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Current Status of the $E(1420)/\iota(1440)$ and Future Prospects of the g_T decaying into $\phi\phi$[†]

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ABSTRACT

A survey is given of the current status of the $f_1(1420)/E$ and the $\eta(1440)/\iota$ in the channels $K\bar{K}\pi$ and $\eta\pi\pi$. There is now strong evidence that the $\eta(1440)/\iota$ is split into two $J^{PC} = 0^{-+}$ states in the 1.4–1.5 GeV range with the lower-mass state coupling mostly to $a_0(980)\pi$ whereas the upper-mass state couples mainly to $K^*(890)\bar{K}$. Both of them cannot be quarkonia. It appears very likely that the $f_1(1420)/E$ is an S-wave $K^*(890)\bar{K}$ molecule with a strong overlap with the $a_0(980)/\delta$.

It is thought that one or more of the $J^{PC} = 2^{++}$ $f_2(2010)/g_T$, $f_2(2300)/g'_T$ and $f_2(2340)/g''_T$ states decaying into $\phi\phi$ may be the tensor glueball. The future prospects at BNL and elsewhere for further experimental work on these and other exotic states coupling to $\phi\phi$ are discussed.

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1. Introduction

This review covers several meson states in the 1.4 GeV mass region. A particular emphasis is given on the current status of the states observed in the so-called $E(1420)/\iota(1440)$ region.[1]

The three g_T states, at masses 2010, 2300 and 2340 MeV and all decaying into $\phi\phi$, are thoght to be candidates for the $J^{PC} = 2^{++}$ glueballs. A new experiment, to be carried out with the BNL MultiParticle Spectrometer (MPS), has been approved to continue the search for states coupling to $\phi\phi$. The aim of the experiment is not only to confirm the previously observed g_T states but also to search for possible J^{PC}-exotic states which might couple to $\phi\phi$. This decay channel is exceptionally powerful for the spin-parity analysis because of the presence of the decay $\phi \rightarrow K^+K^-$.

It appears that the field of hadron spectroscopy is entering a new phase in which hadronic states made up of qqq and $q\bar{q}$ no longer suffice—more complex states requiring valence gluons and mesonic as well as baryonic molecules are certainly needed to account for the observed states.

2. Mesons in the $K\bar{K}\pi$ channel

The channel $K\bar{K}\pi$ is a rich source of resonances and enhancements in the 1.3 to 1.5 GeV mass region. They are produced in a variety of production modes; π^-p, K^-p, and $\bar{p}p$ peripheral interactions, $\bar{p}p$ annihilations at rest, π^+p and pp central productions, $\gamma\gamma$ and $\gamma\gamma^*$ initial systems, and J/ψ radiative decays. The decay channel $\eta\pi\pi$ provides a complementary mode for the study of these resonances.

A total of seven distinct states has so far been detected in this mass region. In the increasing order of mass, they are the $f_1(1285)/D$ and the $\eta(1295)$ in the so-called the $D(1285)$ region. In the E/ι region, one observes two η's with masses between 1.4 to 1.5 GeV (the ι mesons), one $J^{PC} = 1^{++}$ at 1.42 GeV (the E meson), an $s\bar{s}$ state $h_1'(1380)$ with $J^{PC} = 1^{+-}$ and another $s\bar{s}$ state with opposite C-parity, i.e. the $f_1(1510)$, which is often called the $D'(1510)$.

Fig. 1 shows a partial-wave decomposition of the $K\bar{K}\pi$ system, from the data of BNL-E771 in the reaction $\pi^-p \rightarrow K^+K_S\pi^-n$ at 8 GeV/c. The results shown here are slightly different from those presented by Zieminska[2](the latter analysis used a different set of $-t$ cuts on the data and also included spin-two states). It should be emphasized that the two results are qualitatively the same. The mass-dependent fits by Blessing,[3] presented later in this paper, have been based on the results of Fig. 1.

In the $D(1285)$ region, the 1^{++} state dominates, but a small 0^{-+} enhancement is also seen in the same vicinity. The masses and widths are $M = (1299 \pm 1)$ MeV and $\Gamma = (30 \pm 6)$ MeV for the 1^{++}, and $M = 1312 \pm 3$ and $\Gamma = 29 \pm 6$ for the 0^{-+}. The E/ι region shows three separate J^{PC} states: 0^{-+} (which is resolved into two distinct states in this data), 1^{++} and 1^{+-}. The 1^{+-} bump at the $K^*\bar{K}$ threshold could be attributed to the $h_1'(1380)$, as it is produced predominantly in the BNL-E771 K^-p data (Fig. 2). This state was originally observed by the LASS[4] collaboration in the same reaction. Evidently, the $h_1'(1380)$ harbors some admixture of a non-strange quarkonium.

It is seen that the E/ι enhancement in this data is largely due to the 0^{-+} state and that it exhibits a sharp rise at 1.4 GeV followed by a gradual dropoff to 1.52 GeV. A study of this state as a function of $-t$ and of the decay modes demonstrates that this enhancement in fact consists of two separate states with different masses and decay modes. The best evidence for this, as presented by Zieminska[2] in 1988, comes from the observation that the coherence of the two decay modes, $a_0(980)\pi$ and $K^*\bar{K}$, decreases as a function of the $K\bar{K}\pi$ mass, reaching near zero at 1.5 GeV. In another words, it is as if the first is produced entirely be nucleon spin-flip, whereas the second is mediated solely by nucleon spin-nonflip. It would be difficult to explain this behaviour under the assumption of a single 0^{-+} state in this mass region.

