f_0\,(975)$ $\pi^0\pi^0$ $K\bar{K}$	$K\bar{K}$ molecule
1^-	0^{++}	$a_0\,(980)$ $\pi\eta$ $K\bar{K}$	$K\bar{K}$ molecule
1^-	0^{-+}	$\pi\,(1300)$ $\pi\pi\pi$	2^1S_0
0^+	0^{-+}	$\eta\,(1280)$ $\pi\pi\eta$ $\pi^0 a_0^0\,(980)$	2^1S_0
0^+	0^{-+}	$\eta\,(1430)$ $\pi\pi\eta$ $K\bar{K}\pi$	Hybrid ? 2^1S_0 ? Possibly two states at 1.42 and 1.48 GeV.
0^+	1^{++}	$f_1\,(1420)$ $\pi\pi\eta$ $K\bar{K}\pi$	$K^*\bar{K}$ molecule ?
0^+	0^{++}	$f_0\,(1590)$ $\eta\eta'$ $\eta\eta$	Glueball ?

[a] Particles from the Meson Summary Table.

[b] All-neutral decay modes, where possible, are explicitly given.

[c] The lowest allowed orbital-angular momentum (≤ 3) is given as a subscript.

[d] Notation: $n^{2S+1}L_J$ where n is the radial quantum number.

Table V: Mesons omitted from previous tables[a]—cont'd

I^G	J^{PC}	Particle Decay Modes [b],[c]	Comments [d]
0^-	1^{--}	$\phi(1680)$ $[K^*\bar{K}]_P$ $\pi\pi\omega$	2^3S_1
1^+	1^{--}	$\rho(1700)$ 4π $\pi\pi$	2^3S_1 plus 1^3D_1 ?
0^{+}	2^{++} 0^{++}	$f_2(1720)$ $K\bar{K}$ $\eta\eta$	Hybrid ? 2^3P_0 ?
0^+	2^{++}	$f_2(2010)$ $\phi\phi$	Glueball ?
0^+	2^{++}	$f_2(2300)$ $\phi\phi$	Glueball ?
0^+	2^{++}	$f_2(2340)$ $\phi\phi$	Glueball ?
1/2	1^+	$K_1(1270)$ $[K\rho]_S$	K_{1a} plus K_{1b}
1/2	1^+	$K_1(1400)$ $[K^*\pi]_S$	K_{1a} plus K_{1b}
1/2	1^-	$K^*(1415)$ $[K^*\pi]_P$	2^3S_1 ?
1/2	1^-	$K^*(1715)$ $K\pi$	1^3D_1 ?
1/2	2^-	$K^*(1715)$ $[K_2^*\pi]_S$	2^{--} plus 2^{-+} ?

Table VI: Exotic Hybrids or Multi-quark states[a]

I^G	J^{PC}	Particle [b]	Decay Modes [c],[d]	Width (MeV)
1^+	0^{+-}	$\tilde{a}_0\,(1900)$	$\pi\pi\,(1300)$ $[\pi a_1]_P$ $[\pi h_1]_P$ $[\eta b_1]_P$	1800
0^-	0^{+-}	$\tilde{f}_0\,(1900)$	$[\pi^0 b_1^0]_P$	250
0^-	0^{+-}	$\tilde{f}'_0\,(2100)$	$[\bar{K}K_1]_P$ $[\bar{K}K_2^*]_P$	1650
1^+	0^{--}	$\tilde{\pi}_0\,(1900)$[e]	$[\pi\omega]_P$ $[\eta\rho]_P$ $[\pi a_2]_D$	
0^-	0^{--}	$\tilde{\eta}_0\,(1900)$[e]	$[\eta\omega]_P$	
0^-	0^{--}	$\tilde{\eta}'_0\,(2100)$[e]	$[\bar{K}K^*]_P$ $[\bar{K}K_2^*]_D$	

[a] Masses and some decay modes are from the flux tube model.

[b] Particle names with 'tilde' stand for those with a 'wrong C.'

[c] All-neutral decay modes, where possible, are explicitly given.

[d] The lowest allowed orbital-angular momentum (≤ 3) is given as a subscript.

[e] Masses are assumed to be the same as those of the flux tube model.

Table VII: Exotic Hybrids or Multi-quark states[a]—cont'd

I^G	J^{PC}	Particle [b]	Decay Modes [c],[d]	Width (MeV)
1^-	1^{-+}	$\tilde{\rho}_1\,(1900)$	$[\pi b_1]_S$ $[\pi f_1]_S$ $\pi\eta$ $[\pi f_2]_D$ $[\eta a_2]_D$ $[\omega\rho]_P$	180
0^+	1^{-+}	$\tilde{\omega}_1\,(1900)$	$[\pi^0 a_1^0]_S$ $\pi^0\pi^0\,(1300)$ $[\bar{K}K_1]_S$ $[\pi^0 a_2^0]_D$ $\eta\eta'$ $[\omega\omega]_P$ $[\eta f_1]_D$ $[\eta f_2]_D$	370
0^+	1^{-+}	$\tilde{\phi}_1\,(2100)$	$[\bar{K}K_1]_S$ $[\bar{K}K_2^*]_D$ $[\bar{K}K^*]_P$	360
1^+	2^{+-}	$\tilde{a}_2\,(1900)$	$[\pi a_2]_P$ $[\pi a_1]_P$ $[\pi h_1]_P$ $[\pi\omega]_D$ $[\eta b_1]_P$ $[\eta\rho]_D$	700
0^-	2^{+-}	$\tilde{f}_2\,(1900)$	$[\pi^0 b_1^0]_P$ $[\eta\omega]_D$	500
0^+	2^{+-}	$\tilde{f}_2'\,(2100)$	$[\bar{K}K_1]_P$ $[\bar{K}K_2^*]_P$ $[\bar{K}K^*]_D$	450

