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NEUTRAL MESONS WHICH DECAY INTO $4\pi^0$

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(Joint CERN - IHEP experiment)

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Abstract

Data on the $4\pi^0$ decay mode of mesons have been obtained in a search for glueballs performed at the CERN SPS with the GAMS - 4000 multiphoton spectrometer. A new tensor glueball candidate X(1810) appears as a clear peak in the $4\pi^0$ mass spectrum. The $4\pi^0$ decay of G(1590) is also observed. The measured value of $BR(G \rightarrow 4\pi^0)/BR(G \rightarrow \eta\eta) = 0.8 \pm 0.3$ further supports the glueball assignment of this scalar particle. The rare decay of $f(1270)$ into $4\pi^0$ has been measured : $BR(f \rightarrow 4\pi^0) = (3 \pm 1) \cdot 10^{-3}$.

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The study of the 4 π^0 decay mode of neutral mesons is of special interest for an understanding of their internal structure. For $q\bar{q}$ mesons this decay mode is expected to be rare in comparison with other 4 π decay modes which are enhanced by ρ - dominance : $M^0 \rightarrow (\rho\rho) \rightarrow 2\pi^+2\pi^-$ or $2\pi^0\pi^+\pi^-$ but not to 4 π^0 as ρ^0 cannot decay into 2 π^0 . For mesons with an exotic structure, e.g. glueballs, the ratio 4 $\pi^0/4\pi$, i.e. $\text{BR}(M^0 \rightarrow 4\pi^0)/\text{BR}(M^0 \rightarrow 4\pi)$, may become as large as 1/5 [1]. Thus, ordinary $q\bar{q}$ mesons like $f(1270)$, $D(1235)$, $h(2030)$ etc. are expected to decay rarely into 4 π^0 ($< 1\%$) while this could be one of the main decay channels for exotic mesons like $G(1590)$ [2], a scalar glueball candidate, for which $\text{BR}(G \rightarrow 4\pi^0)$ could be of the order of 10% [3].

The study of the 4 π^0 decay channel thus opens a new way to the search for exotic states : glueballs, hybrids, etc. It has not been previously measured because of a series of experimental difficulties including the need to detect and measure momentum and coordinates of eight gammas and disentangle the large combinatorial background (twenty eight two - gamma combinations for each decay event).

The present experiment, which has been performed at the CERN SPS (NA12 Exp.), brings evidence for such a decay mode in several mesons produced in the exclusive reaction :

$$\pi^- p \rightarrow M^0 n, \quad M^0 \rightarrow 4\pi^0 \rightarrow 8\gamma \quad (1)$$

with 100 GeV/c negative pions incident on a liquid hydrogen target.

The experimental setup has been described earlier [5]. The main detector is the hodoscope electromagnetic calorimeter GAMS - 4000 which can record as many as 20 photons simultaneously [6,7]. Procedures for GAMS calibration, for measurements and data handling are explained in [5,8 - 10]. The target - to - GAMS distance, which defines angular and mass acceptance of the setup, was 15 meters for two thirds of the data and 20 meters for the others. Preliminary results (20 m data) have already been presented [4].

After reconstruction of the momentum - vector of each gamma, the final sample of 350,000 eight - gamma events has been submitted to a 5 - C fit, fixing the mass of each π^0 and the mass of the recoil neutron in reaction (1). Fig. 1a shows the invariant mass spectrum of the fourth gamma pair after the first three have been identified as π^0 (4 - C fit). The background is small, less than 10%. One hundred thousand events remain after the 5 - C fit (C.L. > 0.1).

A study has been made of possible contributions of $2\pi^0$ and $3\pi^0$ subprocesses. The mass spectrum of π^0 -pairs shows no structure except for a weak shoulder in the f -meson region. This spectrum is well described by pure phase space (S-wave). On the other hand, the spectrum of $3\pi^0$ -subsystems (fig. 1b) shows a prominent narrow peak of η -mesons decaying into $3\pi^0$ [11]. About 30% of the $4\pi^0$ events are due to $\eta\pi^0$ decays. The $\eta\pi^0$ spectrum is dominated by the $A_2(1320)$ -meson [12]. These events are removed by an appropriate cut of the η peak in the $M_{3\pi^0}$ spectrum. The background from the reaction $\pi^-p \rightarrow K_s^0 K_s^0 n$ with $K_s^0 \rightarrow 2\pi^0$ has been evaluated by Monte Carlo. It is largest (5%) in the $f(1270)$ region.