A variety of mass-dependent fits have been performed and presented in 1988 by Blessing.[3] The most economical fit, in the sense that it envokes the least number of separate states to fit the data, is the Fit E. The masses and widths quoted below are from this fit; for other possible fits, the reader is referred to the original work by Blessing.[3]

The first 0^{-+} state with $M = 1407 \pm 3$ and $\Gamma = 75 \pm 6$ decays predominantly to the $a_0(980)\pi$ channel, while the second 0^{-+} state with $M = 1405 \pm 10$ and $\Gamma = 135 \pm 21$ couples to $K^*\bar{K}$, as determined from that portion of the $0^{-+}(K^*)$ wave incoherent with the $0^{-+}(a_0)$ wave. It should be noted that the width of the latter is almost twice that of the former and that its mass is determined using a mathematical formula allowing for the

Breit-Wigner to be extended below the $K^*\bar{K}$ threshold through the K^* tail. In addition to the two 0^{-+} states, the E/ι region harbors a small 1^{++} state; in the Fit E the measured parameters are $M = 1432 \pm 5$ and $\Gamma = 63 \pm 15$.

The results of an analysis of the $K\bar{K}\pi$ system by the Mark III group on their J/ψ radiative decays have been published in 1990.[5] The partial-wave decomposition (Fig. 3) reveals that the E/ι bump consists of two 0^{-+} states and one 1^{++} state. For the two 0^{-+} state the parameters are $M = 1416^{+8+7}_{-8-5}$ and $\Gamma = 54^{+37+13}_{-21-24}$ with an $a_0(980)\pi$ decay mode, and $M = 1490^{+14+03}_{-08--16}$ and $\Gamma = 91^{+67+15}_{-31-38}$ with a $K^*\bar{K}$ decay mode. For the 1^{++} state they are $M = 1443^{+7+3}_{-6-2}$ and $\Gamma = 68^{+29+8}_{-18-9}$.

It is seen that the fitted parameters for the 1^{++} state are consistent between BNL-E771 and Mark III data; however, the two 0^{-+} states are not in good agreement. One key difference can be traced to the fact that the lower-mass 0^{-+} state in the BNL-E771 data couples not only to $a_0(980)\pi$ via S-wave but also to $K^*\bar{K}$ via P-wave. Although the $K^*\bar{K}$ decay mode appears to be small (undoubtedly due to the barrier factor), its decay amplitude is evidently substantial in this data. The results of the Mark III data, on the other hand, indicate a 100% $a_0(980)\pi$ decay mode for the lower-mass peak. Another difference is that in the BNL-E771 data the $0^{-+}(K^*)$ amplitude incoherent with the $0^{-+}(a_0)$ wave (hence the two cannot be the same resonance) is large at or below the $K^*\bar{K}$ threshold, shifting the mass peak to 1.405 GeV.

The $1^{++}(K^*)$ state seen in the BNL-E771 data can be explained most readily within the framework of the model proposed by Longacre.[6] This model incorperates three one-particle-exchange diagrams, $K^*\bar{K} \to K\bar{K}^*$ (π exchange), $K^*\bar{K} \to \pi a_0$ (K exchange) and $\bar{K}^*K \to \pi a_0$ ($\bar{K}$ exchange), in a unitarized formalism. The picture that emerges here is that the $K\bar{K}$ forms the $a_0(980)$ resonance at the center of gravity, with the pion revolving around the center in a P-wave forming alternately a K^* or $\bar{K}^*$ resonance. Longacre asserts that only the $J^{PC} = 1^{++}$ wave for the $K\bar{K}\pi$ system shows this enhancement (but not the 0^{-+} wave). His model is therefore that of a 1^{++} $K^*\bar{K}$ molecule communicating strongly with the final state $a_0(980)\pi$. The predicted mass spectrum tracks well the 1^{++} waves of BNL-E771 and of WA76[7](see Fig. 4).

A unique feature of the model is that the phase motion associated with this enhancement is flattened off with only about 45 degrees of advance (see Fig. 5). This explains why the BNL-E771 group failed to observe a clean and consistent 180 degrees motion of the phase of the 1^{++} wave expected of a genuine resonance over a stationary background. It should be interesting to confirm this picture with the data of WA76, if and when a full partial-wave analysis has been performed with information on the phase of each wave.

3. $J^{PC} = 2^{++}$ glueball candidates

The BNL-E747 group[8] has accumulated some 7,000 events of the type $\pi^- p \to \phi\phi n$ at 22 GeV/c. The $\phi\phi$ mass spectrum (Fig. 6) shows a broad enhancement from threshold to 2.4 GeV, while the experimental acceptance remains flat up to 2.6 GeV. A partial-wave analysis of the bump reveals that it consists of three distinct 2^{++} states, 2^{++} $f_2(2010)/g_T$, $f_2(2300)/g'_T$ and $f_2(2340)/g''_T$ (see Fig. 6). Using the notation L_S where L is the orbital angular momentum and S is the total intrinsic spin for $\phi\phi$, they are: g_T with $M = 2011^{+62}_{-76}$ and $\Gamma = 202^{+67}_{-62}$ (about 98% S_2); g'_T with $M = 2297 \pm 28$ and $\Gamma = 149 \pm 41$ (about 25% D_2 and 69% D_0); and g''_T with $M = 2339 \pm 55$ and $\Gamma = 319^{+81}_{-69}$ (about 37% S_2 and 59% D_0). As they are produced in the OZI-forbidden channel, they are thought to be candidates for tensor glueballs.

