The Radphi Experiment at Jefferson Lab

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Abstract

The scalar mesons, the $f_0(980)$ and the $a_0(980)$, have been receiving much attention of late. The low values of their masses and widths bring into question their assignment to the ${}^3P_0$ $\overline{q}q$ scalar nonet and recent Crystal Barrel results have uncovered scalar states with more appropriate masses and widths. It has been suggested that the $f_0(980)$ and the $a_0(980)$ are molecules or 4-quark states. This talk reviews the theoretical status of these states, and the variety of experimental observations which have a bearing on their interpretation. At JLab (formerly CEBAF), an experiment is underway to look for the rare radiative decays $\phi \to f_0(980)\gamma$ and $\phi \to a_0(980)\gamma$ using ϕ's photoproduced from an intense 6GeV photon beam. The ratio of these branching ratios is expected to discriminate between competing models of the substructure of these scalars. The experiment will also measure the poorly-known branching ratio for $\phi \to \eta'\gamma$.

1 Experimental overview

The status of the $f_0(980)$ as a scalar hadronic resonance is well established. It appears as a rapid variation in the phase of the $\pi\pi$ S-wave between 0.9 and 1.1 GeV/c^2. In the data of Buttram *et.al.* [1] who measured the $\pi^+\pi^-$ system recoiling from the target nucleon in a π^- beam, the production cross section undergoes a rapid drop at around 0.96GeV/c^2, the consequence of interference between a scalar resonance and the (strong) non-resonant $\pi\pi$ S-wave. The same paper also presents evidence for the decay of this state to K^+K^-, although the nearness to the $\overline{K}K$ threshold makes extraction of resonance parameters more difficult for this channel. The mere observation of $\overline{K}K$ decays so close to threshold gives evidence of a strong strangeness component in the f_0. This can be expressed in the ratio of couplings $g_{KK}/g_{\pi\pi} \approx 4$ which emerges from coupled-channel analyses of these data. An analogous situation exists in the isovector channel, where a narrow resonance the $a_0(980)$ is seen in the $\eta\pi$ S-wave with parameters similar to the $f_0(980)$. The Crystal Barrel experiment presents a Dalitz plot of the $\pi^0\pi^0\eta$ final state from $\overline{p}p$ annihilation in Ref. [2] where both the a_0 and the f_0 appear as interference structures in their respective channels. Another place where a strong a_0 signal has been seen is in the decay of the $f_1(1285) \to a_0\pi$. The a_0 is seen in both the $\overline{K}K$ and $\eta\pi$ systems, indicating a significant strangeness content in the a_0 as well.

Another important clue to the flavour content of the $f_0(980)$ comes from measurements of J/ψ decays by Mark III [3]. A systematic analysis of these data in channels $\psi \to \gamma X$, $\psi \to \phi X$ and $\psi \to \omega X$ revealed the f_0 in the $X = \pi^+\pi^-$ spectrum of all three decays. In particular, the ratio of branching ratios between the ϕX and ωX channels can be interpreted in light of the OZI rule as a strangeness filter. The f_0 is the largest structure in the X-spectrum when recoiling against a ϕ, whereas it appears as a small glitch in the X-spectrum when recoiling against the ω, confirming the hypothesis that the f_0 is dominantly $\overline{s}s$. Data from hadronic Z^0 decays, however, appear to favour a non-strange flavour for the f_0. A clear f_0 signal is seen in the inclusive $\pi^+\pi^-$ mass spectrum from OPAL shown at this conference [4]. The f_0 production rates display a similar behaviour to the $f_2(1270)$, and are considerably stronger than the rates for the ϕ even though s-wave mesons are more readily produced by a fragmenting string than are p-wave mesons like the f_0. These data are presented as evidence for the conventional $\overline{n}n$ structure of the f_0.

In the literature considerable differences exist in the numbers given for the width of the f_0 and a_0. Most of the differences can be accounted for by the variety of resonance parameterisations that have been used to describe them. In the case where a resonance straddles the threshold of a channel to which it is strongly coupled, a visible width such as is extracted with a Breit Wigner fit is not physically meaningful. The width and branching ratios have large variations across the resonance peak and the width and centroid are dependent on the form used to parameterise the resonance. Once this is taken into account, there is a broad agreement between experimental results as to the existence and properties of these two scalars.