The final mass spectrum of the 60,000 remaining $4\pi^0$ events (fig. 2a) shows structures at 1.3 GeV, 1.6 GeV and 1.8 GeV. The shape of the distribution of these events as a function of t , the square of the four-momentum transferred to the recoil neutron in reaction (1), does not depend on the mass (fig. 3). It is strongly peaked in the forward direction, a characteristic of one-pion exchange mechanism (OPE). In order to reduce the possible contributions of other production processes with exchange of heavier mesons (ρ , A_2 , etc.), characterized by larger t -distributions, events with $|t| > 0.15$ (GeV/c)² have been cut. As a result the $4\pi^0$ sample is reduced by 20%, with no apparent influence on the shape of the mass spectrum.

The OPE dominance facilitates the spin-parity analysis of the process : the spin of the $4\pi^0$ -system is aligned, i.e. its projection along the z -axis of the Gottfried-Jackson frame is zero (OPE without absorption). Moreover the quantum numbers of such systems are limited to even spin and parity and positive charge conjugation : $J^{PC} = 0^{++}, 2^{++}$, etc.

Taking this into account, the matrix element for the production of two π^0 -pairs in S-waves with a relative orbital momentum $L=2$, symmetric under the exchange of any two pions (Bose-Einstein statistics), reduces to the expression :

$$|\mathcal{M}| \sim \sum_{j=2}^4 [3 (\bar{e}_z \bar{p}_{1j})^2 - \bar{p}_{1j}^2] \quad (2)$$

$\bar{e}_z$ is a unit-vector and $\bar{p}_{ij} = \bar{p}_i + \bar{p}_j$ where $\bar{p}_i$ is the momentum of the i -th π^0 in the Gottfried-Jackson frame. If one introduces a symmetrized dimensionless parameter defined as the cosine of an auxiliary angle, θ_{OB} ,

$$\cos^2\theta_{OB} = \frac{\sum_{i < j} \bar{p}_{ij}^2 \cos^2\theta_{ij}}{\sum_{i < j} \bar{p}_{ij}^2} \quad (3)$$

where $i, j = 1, 2, 3$ and $\cos\theta_{ij} = \bar{e}_z \cdot \bar{p}_{ij} / |\bar{p}_{ij}|$, then the matrix element may be expressed in the form $|M| \sim (3\cos^2\theta_{OB} - 1)$ similar to that obtained for spin 2 two-body decays, e.g. $M^0 \rightarrow 2\pi^0$, where θ_{OB} is simply replaced by the polar Gottfried-Jackson angle θ_{GJ} .

The spin of the $4\pi^0$ -system may thus be determined through the analysis of the $\cos\theta_{OB}$ distribution in the same manner that was used for determining the spin of $h(2030)$ and $r(2510)$ mesons through their θ_{GJ} distribution [13]. Monte Carlo calculations show that $4\pi^0$ decays of spin 2 states are enhanced if $\cos\theta_{OB} < 0.4$ and that they may be observed in this region in an optimal way. Those of zero spin states are enhanced if $\cos\theta_{OB} > 0.5$.

Fig. 2b and 2c show the mass spectrum after applying such cuts to the data. The two peaks at 1.3 GeV and 1.8 GeV are now much more prominent in the spin 2 favoured sample and the shoulder at 1.6 GeV nearly vanishes. The reverse is true for the 0^+ favoured spectrum : the 1.3 GeV and 1.8 GeV are reduced and the 1.6 GeV signal is much stronger.

The $4\pi^0$ events that build up the spectrum of Fig. 2 satisfy the criterium of C.L. > 0.1 . In 30% of the cases a second solution also satisfies the fit, with a lesser probability but again with a C.L. > 0.1 . Monte Carlo calculations show that this group is mainly composed of good $4\pi^0$ events and that the second solution is due to the finite resolution of the setup. Nevertheless, in view of the high statistics of the experiment and in order to guarantee the purity of the $4\pi^0$ sample, only those with a unique solution are kept for further analysis. Their spectrum is shown on fig. 4. It does not essentially differ from fig. 2.

Each spectrum of fig. 4 has been fit with three resonance curves and a polynomial continuum. The table gives the ratios of the number of events in the different peaks for the two intervals, $\cos\theta_{OB} > 0.5$ and $\cos\theta_{OB} < 0.4$. Comparing with the values expected from Monte Carlo evaluations, quantum numbers of these resonances may be unequivocally attributed : spin 2 to the 1.3 GeV and 1.8 GeV states and spin 0 to the 1.6 GeV state.