A new experiment BNL-E881 for further study of the $\phi\phi$ system has been approved and slated to be carried out in 1992 with the BNL Multi-Particle Spectrometer (MPS). The reaction to be studied is the same, i.e. $\pi^- p \to \phi\phi n$, but the beam momentum is reduced to 8 GeV/c (from 22 GeV/c before). The idea is to take adavantage of the medium-energy spearated beam, which allows for tagged K^- and $\bar{p}$ beams as well as the π^- beam. The aim of the experiment is to search for glueballs, hybrids and other exotic hadrons which are J^{PC}-exotic. The search with the π^- beam is to be carried out with high-t events, which could involve J^{PC}-exotic states produced with the $a_1(1260)$ exchange, for example, but not with the π exchange.

The SuperLEAR facility provides a new opportunity for further study of the $\phi\phi$ system. The reaction of interest is

$$\begin{aligned}\bar{p}p &\to \phi\phi\pi^0 \\ &\to \phi\phi\eta \\ &\to \phi\phi\omega\end{aligned}$$

where the beam momentum may range from 6 to 12 GeV/c. If the $\phi\phi$ system is produced forward, then it is plausible to assume that baryon exchanges are responsible for its production. Depending on the nature of the virtual baryon, it is possible that a J^{PC}-exotic meson system could be produced in the forward meson system.

A conceptual design for such an experiment is given in Fig. 7. It is clear that an ideal vertex detector calls for a solenoidal magnet with both neutral and charged particle capabilities. An example would be the Crystal Barrel detector of LEAR. As a rough guess for the downstream detector system, one may choose the CERN Omega spectrometer with its RICH counter downstream of the magnet. For neutral particle identification in the forward direction, one may use the lead-glass GAMS detector of CERN or Serpukhov.

Given the complexity of the mesons in the 2 to 3 GeV mass range, it is clear that the projected BNL epxeriment for the $\phi\phi$ system will necessarily constitute only a partial answer to the quest for gluonic degrees of freedom in hadronic matter. With more intense $\bar{p}$ beam available at the SuperLEAR (perhaps a factor of 100 over that at BNL), one is in an excellent position to carry out this study with high statistical sensitivity.

4. Future Prospects

It appears that the late 1990s will bring in a new era of high-statistics meson experiments. In addition to the SuperLEAR expected in 1997, one must keep in mind the tau-charm factory slated for Sevilla, Spain at about the same time. Study of the J/ψ radiative decays, for instance, can be done with one hundred times the sensitivity of that at SPEAR. The ϕ factory projected in Frascati, Italy, at about the same time, may provide yet another source for production of the gluonic states in the 1 GeV mass region.

The late 1990s should usher in an era of the asymmetric B factories at KEK, Japan and at Cornell or SLAC in the U.S.A. These facilities offer unprecedented opportunities for two-photon production of hadronic states. As photons couple to charge, this channel should be rich in the states communicating with the $u\bar{u}$- or $c\bar{c}$-bound systems.

Recently, the Canadian Government gave approval to the KAON Factory proposed at TRIUMF. This facility, when completed in the late 1990s, will enable physicists to carry out the type of physics currently done at BNL with a hundred-fold increase in sensitivity.

The relativistic heavy-ion collider (RHIC) at BNL is under construction and is expected to be ready for physics in 1997. This machine is capable of providing collisions of $p \times p$ at $\sqrt{s} = 500$ GeV and $Au \times Au$ at $\sqrt{s} = 40$ TeV. A group of physicists at BNL has proposed to carry out a study of the meson systems with mass up to 20 GeV, nearly at rest in the laboratory, using RHIC as the energy source.

They envision a modern 4π detector, about the size of the DELPHI, in one of the six intersection regions at RHIC. It is shown that a region of phase space exists, accessible by a simple set of triggers, in which the double-Pomeron exchange mechanism dominates in the case of $p \times p$ and in which the two-photon physics takes over for heavy-ion collisions such as $Au \times Au$. Thus RHIC could furnish a novel and rich source of mesonic systems for further study of the gluonic excitations.[9]

