Isospin breaking exposed in $f_0(980) - a_0(980)$ mixing

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**Abstract**

We suggest that mixing between the $f_0(980)$ and $a_0(980)$, due to their dynamical interaction with the nearby $K\bar{K}$ thresholds, can give rise to a significantly enhanced production rate of $a_0(980)$ relative to $a_2(1320)$ in $pp \rightarrow p_s(\eta\pi^o)p_f$ as $x_F \rightarrow 0$. The peaking of the cross section as $\phi \rightarrow 0$ should also occur. We show that such effects are seen in data and deduce that the $f_0(980) - a_0(980)$ mixing intensity is $8 \pm 3 \%$. 
The enigma of the scalar mesons may be boiled down to an essential question: what are the \( f_0(980) \) and \( a_0(980) \)? Do they have a common origin and, if so, what is it? Understanding the \( f_0(980) \) in particular is a central problem for identifying the dynamics associated with the long sought scalar glueball.

There have even been suggestions that the \( f_0(980) \) itself may be the eponymous glueball, perhaps mixed with \( q\bar{q} \); in such a case the mass degeneracy with the \( a_0(980) \) would be somewhat accidental and the two mesons not clearly related. An interpretation of the \( f_0(980) \) as a \( q\bar{q} \) state is still consistent with the present data (see for example ref. [1]). By contrast, there is a large body of work drawing on the observation that the \( f_0(980) \) and \( a_0(980) \) are very close to the \( K\bar{K} \) threshold, and that the \( K\bar{K} \) channel drives the dynamics [2]. As an extreme, there is the possibility that these mesons are truly bound states of \( K\bar{K} \) [3].

Traditionally in strong interactions isospin is believed to be a nearly exact symmetry, broken only by the slightly different masses of the \( u \) and \( d \) quarks and/or electroweak effects. The small difference in mass between \( K^+ \) and \( K^0 \) is a particular example. However, the mass gaps between the \( f_0(980)/a_0(980) \) and the \( K^+K^- \) and \( K^0\bar{K}^0 \) thresholds are substantially different with the result that the dynamics of bound \( K\bar{K} \) states can be described better in a basis specified by mass eigenstates. Such dynamics would give rise to a violation of isospin and lead to mixing of states with different G-parities.

The possibility of such an effect was suggested long ago in ref. [4]. In ref. [5] a study was performed of the production of the \( a_0(980) \) in the reaction \( \pi^+\pi^- \rightarrow \eta\pi \) which due to G parity is forbidden and can only occur through \( f_0(980) - a_0(980) \) mixing. This showed that (6–33)% of the \( a_0(980) \) cross section in \( \pi^-p \) reactions could be due to \( f_0(980) - a_0(980) \) mixing. Further discussions along this line have been made by ref. [6] who have specifically drawn attention to the relation between the existence of \( K\bar{K} \) molecular bound states and large violations of isospin. Very recently, attention has been drawn to such mixings having observable effects in threshold photoproduction, such as at CEBAF [7]. These papers have all concentrated on the production of the \( f_0(980)/a_0(980) \) by flavoured mesons or photons; in this paper we propose that their production by gluonic systems, such as the \( P \) (Pomeron)-induced production in the central region at high energy: \( pp \rightarrow pp + f_0(980)/a_0(980) \), may provide rather clean tests of the mixing. Furthermore, we shall suggest that new data from the WA102 collaboration at CERN [8] are already consistent with a significant mixing. We shall consider alternative interpretations and suggest ways of eliminating these in future experiments.

These data potentially may help to elucidate the nature of the \( f_0(980)/a_0(980) \) states. Our hypothesis is based on recent breakthroughs in understanding the dynamics and topology (momentum and spatial distributions) of meson production in the central region of rapidity, \( pp \rightarrow pMp \) [4, 14]. In particular, we shall focus on the description of the observed \( \phi \) dependences [14], where \( \phi \) is the angle between the \( p_T \) vectors of the two outgoing protons. In such processes at high energy, where \( PP \) fusion dominates the meson production, \( C = +, I = 0 \) resonances such as the \( f_0(980) \) are very strongly produced [11] whereas in general isospin 1 states are suppressed [12]. Even at the energies of the WA102 data, there is considerable evidence that \( PP \) fusion is an important part of the production dynamics [12]. It is tantalising therefore that recent data from the WA102 collaboration on the centrally produced \( \eta\pi \) final state [8] show interesting effects in that they are in accord with substantial \( f_0(980) - a_0(980) \) mixing.
In particular it is instructive to compare the systematics of the well understood \( f_2(1270)/a_2(1320) \) \((^3P_2q\bar{q})\) states with the \( f_0(980)/a_0(980) \) states. In the reaction \( pp \to p(\eta\pi^0)p \) the centrally produced \( a_0(980) \) and \( a_2(1320) \) are suppressed relative to their \( I = 0 \) partners, as expected for \( I = 1 \) states. Nonetheless, there appears to be an extra affinity for \( a_0(980) \) production here, since

\[
\frac{\sigma(pp \to pp[a_0^0(980) \to \eta\pi])}{\sigma(pp \to pp[a_2^0(1320) \to \eta\pi])} \approx 2.0 \pm 0.4 \tag{1}
\]