2 Theoretical classification

In contrast to their experimental status, the theoretical interpretation of the $f_0(980)$ and $a_0(980)$ is far from established. Within the standard quark model, they are misfits. Their masses are too small to fit neatly into the $^3P_0$ fundamental nonet, whose strange member is the lightest scalar kaon, the $K_0^*(1430)$. Their couplings to two pseudoscalars are an order of magnitude smaller than expected for conventional $\overline{n}n$ states. This might be understood if the f_0 were a conventional $\overline{s}s$ state, but in this case its light mass is even more mysterious, as is its degeneracy with and apparent similarity to the $a_0(980)$. These observations, plus the fact that these states occur within a few MeV of the $\overline{K}K$ threshold, lead naturally to the suspicion that they are not ordinary quark-model states, but rather something like a quasi-bound state of two ordinary mesons [5]. This suspicion has been bolstered recently by the identification of new scalar states by Crystal Barrel with masses and widths appropriate to quark-model partners of the $K_0^*(1430)$.

However this is not the only way to solve the riddle. It was pointed out some time ago [6] that the strong couplings of conventional $\overline{q}q$ scalars to two pseudoscalars, under the constraint of unitarity, can greatly distort the pattern of their masses and decays. Other variations on this theme have appeared recently [7, 8]. In these models the $f_0(980)/a_0(980)$ appear as "unitarised remnants" of the original quark-model scalars, with large admixtures from the two-pseudoscalar continuum in their wavefunction. Another theoretical interpretation that has been put forward for these states is a $\overline{q}\overline{q}qq$ hybrid [9]. Such states can be made orthogonal to molecular states by coupling the $\overline{q}q$ pairs to colour-octets rather than singlets.

Qualitatively these suggestions have a great deal in common with each other. The continuum component of the unitarised remnant state is phenomenologically similar to the quasi-bound molecule. The pair of octets in the 4-quark state will mix with the pair of singlets in the molecule through diagrams that involve the exchange of one or more gluons between the pairs. Quantitatively, however, these models can result in quite different behaviour in some observables. In 1993 [10] Close, Isgur and Kumano proposed a measurement of the radiative decay width of the ϕ to f_0/a_0 as a test of the molecular interpretation for these states. Although predictions for the individual radiative widths are quite model-dependent, the ratio of couplings between the f_0 and a_0 provides powerful discrimination between models for which the two states are similar to each other in structure. Predictions for the ratio of branching ratios for two of the above hypotheses are compared in Table 1 to the expectation for conventional quark model states with $f_0(980)$ taken as the $\bar{s}s$ nonet member. At the present, predictions for radiative widths are not available from unitarised quark models, which are perhaps better viewed as generalised methods of data analysis than as theoretical models.

3 The Radphi experiment

The Radphi experiment (E94-016 at Jefferson Lab) has as its primary objective the measurement of the radiative decays of the ϕ meson to all-neutral final states, in particular $\phi \to f_0(980)\gamma \to \pi^0\pi^0\gamma$ and $\phi \to a_0(980)\gamma \to \pi^0\eta\gamma$. The ϕ's are produced by the process of diffractive photoproduction from a tagged bremsstrahlung beam. Photons are a better source of ϕ's than are proton or pion beams, whose ϕ couplings are suppressed by the OZI rule. The ϕ photoproduction cross section is about 5μb above 3GeV lab photon energy, where it reaches its saturation value; the highest energy point from ZEUS [11] indicates a weak logarithmic rise in the cross section with photon energy, reaching 8μb at 70GeV. Hence the beams and energies available at CEBAF are well matched to this experiment. Initial running during 1998 will take place with a 4GeV beam, increasing to 6GeV for the primary physics run in 1999.

A diagram of the Radphi experiment is shown in Fig. 1. Installed in the alcove behind the CLAS detector in Jefferson Lab's Hall B, the experiment is designed to be able to run in tandem with other experiments using the same tagged photon beam. The shielding which protects the apparatus from what is taking place upstream is not shown in the figure. In its initial phase the experiment makes use of a 2.54cm beryllium target. This target has the advantage of being more simple and compact than a liquid hydrogen target of comparable thickness and provides a point-like vertex for event reconstruction. It also has the disadvantages of nuclear recoil and increased multiple-scattering in the target which reduce somewhat the sensitivity of a trigger designed to to select on photoproduced mass based upon the recoil proton kinematics. The recoil proton detector (RPD) is a 12-fold segmented annulus of plastic scintillator arranged in a thin followed by a thick layer, operated in coincidence. The annulus covers the full 360^o in azimuth and polar angles between 40^o and 60^o in the lab, which accepts about 2/3 of the ϕ's photoproduced from protons in the beryllium target.