Acknowledgement

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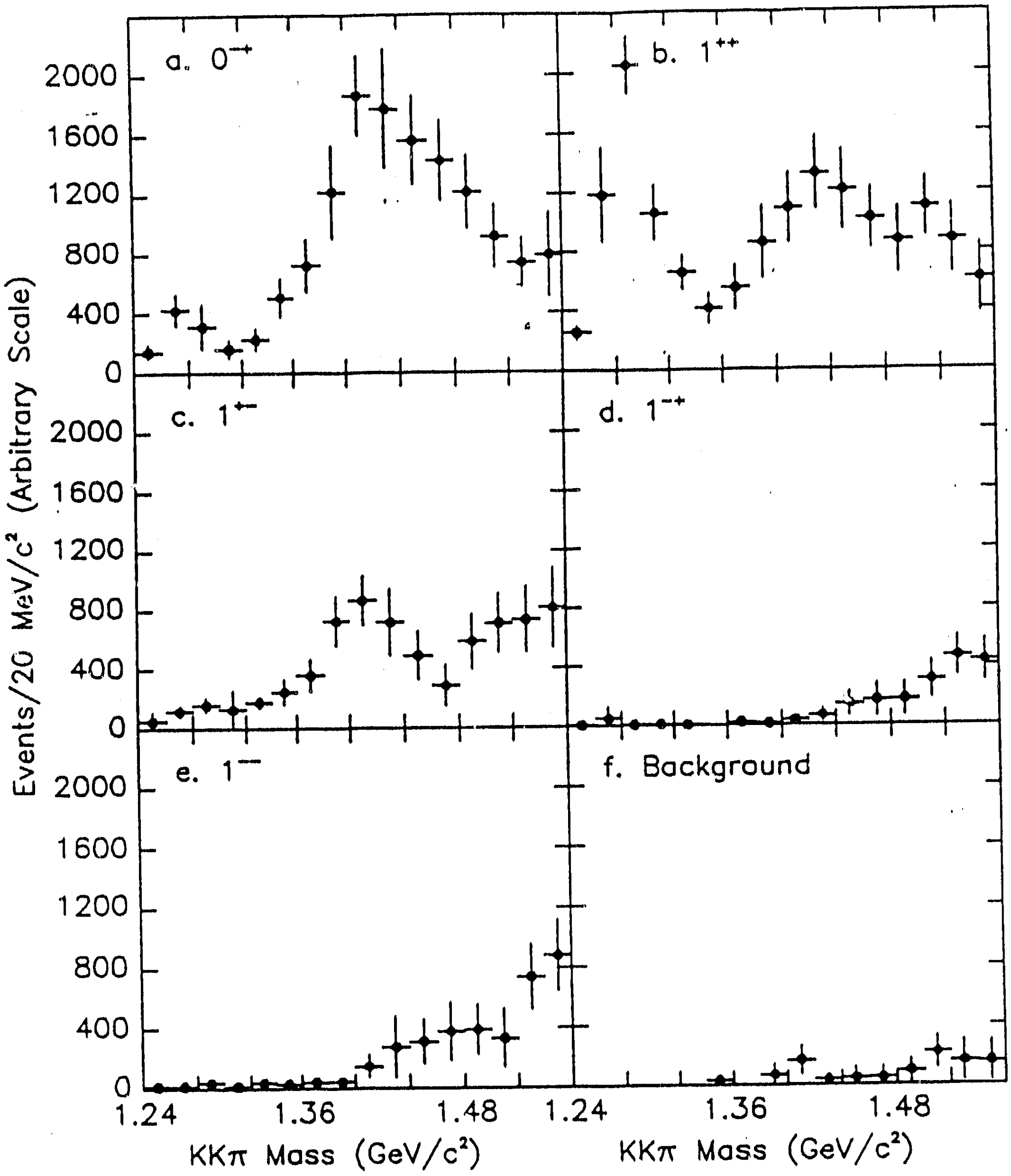

Figure 1: Partial-wave decomposition of the $K\bar{K}\pi$ system from the π^-p data (BNL-E771). The analysis was done independently on three separate $-t$ bins, 0.0–0.20–0.45–1.00 GeV/c, and the results have been summed over.

