NEUTRAL DECAYS OF $\eta'(958)$

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(Joint CERN-IHEP experiment)

Abstract

The partial widths of the $\eta'(958)$ decays into $2\gamma$, $\omega\gamma$, $3\pi^0$ and $\eta\pi^0\pi^0$ have been measured with the GAMS-2000 spectrometer at the 70 GeV IHEP accelerator. Upper limits for the $\eta'$ decays into $3\gamma$, $\pi^0\gamma\gamma$, $2\omega$ and $4\pi^0$ have also been obtained. The slope of a linear matrix element for the C-parity violating decay $\eta' \to 3\pi^0$ has been determined.

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INTRODUCTION

Precision measurements have been made of the partial widths of the neutral decay modes of the \( \eta'(958) \)-meson into two \( \gamma \)
\[ \eta' \rightarrow 2\gamma \]
into an \( \eta \)-meson and two neutral pions
\[ \eta' \rightarrow \pi^0\pi^0 \rightarrow 2\gamma \]
\[ \eta' \rightarrow \pi^0\pi^0 \rightarrow 2\gamma \]
into an \( \omega \)-meson and one \( \gamma \)
\[ \eta' \rightarrow \omega\gamma \]
and an investigation has been made of its decay into three neutral pions
(G-parity violating decay)
\[ \eta' \rightarrow 3\pi^0 \]
Upper limits have been obtained for the decay widths of
\[ \eta' \rightarrow \pi^0\gamma \gamma \]
of the C-parity non-conserving decay into three \( \gamma \)
\[ \eta' \rightarrow 3\gamma \]
as well as for the parity-non-conserving decay
\[ \eta' \rightarrow 2\pi^0 \]
and the decay
\[ \eta' \rightarrow 4\pi^0 \]
The slope of a linear matrix element has been determined from the Dalitz plots for decays (2) and (4).

1. EXPERIMENTAL SETUP AND DATA HANDLING

Neutral decay modes of the \( \eta'(948) \)-meson have been studied with the Cerenkov multiphoton spectrometer GAMS-2000 [1] at the 70 GeV IHEP accelerator. In order to uncover possible systematic errors, the measurements have been performed with 38 GeV/c incident \( \pi^- \) for distances, \( L \), between the target and GAMS of 10 m and 12 m; and with 30 GeV/c incident \( \pi^- \) at \( L = 10 \) m.
Charge exchange processes of the class

\[ \pi^- p \rightarrow M^0 n \rightarrow kY \]  \hspace{1cm} (9)

are selected by triggering on neutral events and with the help of the guard system of counters surrounding the liquid hydrogen target [2].

The GAMS-2000 spectrometer can detect with high efficiency events produced in reaction (9) with photon multiplicities, \( k \), as large as 10. Neutral decays of the \( \eta' \)-meson are observed as a subset of these events in the specific reaction

\[ \pi^- p \rightarrow \eta' n \]  \hspace{1cm} (10)

Detailed descriptions of the experimental layout, of the apparatus and the methods of measurements have been given in previous works [1-5].

The analysis of the data starts with the determination of the coordinates and energy of the photons using a geometrical reconstruction program of the electromagnetic showers in the spectrometer. Events are then sorted on the basis of kinematical fits to various hypotheses. Selection criteria are chosen in order to optimize the \( \eta' \) signal and to suppress as much as possible background processes. The number of events produced in each \( \eta' \)-decay channel in reaction (10) is determined taking into account the efficiencies of the apparatus and of the adopted selection criteria.

The detection efficiency has been determined by the method of Monte Carlo using a bank of real electromagnetic showers measured with GAMS [6]. The events have been generated according to the \( t \)-dependence of the differential cross-section of reaction (10) [7] and, moreover, decay (2) events have been simulated using the known parametrization of its matrix element [8]. The resulting events have been analysed with the same reconstruction and kinematics programs that are used for the analysis of the experimental data. The value of the detection efficiency obtained in this manner takes into account, de facto, the acceptance of the system, the efficiency of the geometrical and kinematical reconstruction programs as well as the influence of the adopted selection criteria. These procedures have been described in detail elsewhere [4,8,9].
2. RATIO OF THE DECAY RATES OF \eta' \rightarrow 2\gamma AND \eta' \rightarrow \eta\pi^+\pi^-

Previous measurements of the 2-\gamma decay channel have a low statistical significance [10] (few tens of events), with the exception of one work [7] in which however the probability of this decay is determined indirectly from the data [7,11]. In the present work, BR(\eta' \rightarrow 2\gamma) has been determined directly as a result of the simultaneous measurement of this decay (1) and of decay (2) which has a well known BR(\eta' \rightarrow \eta\pi^+\pi^-) value [10].

A typical invariant mass spectrum of events with two photons in the final state, produced by 38 GeV/c incident \pi^- (L = 12 m), is shown in Fig.1 (1-C fit, 98% C.L., fixing the mass of the recoiling neutron in reaction (9)). A peak dominates in the region of the \eta'-meson which corresponds, within the limits of the experimental errors (0.3%), to the tabulated value of the \eta' mass and its width corresponds to the instrumental resolution of the spectrometer. The number of measured decay (1) events exceeds eight thousand. The measured t-dependence of the differential cross-section is in good agreement with previous data [7].