The parameters of the first 2^{++} resonance are :

$$M = (1806 \pm 10) \text{ MeV}, \quad \Gamma = (190 \pm 20) \text{ MeV}. \quad (4)$$

1600 ± 100 events are observed in the peak. The production cross-section of this meson $X(1810)$ in reaction (1) at 100 GeV, after correction for efficiency and normalization to the cross-section of reaction $\pi^- p \rightarrow \eta' n$, $\eta' \rightarrow \eta \pi^0 \pi^0 \rightarrow 6\gamma$ for which events have a close topology and which has simultaneously determined with reaction (1), is :

$$\sigma(\pi^- p \rightarrow X n) \cdot \text{BR}(X \rightarrow 4\pi^0) = (8 \pm 2) \text{ nb}. \quad (5)$$

$X(1810)$ cannot be identified with any known meson decaying into $\pi\pi$ or into $K\bar{K}$. Earlier communications on the possible existence of such a state in this mass region [2] have not been confirmed by more recent high-statistics experiments [2,5].

A 2^{++} state with a mass of (1870 ± 40) MeV and a width of (250 ± 30) MeV has been proposed as one of two possible solutions obtained in a partial wave analysis of the production of mesons decaying into η -pairs at 100 GeV/c [5]. A similar conclusion has also been reached in the analysis of $\eta\eta$ systems at 38 GeV/c [14]. If both observations correspond to the same object then $\text{BR}(X \rightarrow 4\pi^0)/\text{BR}(X \rightarrow \eta\eta) = 0.8 \pm 0.3$.

The non-observation of the $X(1810) \rightarrow 2\pi^0$ decay in the present experiment gives the following upper limit :

$$\text{BR}(X \rightarrow 2\pi^0)/\text{BR}(X \rightarrow 4\pi^0) < 1/4 \quad (6)$$

This ratio should exceed 10 for an ordinary $q\bar{q}$ meson. This resonance is also not observed to decay into $2\pi^+ 2\pi^-$ [15], so it does not decay through $(\rho\rho)$ into 4π . All these facts point to the exotic nature of $X(1810)$, making it a tensor glueball candidate.

The second tensor meson is observed as a peak of 400 ± 50 events in the $4\pi^0$ channel with the following parameters :

$$M = (1283 \pm 6) \text{ MeV}, \quad \Gamma = (150 \pm 20) \text{ MeV} \quad (7)$$

There are three well known mesons in this mass region : $f(1270)$, $D(1285)$ and $A_2(1320)$. A_2 does not directly decay into $4\pi^0$ due to G -parity conservation. $\eta\pi^0$ events have been suppressed in the selection procedure (see above). Monte Carlo evaluations show that leakage of such events into the final data sample cannot be more than a few percent. The forward peaked t -distribution (fig. 3) confirms this observation.

The number of $D(1285) \rightarrow 4\pi^0$ events is also small. It has been shown above that $2\pi^0$ subsystems are predominantly in S -waves. For a 1^+ meson only one such pair may be in an S -wave. The t -distribution on Fig. 3 shows that $D(1285)$ (which like A_2 cannot be produced by OPE) cannot be more than 10% of the observed sample. One may conclude from the extrapolated cross-section for the reaction $\pi^-p \rightarrow Dn$ at 100 GeV/c that :

$$\text{BR}[D(1285) \rightarrow 4\pi^0] < 7 \cdot 10^{-4} \quad (8)$$

so that $4\pi^0/4\pi$ is smaller than 1/500 for the D -meson.

In these conditions this $4\pi^0$ resonance may be safely identified with $f(1270)$. The production cross-section of $f(1270)$ in reaction (1) is :

$$\sigma(\pi^-p \rightarrow fn) \cdot \text{BR}(f \rightarrow 4\pi^0) = (2.5 \pm 0.7) \text{ nb}. \quad (9)$$

Using the value of $\sigma(\pi^-p \rightarrow fn)$ at 100 GeV/c [5], one obtains :

$$\text{BR}(f \rightarrow 4\pi^0) = (3 \pm 1) \cdot 10^{-3} \quad (10)$$

The small ratio $4\pi^0/4\pi \approx 1/30$ of this decay confirms the ρ -dominance in the $f \rightarrow 4\pi$ charged decays.