In the forward region, the detector is instrumented with a 640-element lead-glass calorimeter (LGD) [12]. The ϕ's are reconstructed from multi-photon final states such as the one shown in the figure. In front of the calorimeter is a plane of plastic scintillator to act as a charged-particle veto (CPV). An additional veto plane upstream of the target (not shown in Fig. 1) is used to reduce backgrounds from charged particles in the halo around the beam. The trigger for the experiment is based upon four basic elements: (a) a proton in the RPD, (b) no signal in the CPV, (c) coincidence with the tagger hodoscope used to identify ("tag") beam photons within the desired energy range and (d) an interesting pattern in the LGD. An intelligent processor coupled to the LGD readout gives the possibility of a fast on-line decision based upon global properties in the LGD, such as total energy, cluster multiplicity, transverse energy, or total invariant mass of all clusters.

The Radphi apparatus and trigger have been designed for operation at the highest rates that the tagger is capable of running, estimated to be $5 \cdot 10^7\gamma$/s. Under these conditions there are 30 ϕ/s photoproduced in the target in association with tagged photons. The number of reconstructed events for selected all-neutral decay modes from a 1000h run is shown in Table 2. Losses due to unseen decay modes of daughter particles and from trigger and reconstruction inefficiencies are taken into account in these estimates. For the $\phi \to f_0\gamma$ and $\phi \to a_0\gamma$ modes the preliminary numbers for the branching ratios reported at this conference by the SND collaboration [13] have been used.

A brief running period was obtained by Radphi during the tagger commissioning period in 1997, when

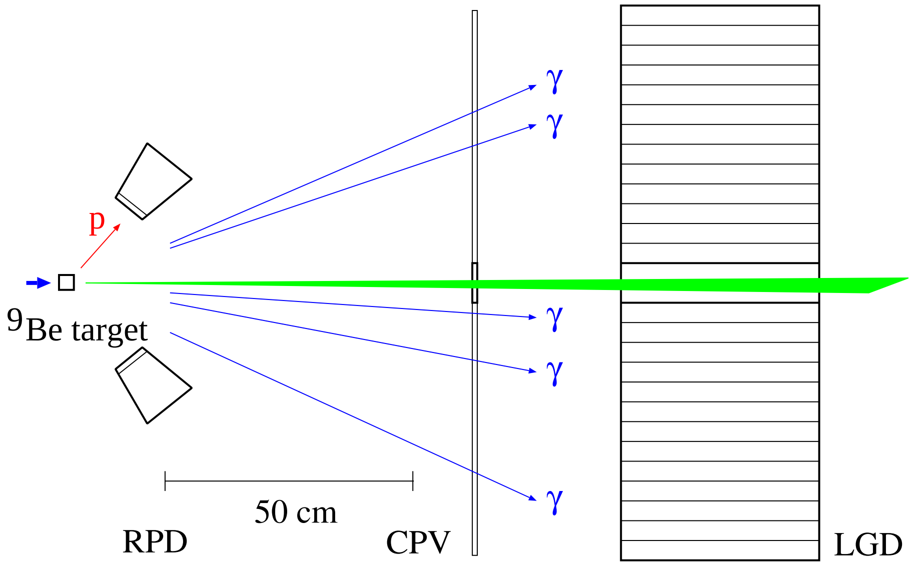

Figure 1: Layout of CEBAF experiment E94-016, showing photon beam incident from the left (arrow) on a 2.54cm thick ^{9}Be cylindrical target 2.54cm in diameter. The final state shown is the one for which the trigger selects, with the 5γ invariant mass near $1.02\mathrm{GeV}/c^2$. There is no magnetic field, so that the majority of $e^\pm$ pairs created in the target escape through the 8cm×8cm hole in the forward region of the detector.

a 4GeV photon beam was incident on the Radphi target. With these data a preliminary calibration of the lead-glass detector was performed, yielding the two-cluster invariant mass spectrum shown in Fig. 2. A π^0 peak is clearly visible. For a period in the summer of 1998 Hall B is scheduled for physics running with 4GeV photons, during which Radphi will operate as a secondary user of the beam and collect the first physics data for the experiment.