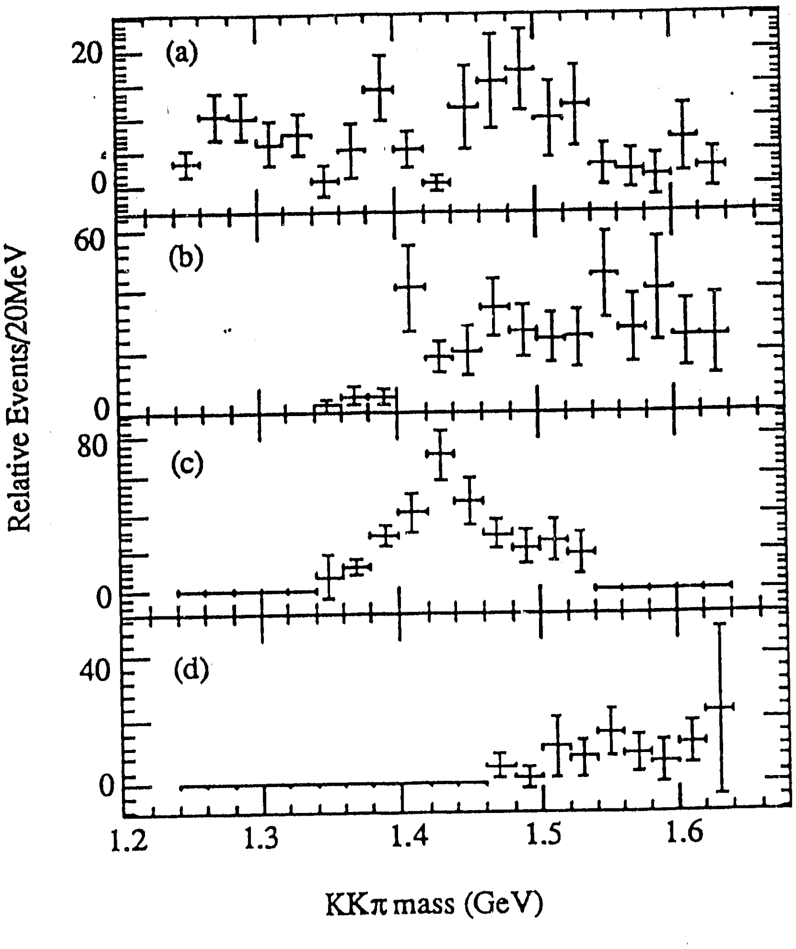

Figure 2: Partial-wave decomposition of the $K\bar{K}\pi$ system from the K^-p data (BNL-E771). (a) 0^{-+}; (b) 1^{++}; (c) 1^{+-}; (d) 1^{-+}.

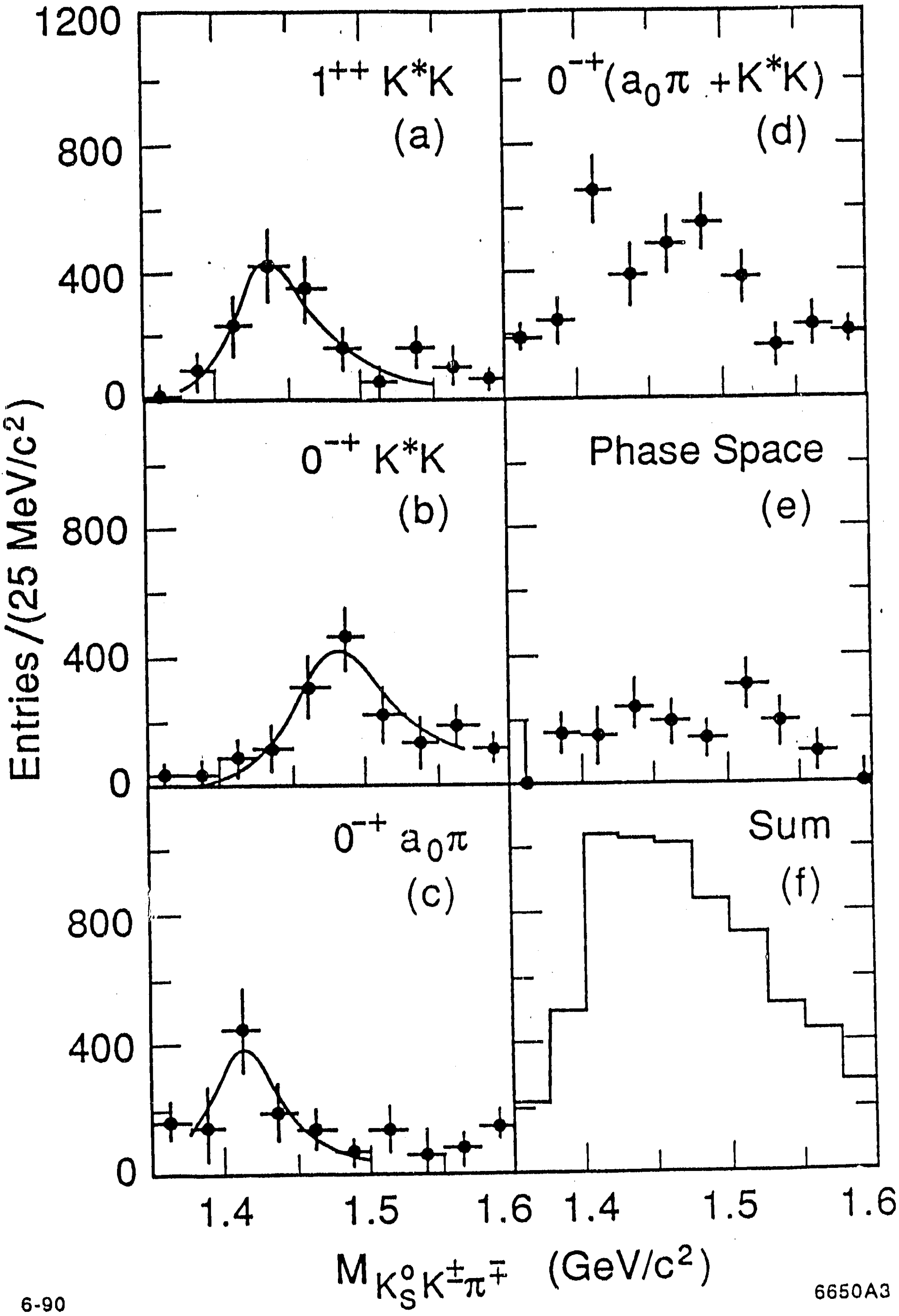

Figure 3: Partial-wave intensities from the data of J/ψ radiative decays (Mark III).