Similar conclusions may be drawn from the upper limit obtained for $h(2030)$ production :

$$\sigma(\pi^-p \rightarrow hn) \cdot \text{BR}(h \rightarrow 4\pi^0) < 5 \text{ nb} \quad (11)$$

namely

$$\text{BR}(h \rightarrow 4\pi^0) < 1.2 \cdot 10^{-2} \quad (12)$$

and $4\pi^0/4\pi$ is smaller than 1/50.

The parameters of the $0^{++} 4\pi^0$ -state (600 ± 70 events) are :

$$M = (1570 \pm 20) \text{ MeV}, \quad \Gamma = (150 \pm 20) \text{ MeV} \quad (13)$$

in agreement with those of the scalar $G(1590)$ -meson, a glueball candidate previously observed through its $\eta\eta$ and $\eta'\eta$ decay modes [2, 5, 16]. The data do not contradict the interpretation of $G(1590)$ as a meikton either [17]. It is produced in reaction (1) at 100 GeV/c with a cross-section :

$$\sigma(\pi^- p \rightarrow G n) \cdot \text{BR}(G \rightarrow 4\pi^0) = (3 \pm 1) \text{ nb} \quad (14)$$

The comparison of these data with those on the $\eta\eta$ channel gives :

$$\text{BR}(G \rightarrow 4\pi^0)/\text{BR}(G \rightarrow \eta\eta) = 0.8 \pm 0.3 \quad (15)$$

This large value is an independent argument in favour of a strong gluon component in $G(1590)$.

The $\eta\eta$, $\eta\eta'$ and 4π modes practically saturate the decay of $G(1590)$ which is known to have a low decay rate into $\pi\pi$, $K\bar{K}$, $K\bar{K}\pi\pi$, etc [13,16]. Using the measured ratio $\eta'\eta/\eta\eta = 2.8 \pm 0.7$ [13] and taking $4\pi/4\pi^0 = 5$ [1] one gets :

$$\begin{aligned} \text{BR}(G \rightarrow 4\pi) &= 0.5 \pm 0.1 \\ \text{BR}(G \rightarrow \eta'\eta) &= 0.35 \pm 0.10 \\ \text{BR}(G \rightarrow \eta\eta) &= 0.12 \pm 0.03. \end{aligned} \quad (16)$$

in good agreement with values expected for a scalar glueball.

Data collected at 38 GeV/c at IHEP by the Collaboration confirm the results of the present work [14].

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TABLE

Ratio $R = N(\cos \theta_{OB} > 0.5)/N(\cos \theta_{OB} < 0.4)$ for $4\pi^0$ events

State	Exp. result	$J=0^*)$	$J=2^*)$
f(1270)	0.27 ± 0.08	0.9	0.20
G(1590)	1.3 ± 0.5	0.8	0.17
X(1810)	0.08 ± 0.05	0.7	0.15

*) Monte Carlo result

FIGURE CAPTIONS.

Fig. 1 a) Mass distribution of the 4-th γ -pair after three other pairs have been identified as π^0 ;
 b) invariant mass spectrum of $3\pi^0$ -systems produced in the reaction $\pi^-p \rightarrow 4\pi^0n$
 at 100 GeV/c (four entries per event).

Fig. 2 Invariant mass spectrum of $4\pi^0$ -systems produced in reaction (1) at 100 GeV/c with
 $|t| < 0.15 \text{ (GeV/c)}^2$:

- a) all events, dashed line shows phase space (p.s.) after correction for efficiency;
- b) events with $\cos \theta_{OB} < 0.4$ (favouring $J^P = 2^+$);
- c) events with $\cos \theta_{OB} > 0.5$ (favouring $J^P = 0^+$).

Dashed curves in b) and c) are the efficiencies.

Fig. 3 Number of $4\pi^0$ events versus t in mass intervals around $f(1270)$ (Δ), $G(1590)$ ($\circ$) and
 $X(1810)$ ($\bullet$ and full histogram). The dashed histogram is the t -dependence for
 $A_2(1320) \rightarrow \eta\pi^0 \rightarrow 4\pi^0$ events measured in the same experiment.

Fig. 4 a),b) same as in fig. 2b and 2c but for events with a single solution (see text);
 full curves are the result of a fit; dashed lines show the continuum; c),d) after
 subtraction of the continuum.

FIG. 1

M_{π^0} [MeV]

FIG. 2

FIG. 3

$M_{4\pi^0}$ [MeV]

FIG. 4