By contrast, when the charged members of these isovectors are produced, as in \( pp \to p(\eta\pi^-)\Delta^{++} \), \( a_0^-(980) \) and \( a_2^- (1320) \) production rates are found to be similar. Fits to the \( \eta\pi^- \) mass spectrum in central production give

\[
\frac{\sigma(pp \to p\Delta^{++}[a_0^0(980) \to \eta\pi^-])}{\sigma(pp \to p\Delta^{++}[a_2^0(1320) \to \eta\pi^-])} \approx 0.8 \pm 0.2 \tag{2}
\]

The significance of these ratios becomes more apparent when compared with the case of the charge exchange reaction, where (as in eq. (2)) \( I = 1 \) exchanges are necessarily present. In this case the \( a_2(1320) \) meson dominates the mass spectrum, and the ratio

\[
\frac{\sigma(\pi^-p \to [a_0^0(980) \to \eta\pi]|n)}{\sigma(\pi^-p \to [a_2^0(1320) \to \eta\pi]|n)} \approx 0.15 \tag{3}
\]

at 38 GeV/c beam momentum.

First we shall explain this hierarchy and motivate the enhancement in \( f_2 \) as indicative of direct \( f_0(980) \) production with \( f_0(980) - a_0(980) \) mixing. Then we show how the characteristic momentum and \( \phi \) dependences of \( f_0(980) \) production will, through mixing, spill over to \( a_0(980) \) production. Finally we shall see that such signatures are indeed present in the \( a_0(980) \) production data and consistent with a substantial \( f_0(980) - a_0(980) \) mixing.

In \( \pi^-p \to a_0(2n) \), it is easy to make the \( a_2(1320) \) via \( \rho \) exchange. However in order to produce the \( a_0(980) \), \( \rho_2 \) and/or \( b_1 \) exchange is needed which is relatively suppressed \([4]\). In \( pp \to p(\eta\pi^-)\Delta^{++} \) the \( a_2 \) production is again consistent with \( \pi\rho \) fusion \([3]\). Fig. \( \text{ll}b \) shows the observed \( \phi \) distribution for the \( a_2^-(1320) \) \([3]\). As can be seen the distribution is isotropic in \( \phi \), as expected for \( \pi \) exchange \([3, 3]\), and the \( t \) slopes \([3]\) are consistent with \( \pi \) and \( \rho \) being produced at either vertex, (it is known that the \( \rho \) can be produced at the \( p\Delta^{++} \) vertex from the WA102 data on \( pp \to p\Delta^{++}\rho^- \)) \([4]\). However, some other mechanism is needed to explain the relatively enhanced \( a_0(980) \) signal. The \( \phi \) distribution for the \( a_0^- \) (980) is shown in fig. \( \text{ll}a \) and as can be seen it is also isotropic.

There are four particular exchanges that can enhance the \( a_0(980) \) signal in \( pp \to p(\eta\pi^-)\Delta^{++} \) relative to its suppressed rate in charge exchange \([3]\). First, \( I=0 \) exchange (\( \eta \)) can occur at the proton vertex and cause \( \pi\eta \to a_0(980)/a_2(1320) \). Though \( \eta \) exchange will be isotropic in \( \phi \), in accord with data, it is generally agreed to be small and hence unlikely on its own to drive the enhanced \( a_0(980) \) signal.

The second possibility is production by \( \pi b_1 \) fusion. Although the \( ppb_1 \) vertex is small, for \( p\Delta b_1 \) the quantum numbers match in \( S \)-wave and so \( \pi b_1 \) fusion could be significant in
\[ pp \rightarrow p\Delta a_{0,2} \]. Because of the \( \pi \) exchange, the \( \phi \) distribution will be isotropic \([8] [13]\), as in the data. However, empirically \( \sigma(pp \rightarrow pp\pi_0) \sim \sigma(pp \rightarrow p\Delta a_{2}(1320)) \) which suggests that \( b_1 \) exchange is not the major mode and further points to \( \pi \pi \rightarrow a_2(1320) \) as the dominant dynamics. If \( a_0(980) = 3P_0(q\bar{q}) \) then in the quark model the ratio of amplitudes \( \pi b_1 \rightarrow a_0(980)/a_2(1320) \sim 1 \) and we would still be left with the mystery of its production. Even if \( a_0(980) \neq 3P_0(q\bar{q}) \), the \( \pi b_1 \) production would be expected to be minimal in \( pp \) and so the enigma of \( a_0(980) \) production there would remain.