In order to compare the 2-\gamma decay rate of the \eta' with the intense neutral decay rate (2), which is known with a precision of 2.5% [10], events produced with six and ten photons in the final state have been selected. They satisfy the kinematics of reactions \pi^-p \rightarrow \eta\pi^+\pi^-n, n \rightarrow 2\gamma and \pi^-p \rightarrow \eta\pi^+\pi^-n, n \rightarrow 3\pi^0, respectively (4-C fit and 7-C fit, fixing the masses of the \eta and \pi^+-mesons and of the recoiling neutron). The 6-\gamma decays have been studied in detail previously [8]. To identify the 10-\gamma decay events, a threshold energy has been introduced for the photons E_\gamma > E_\gamma^{th} = 0.3 GeV in addition to the kinematical selection criteria. The mass spectra of the \eta\pi^+\pi^- systems selected in the region of the \eta'-meson are shown on Fig. 2. Clean peaks corresponding to both decays are seen.

The real number of events in each \eta'-decay channel are given by N/\epsilon, where N is the number of events in the corresponding peak and \epsilon is the corresponding detection efficiency. Possible systematic errors on N/\epsilon have been estimated by varying the effective dimensions of the detector (overall GAMS size and central hole size), the threshold energy and other parameters. For example, Fig. 3b shows how the numbers of real decay (1) and (2a) events vary with the effective dimensions of GAMS. The small decrease in N/\epsilon observed when only the first external rows of GAMS cells are excluded is due
to the aperture defining counters of the setup; their influence is not exactly reproduced by the event simulation program. In order to exclude these edge effects in GAMS, an effective configuration 43x27 cells (out of 48x32) has been adopted for further analysis. A further decrease of the effective aperture does not change the value of $N/\epsilon$ further, within the limits of the statistical fluctuations (Fig. 3b), even for large variations of the acceptance (e.g. a factor 6 in the case of decay (2a), see Fig. 3a). This shows the absence of measurable systematic errors in the evaluation of $N/\epsilon$ for both $2\gamma$ and $3\gamma$ decays and, moreover, in their ratio.

The influence of the threshold energy in GAMS on the number of recorded events is illustrated in Fig. 4. Whereas the detection efficiency for decays (1) and (2a) drops several times by increasing $E_{th}$, $N/\epsilon$ remains constant within the limits of statistical fluctuations (a few percent). Variations of other parameters have only little influence on the value of $N/\epsilon$.

The measured ratio of real numbers of decays (1) and (2a) is equal to $0.333 \pm 0.006$ (statistical error only). To determine the ratio of decay probabilities, a series of corrections should be applied. They take into account the absorption of photons inside the liquid hydrogen target and in some counters of the setup, the creation of spurious photons due to the superposition of nearly time-coincident events happening when the center of the spectrometer is strongly irradiated, etc. These small corrections have been discussed in detail elsewhere [5]. Taking them into account as well as the known values $\text{BR}(\eta \to 2\gamma) = 0.389 \pm 0.004$ and $\text{BR}(\pi^\pm \to 2\gamma) = 0.9880 \pm 0.0003$ [10], one obtains the value

$$\Gamma(\eta' \to 2\gamma) / \Gamma(\eta' \to \eta\pi^+\pi^-) = 0.112 \pm 0.002 \pm 0.006$$  \hspace{1cm} (11)

The first error is of statistical origin while the second is systematic. The latter has been estimated from an analysis of the background subtraction procedure, from the dispersion of the data gathered in different experimental conditions and from the errors on the corrections. In what follows, the ratio of widths is given with its full root-mean-square error defined as the square root of the quadratic sum of both errors. The result (11) is slightly higher than the value $0.088 \pm 0.009$ obtained on the basis of indirect measurements [7,11,10].
The comparison of decay modes (2a) and (2b) constitutes a sensible control experiment for the evaluation of the systematic error linked with the complexity of the topology in the final state of \( \eta' \)-decay. The measurement of decay (2b) is especially difficult because of the large combinatorial background and of the low average energy of the photons, which is close to the threshold detection value of the spectrometer. This makes the detection efficiency much more sensitive than in the case of decays (1) and (2a) on the parameters of the setup and on the selection criteria of the events (Fig. 5). Thus, the determination of the ratio \( \Gamma(\eta' \rightarrow \eta \pi^0 \pi^0 \rightarrow 5\pi^0 \rightarrow 10\gamma) / \Gamma(\eta' \rightarrow \eta \pi^0 \pi^0 \rightarrow 6\gamma) \) constitutes an effective way to check the self-consistency of the data treatment procedures as a whole as it must be equal to the ratio \( \Gamma(\eta \rightarrow 3\pi^0 \rightarrow 6\gamma) / \Gamma(\eta \rightarrow 2\gamma) \) measured with great accuracy (1\%) [5]. The value of the latter, determined in the present experiment as a way to control its precision, is

\[
\frac{\Gamma(\eta \rightarrow 3\pi^0)}{\Gamma(\eta \rightarrow 2\gamma)} = 0.815 \pm 0.020
\]