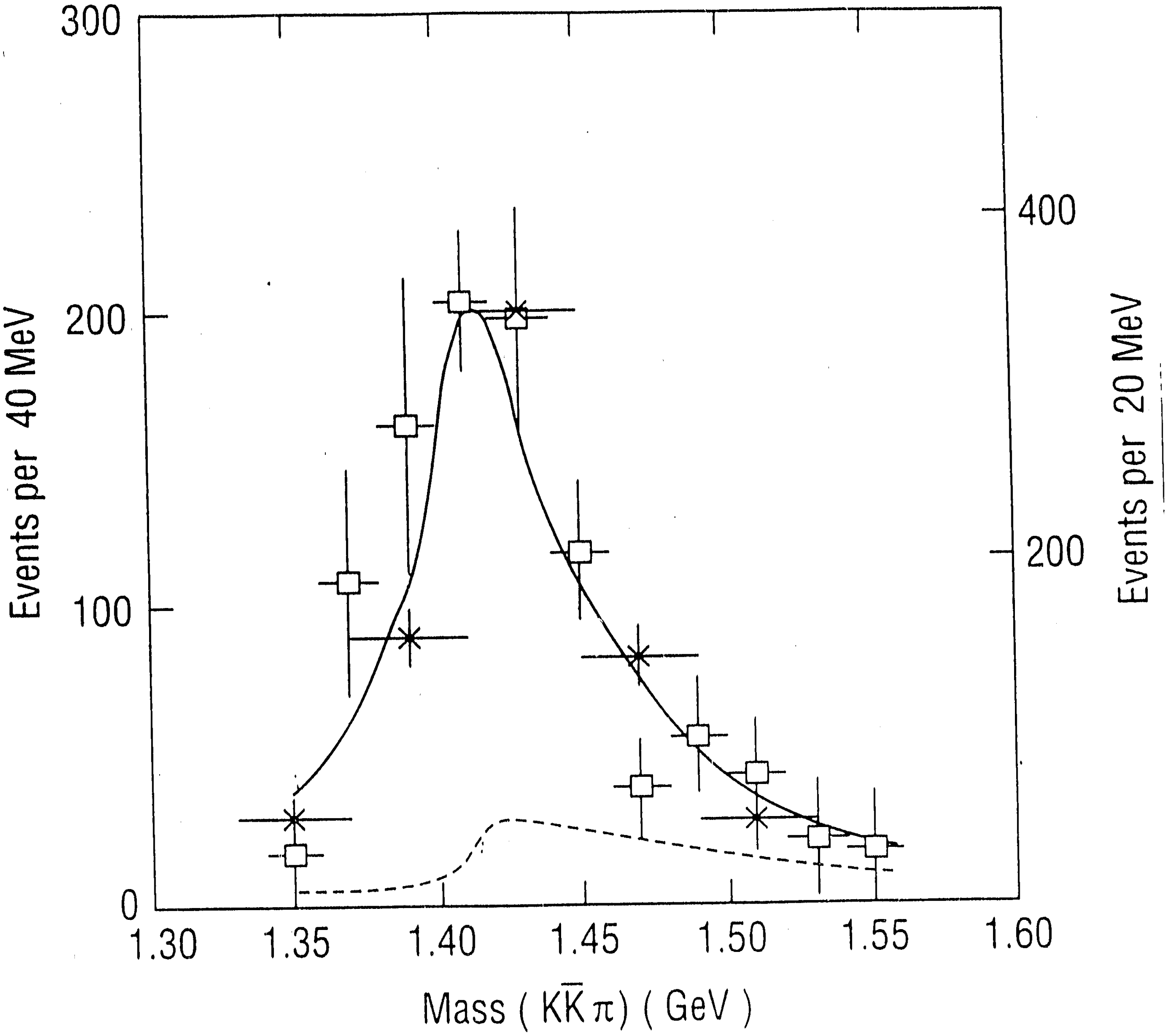

Figure 4: The solid curve corresponds to the $J^{PC} = 1^{++}$ intensity predicted by the Longacre model. The dashed curve is the predicted spectrum before the final-state interaction has been introduced. The histogram in events/20 MeV shown with blank squares come from the BNL-E771 $\pi^- p$ data for $0.20 < -t < 0.45 (\mathrm{GeV}/c)^2$; that in events/40 MeV marked with stars are from the central-production data at CERN Omega Spectrometer (WA76).