The third possibility is that \( \rho \) from the \( p\Delta \) vertex fuses with \( \omega \) from the \( pp \) vertex. This can feed both \( a_0(980) \) and \( a_2(1320) \). Empirically the \( a_2(1320) \) is produced polarised with \( \lambda = 1 \) \([8]\); however, \( VV \rightarrow 2^{++}(\lambda = 1) \) would contain a characteristic \( \sin^2(\phi/2) \) component \([3]\) in marked contrast to the observed isotropy. This suggests that \( \rho \omega \rightarrow a_2(1320) \) is not a major mechanism and to the extent that \( a_{0,2} \) are related as \( 3P_{0,2} q\bar{q} \) states, would also argue against a strong \( a_0(980) \) signal. Furthermore, the empirical absence of \( a_2(1320) \) \( (3P_{2}q\bar{q}) \) with \( (\lambda = 0) \) would in turn also imply a suppressed production of \( a_0(980) \) \( (3P_0q\bar{q}) \). However, it is possible that the \( K\bar{K} \) threshold disturbs the \( a_0(980) \) such that \( \rho \omega \rightarrow a_0(980) \) is controlled by this and not by the \( q\bar{q} \) content; in this case the production strength and properties could be independent of the \( a_2(1320) \). In general the \( \phi \) dependence for a \( 0^{++} \) state produced by vector-vector fusion (where \( L \) is the longitudinal component of the vector and \( T \) is the transverse component) has the following structure \([10]\):

\[
\frac{d\sigma}{dt_1 dt_2 d\phi} \sim [1 + \frac{\sqrt{t_1 t_2} a_T}{\mu^2 a_L} e^{(b_L - b_T)(t_1 + t_2)/2} \cos(\phi)]^2 e^{-b_L(t_1 + t_2)}
\]

(4)

The ratio \( a_T/a_L \), which determines the relative importance of the \( 0^+ \) production by \( T \) or \( L \) components, can be positive or negative, or in general even complex; its value is determined, inter alia, by the internal dynamics of the produced meson. To the extent that the \( \phi \) distributions empirically are consistent with being isotropic, it would appear that longitudinal-scalar amplitudes dominate the production for the \( a_0(980) \); this might be natural were it a \( K\bar{K} \) molecule where \( K \) exchange dominated the production vertex.

The fourth possibility is that \( P \) exchange plays a role at the \( pp \) vertex. In principle there could be significant \( a_{0,2} P \rightarrow a_{0,2} \). If these were dominant, one would expect similar production rates of \( a_0(980) \) in both \( pp\pi_0(980) \) and \( p\Delta a_0(980) \) processes and also a rapid fall off in the \( a_0(980)/a_2(1320) \) production ratio with increasing energy. As the data are only at a single value of \( s \) one cannot immediately eliminate this. However there are two features that argue against this. First, \( a_0(980) P \rightarrow a_0(980) \) will give an isotropic \( \phi \) distribution; while this is seen in the \( p\Delta a_0(980) \) production (fig. \([10]\)), the reaction \( pp\pi_0(980) \) is \( \phi \) dependent (fig. \([2a]\)). Second, the \( x_F \) distributions of the \( a_0^0(980) \) and \( a_2^0(1320) \) formed in \( p\Delta a_{0,2} \) are shown in fig \([3c]\) and \( d \) respectively. As can be seen the distributions are flat for \( x_F \leq 0.1 \) (do not peak as \( x_F \rightarrow 0 \)) which may indicate that there is a significant presence of non-central production. Fig \([3c]\) and \( d \) show the \( x_F \) distributions for the \( a_0^0(980) \) and \( a_2^0(1320) \) formed in \( pp\pi_0 \). The distribution for the \( a_2^0(1320) \) is similar to that observed for the \( a_2^0(1320) \) whereas that for the \( a_0^0(980) \) is significantly different and peaks at \( x_F = 0 \). Indeed this is the only state with \( I = 1 \) that is observed to have a \( x_F \) distribution peaked at zero \([13]\), and moreover the distribution for the \( a_0^0(980) \) looks similar to the central production of states that are accessible to \( PP \) fusion, in particular \( PP \rightarrow f_0(980) \), see fig \([3b]\) and \( d \). If we restrict ourselves to the central production
region $x_F \leq 0.1$, then the relative ratio of $a_0/a_2$ production rates in eq. (1) is even more enhanced and becomes $3.4 \pm 0.4$.

In summary, we are unable to find an explanation of the production of $a_0$ in $pp \rightarrow p\Delta a_0$ if $a_0 = ^3P_2 q\bar{q}$. We will now show evidence that there is significant mixing between $a_0^0(980)$ and $f_0(980)$ in $pp \rightarrow ppa_0/f_0$, which reveals a marked affinity of these states for $K\bar{K}$.