4 Other physics

Beyond the immediate goal of observing ϕ radiative decays to scalar mesons, there are other physics topics that are addressed by this data sample. The branching ratio for $\phi \to \eta'\gamma$ contains important information concerning SU(3) flavour mixing in the pseudoscalar nonet and the possibile admixture of a glueball component inside the η' [14]. This measurement has also been identified as an important test of light-cone wavefunctions for the S-wave mesons [15]. In addition to its own physics goals, Radphi is also a test bed to study the feasibility of a more ambitious future experiment that would involve still higher fluxes of ϕ's for tests of fundamental symmetries [16].

The Radphi collaboration is composed of members from Catholic University, University of Connecticut, Indiana University, Jefferson Lab, University of Notre Dame, Rensselaer Polytechnic Institute, University of Richmond, University of Virginia, and College of William and Mary.

Table 1: Model predictions for ratios of radiative ϕ-decay couplings

model	$\frac{B.R.(\phi\to a_0\gamma)}{B.R.(\phi\to f_0\gamma)}$
quark model	$\ll 1$
$\overline{K}K$ molecule	1
$\overline{qq}qq$ state	9

Table 2: Expected yields for selected all-neutral radiative decay modes for a 1000h experiment

	$B.R. \cdot 10^6$			acceptance	
$\phi \to$	(all decays)	($n\gamma$'s)	$\#\gamma$	(%)	Yield
$\gamma\pi^0$	1300	1300	3	35	45000
$\gamma\eta$	13000	5000	3	35	175000
$\gamma\eta'$	100	2	3	30	70
γa_0	100	40	5	7	300
γf_0	100	30	5	10	300

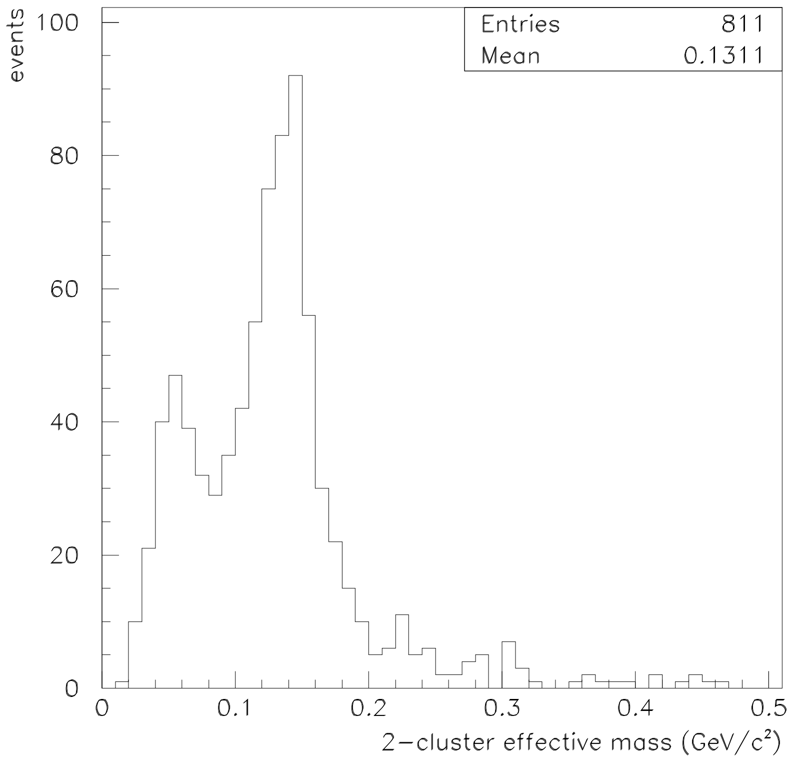

Figure 2: Invariant mass of pairs of clusters from a selected sample of events collected by the Radphi experiment during commissioning of the tagged photon facility at CEBAF in 1997. The peak corresponding to π^0 decays stands out clearly over background from uncorrelated clusters.

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