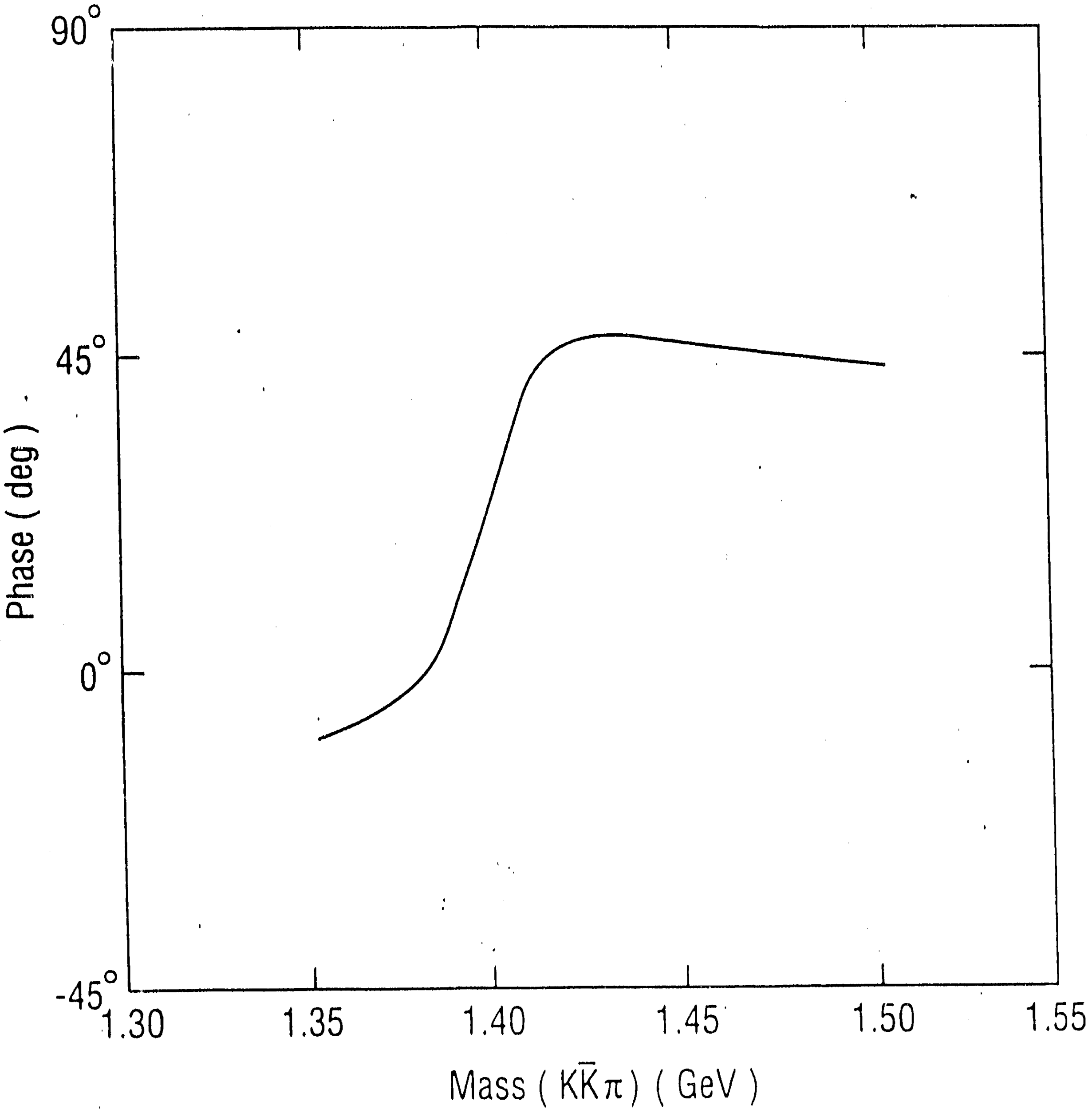

Figure 5: The phase motion of the $J^{PC} = 1^{++}$ amplitude predicted by the Longacre model.