In the process $pp \rightarrow p(\eta\pi^0)p$, there is a prominent new feature allowed, namely $PP$ fusion due to $P$ emission at each proton vertex. As this will feed only $I = 0$ channels, such as the $f_0(980)$ and $f_2(1270)$, one would not expect this to affect $a_0,2$ production unless isospin is broken. As we noted earlier, the $a_0(980)/a_2(1320)$ ratio in the WA102 data is significantly larger in reaction $[1]$ than in reaction $[2]$, especially so when $x_F \leq 0.1$. Furthermore, the $x_F$ distribution of the $a_0(980)$ production is, within the errors, identical to that of the $f_0(980)$ (see fig. 3). In reaction (2) the $\phi$ dependencies for both the $a_0(980)$ and $a_2(1320)$ are flat (fig. 3a) and b) respectively. In reaction (1) although the $\phi$ dependence of the $a_2(1320)$ remains flat (fig. 2b) that of the $a_0(980)$ is peaked as $\phi \rightarrow 0$ (fig. 2a). In fact the $\phi$ distribution for the $a_0(980)$ looks very similar to that observed for the $f_0(980)$ (fig. 3a) and c)). Qualitatively this is what would be expected if part of the centrally produced $a_0^0(980)$ is due to $PP \rightarrow f_0(980)$ followed by mixing between the $f_0(980)$ and the $a_0(980)$.

In order to estimate the amount of the $a_0^0(980)$ that has been produced by mixing we have performed a fit to the $\phi$ distribution of the $a_0^0(980)$ assuming it to be the sum of two incoherent components: (i) a flat distribution similar to the $a_0^0(980)$ and (ii) a distribution of the form $(4 + \cos(\phi))^2$ which describes the $\phi$ distribution of the $f_0(980)$ as shown in fig. 3a). We have determined from the fit to fig. 3a) that $80 \pm 25 \%$ of the $a_0^0(980)$ comes from the $f_0(980)$. Combining this result with the relative total cross sections for the production the $f_0(980)$ and $a_0^0(980)$ [13] we find the $f_0(980) - a_0(980)$ mixing intensity to be $8 \pm 3 \%$.

Technically our analysis only sets an upper limit on the isospin breaking until such time as the energy dependence is determined and the $PP$ production thereby confirmed. Subject to this caveat our analysis adds weight to the hypothesis that the $K\bar{K}$ threshold plays an essential role in the existence and properties of these states. The question of whether they are $K\bar{K}$ bound states or whether it is merely the $K\bar{K}$ threshold which is driving these effects is still to be resolved.

Other lines of study are now warranted. Experimentally to confirm these ideas requires measuring the production of the $\eta\pi$ channel at a much higher energy, for example, at LHC, Fermilab or RHIC where Reggeon exchanges such as $\rho\omega$ would be effectively zero and hence any $a_0(980)$ production must come from isospin breaking effects. In addition, “pure” flavour channels should now be explored. Examples are $D_\ell$ decays [14] where the weak decay leads to a pure $I=1$ light hadron final state. Thus $\pi f_0(980)$ will be (and is [17]) prominent, while our analysis would suggest that $\pi a_0$ should also be present at $8\pm3 \%$ intensity. We recommend that these be studied with high statistics data sets now emerging from E791, FOCUS and BaBar. In addition, we encourage studies of $J/\psi$ decays at Beijing, in particular to the “forbidden” final states $\omega a_0$ and $\phi a_0$ where we predict branching ratios of $O(10^{-5})$. On the theory side, detailed predictions are needed in specific models in order to resolve precisely how the $K\bar{K}$ threshold
relates to the $f_0(980)/a_0(980)$ states.

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Figures

Figure 1: For the reaction $pp \rightarrow \Delta^{++} p \eta \pi^-$: The $\phi$ distributions for a) the $a_0^-(980)$ and b) the $a_2^+(1320)$. The $x_F$ distributions for c) the $a_0^-(980)$ and d) the $a_2^+(1320)$.

Figure 2: For the reaction $pp \rightarrow pp \eta \pi^0$: The $\phi$ distributions for a) the $a_0^0(980)$ and b) the $a_2^0(1320)$. The $x_F$ distributions for c) the $a_0^0(980)$ and d) the $a_2^0(1320)$.

Figure 3: The $\phi$ distributions a) for the reaction $pp \rightarrow pp f_0(980)$ and b) for the $f_0(980)$ compared to the $a_0^0(980)$. The $x_F$ distributions c) for the reaction $pp \rightarrow pp f_0(980)$ and d) for the $f_0(980)$ compared to the $a_0^0(980)$. 
Figure 1
Figure 2
Figure 3