Table VI: Exotic Hybrids or Multi-quark states[a]

I^G	J^{PC}	Particle [b]	Decay Modes [c],[d]	Width (MeV)
1^+	0^{+-}	$\tilde{a}_0\,(1900)$	$\pi\pi\,(1300)$ $[\pi a_1]_P$ $[\pi h_1]_P$ $[\eta b_1]_P$	1800
0^-	0^{+-}	$\tilde{f}_0\,(1900)$	$[\pi^0 b_1^0]_P$	250
0^-	0^{+-}	$\tilde{f}'_0\,(2100)$	$[\bar{K}K_1]_P$ $[\bar{K}K_2^*]_P$	1650
1^+	0^{--}	$\tilde{\pi}_0\,(1900)$[e]	$[\pi\omega]_P$ $[\eta\rho]_P$ $[\pi a_2]_D$	
0^-	0^{--}	$\tilde{\eta}_0\,(1900)$[e]	$[\eta\omega]_P$	
0^-	0^{--}	$\tilde{\eta}'_0\,(2100)$[e]	$[\bar{K}K^*]_P$ $[\bar{K}K_2^*]_D$	

[a] Masses and some decay modes are from the flux tube model.

[b] Particle names with 'tilde' stand for those with a 'wrong C.'

[c] All-neutral decay modes, where possible, are explicitly given.

[d] The lowest allowed orbital-angular momentum (≤ 3) is given as a subscript.

[e] Masses are assumed to be the same as those of the flux tube model.

Table VII: Exotic Hybrids or Multi-quark states[a]—cont'd

I^G	J^{PC}	Particle [b]	Decay Modes [c],[d]	Width (MeV)
1^-	1^{-+}	$\tilde{\rho}_1\,(1900)$	$[\pi b_1]_S$ $[\pi f_1]_S$ $\pi\eta$ $[\pi f_2]_D$ $[\eta a_2]_D$ $[\omega\rho]_P$	180
0^+	1^{-+}	$\tilde{\omega}_1\,(1900)$	$[\pi^0 a_1^0]_S$ $\pi^0\pi^0\,(1300)$ $[\bar{K}K_1]_S$ $[\pi^0 a_2^0]_D$ $\eta\eta'$ $[\omega\omega]_P$ $[\eta f_1]_D$ $[\eta f_2]_D$	370
0^+	1^{-+}	$\tilde{\phi}_1\,(2100)$	$[\bar{K}K_1]_S$ $[\bar{K}K_2^*]_D$ $[\bar{K}K^*]_P$	360
1^+	2^{+-}	$\tilde{a}_2\,(1900)$	$[\pi a_2]_P$ $[\pi a_1]_P$ $[\pi h_1]_P$ $[\pi\omega]_D$ $[\eta b_1]_P$ $[\eta\rho]_D$	700
0^-	2^{+-}	$\tilde{f}_2\,(1900)$	$[\pi^0 b_1^0]_P$ $[\eta\omega]_D$	500
0^+	2^{+-}	$\tilde{f}'_2\,(2100)$	$[\bar{K}K_1]_P$ $[\bar{K}K_2^*]_P$ $[\bar{K}K^*]_D$	450

Table VIII: Exotic Hybrids or Multi-quark states[a]—cont'd

I^G	J^{PC}	Particle [b]	Decay Modes [c],[d]	Width (MeV)
1^-	3^{-+}	$\tilde{\rho}_3$ (1900)[e]	$[\pi b_1]_D$ $[\pi f_1]_D$ $\pi\eta$ $[\pi f_2]_D$ $[\eta a_2]_D$ $[\omega\rho]_P$	
0^+	3^{-+}	$\tilde{\omega}_3$ (1900)[e]	$[\pi^0 a_2^0]_D$ $\eta\eta'$ $[\omega\omega]_P$ $[\eta f_1]_D$ $[\eta f_2]_D$	
0^+	3^{-+}	$\tilde{\phi}_3$ (2100)[e]	$[\bar{K}K_1]_D$ $[\bar{K}K_2^*]_D$ $[\bar{K}K^*]_F$	
1^+	4^{+-}	$\tilde{a}_4$ (1900)[e]	$[\pi a_2]_F$ $[\eta b_1]_F$	
0^-	4^{+-}	$\tilde{f}_4$ (1900)[e]	$[\pi^0 b_1^0]_F$	
0^+	4^{+-}	$\tilde{f}'_4$ (2100)[e]	$[\bar{K}K_1]_F$ $[\bar{K}K_2^*]_F$	

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