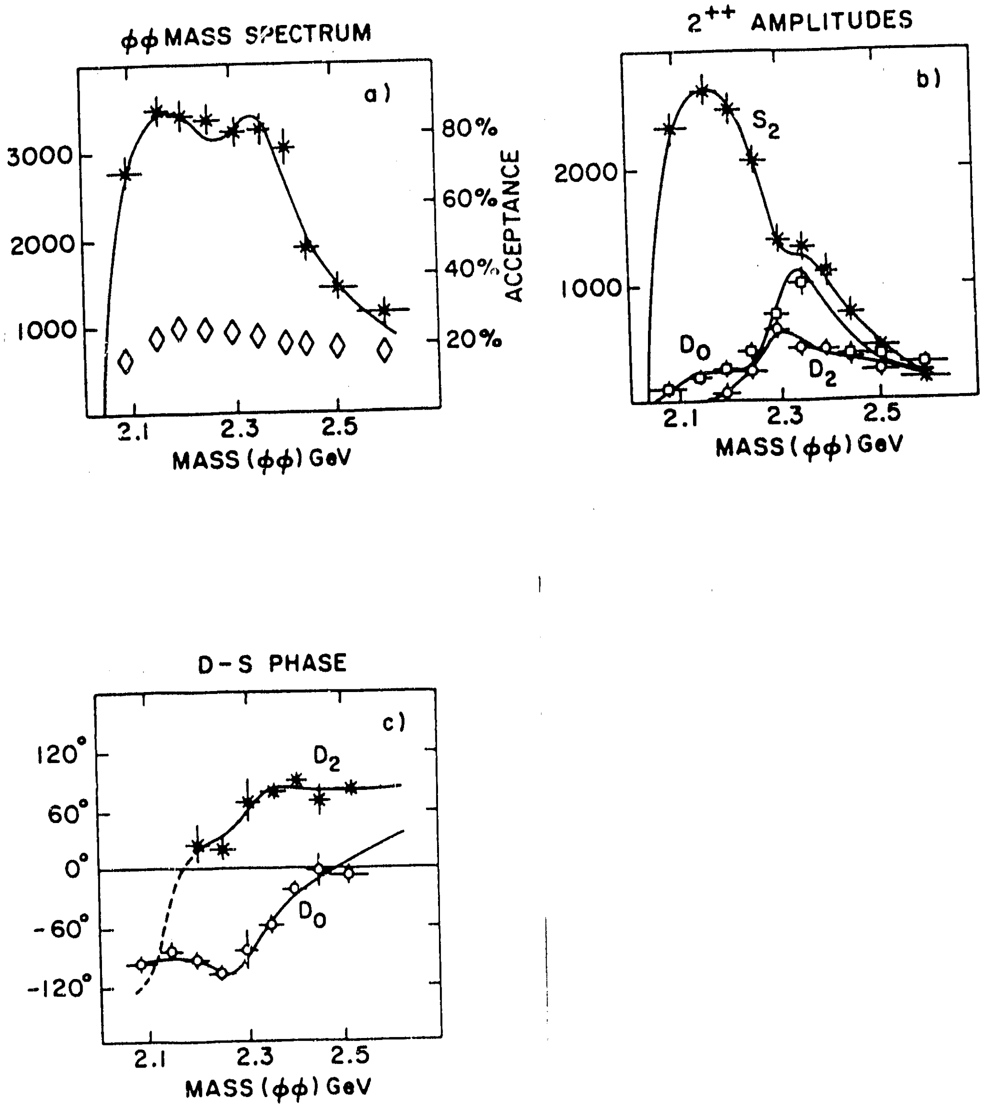

Figure 6: (a) The $\phi\phi$ mas spectrum from the BNL-E747 data. (b) The $J^{PC} = 2^{++}$ intensities for S_2, D_2 and D_0 partial waves. (c) The phase motion of the D_2 and D_0 waves with respect to the S_2 wave. The curves show a fit by three Breit-Wigner resonances.

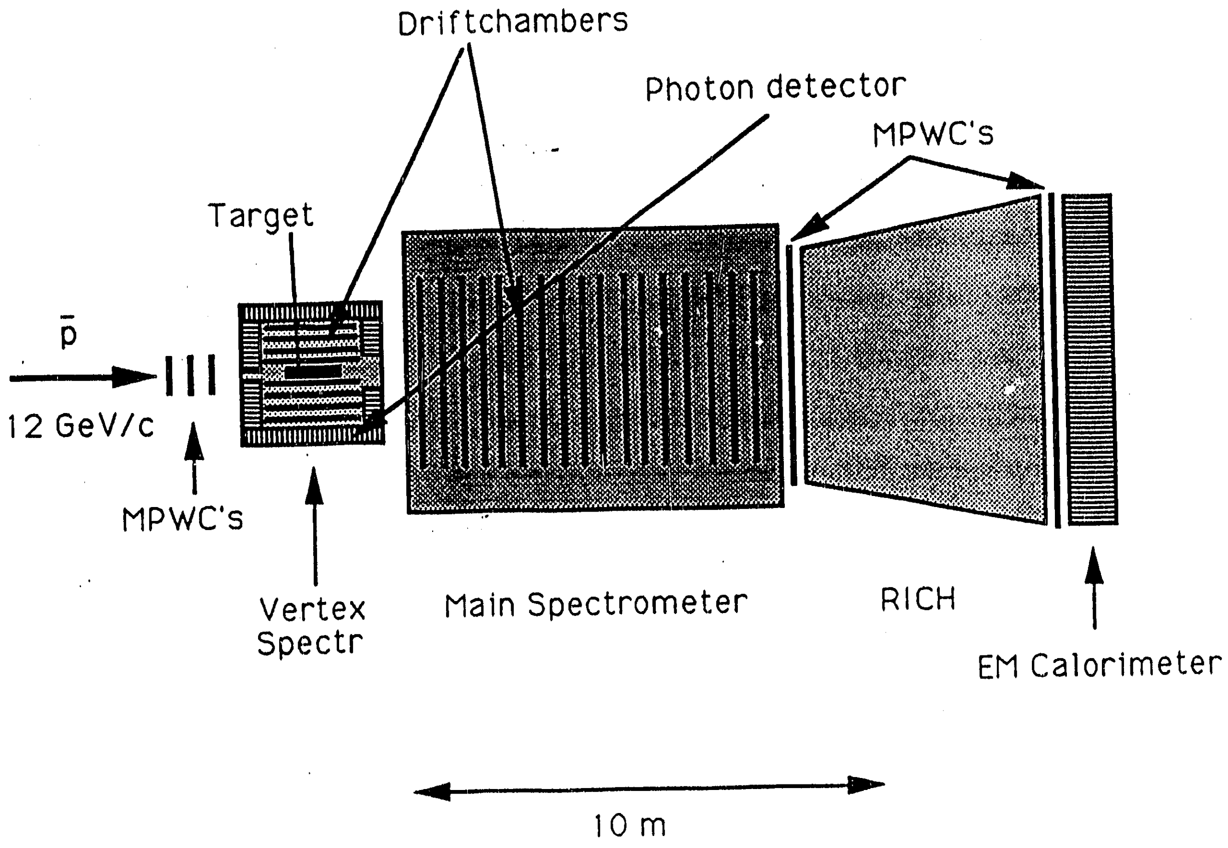

Figure 7: The schematic layout of a possible fixed-target experiment at SuperLEAR. The vertex spectrometer could be patterned after the Crystal-Barrel experiment; the main dipole spectrometer and the RICH counter may be borrowed from the CERN Omega Spectrometer; and the downstream EM calorimeter could be the GAMS-type lead-glass detector.

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