(12)

It coincides with the tabulated value [5,10]. The ratio of partial widths of decays (2a) and (2b), normalized to (12), is

\[
\frac{\Gamma(\eta' \rightarrow \eta \pi^0 \pi^0 \rightarrow 10\gamma)}{\Gamma(\eta' \rightarrow \eta \pi^0 \pi^0 \rightarrow 6\gamma)} \cdot \frac{\Gamma(\eta \rightarrow 2\gamma)}{\Gamma(\eta \rightarrow 3\pi^0 \rightarrow 6\gamma)} = 0.99 \pm 0.05
\]

(13)

(\( \approx 1 \) in the absence of systematic errors).

3. PARTIAL WIDTHS OF THE \( \eta' \)-MESON NEUTRAL DECAYS

The procedures used to separate the rare decays (3) and (4) from the intensive accompanying processes have been described in detail previously [12,4]. These decays stand clearly out of the background (Fig. 6). Their correct identification is confirmed by the measured \( t \)-distribution of the events in the peaks (Fig. 7, see also [12]). The dependence of the number of events on \( E_{\text{th}} \) agrees with estimations as well for decay (4) (Fig. 8) as for decay (3) [12]. The resulting ratios of the partial widths are

\[
\frac{\Gamma(\eta' \rightarrow \omega \gamma)}{\Gamma(\eta' \rightarrow \eta \pi^0 \pi^0)} = 0.147 \pm 0.016
\]

(14)

and

\[
\frac{\Gamma(\eta' \rightarrow 3\pi^0)}{\Gamma(\eta' \rightarrow \eta \pi^0 \pi^0)} = 0.0074 \pm 0.0015
\]

(15)

From (14) and (11) one obtains:

\[
\frac{\Gamma(\eta' \rightarrow \omega \gamma)}{\Gamma(\eta' \rightarrow 2\gamma)} = 1.31 \pm 0.16
\]

(16)

in good agreement with the value 1.2 obtained in a QCD model calculation [13].
The branching ratios $\text{BR}_i = \Gamma_i / \Gamma(\eta' \rightarrow \text{all})$ and the partial widths $\Gamma_i$, obtained by normalization to the tabulated value of $\text{BR}(\eta' \rightarrow \eta \pi \pi)$ [10] and to the world average value of $\Gamma(\eta' \rightarrow 2\gamma)$ [14], are given in Table I. The full width obtained for the $\eta'$-meson is:

$$\Gamma(\eta' \rightarrow \text{all}) = (176 \pm 16) \text{ KeV} \quad (17)$$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\text{BR}_i(%)$</th>
<th>$\Gamma_i(\text{KeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta' \rightarrow 2\gamma$</td>
<td>2.43 ± 0.13</td>
<td>4.25 ± 0.19 [14]</td>
</tr>
<tr>
<td>$\eta' \rightarrow \eta \pi^0 \pi^0$</td>
<td>21.7 ± 0.5 [10]</td>
<td>37.9 ± 2.7</td>
</tr>
<tr>
<td>$\eta' \rightarrow \omega \gamma$</td>
<td>3.20 ± 0.35</td>
<td>5.6 ± 0.7</td>
</tr>
<tr>
<td>$\eta' \rightarrow 3\pi^*$</td>
<td>0.160 ± 0.032</td>
<td>0.28 ± 0.06</td>
</tr>
<tr>
<td>$\eta' \rightarrow 3\gamma$</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>$\eta' \rightarrow \pi^0 \gamma \gamma$</td>
<td>&lt; 0.08</td>
<td>&lt; 0.14</td>
</tr>
<tr>
<td>$\eta' \rightarrow 2\pi^*$</td>
<td>&lt; 0.1</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>$\eta' \rightarrow 4\pi^*$</td>
<td>&lt; 0.05</td>
<td>&lt; 0.09</td>
</tr>
</tbody>
</table>

*) All upper limits are given for a 90% C.L.

A search has also been made for other possible neutral decay modes of the $\eta'$-meson, namely decays (5) – (8).

The invariant mass spectrum of $3\gamma$ events produced in reaction (9) shows a small peak in the region of the $\eta'$-meson which disappears when the energy threshold, $E_{\text{th}}$, in GAMS is increased up to 2.5 GeV. A further reduction of the background level in this mass region was obtained by suppressing the detection of $\pi^0 \gamma$ and $\eta \gamma$ systems generated by the reaction $\pi^- p \rightarrow \pi^0 \pi^0 n$ and $\pi^- p \rightarrow \eta \pi^0 n$ in the case where one of the decay photons has an energy lower than the threshold value in the spectrometer. The following upper limit has been obtained for the C-parity violating decay $\eta' \rightarrow 3\gamma$:

$$\Gamma(\eta' \rightarrow 3\gamma) / \Gamma(\eta' \rightarrow \eta \pi^0 \pi^0) < 4.6 \times 10^{-4} \quad (18)$$

(here and below the estimated limits for the decay probabilities correspond to a 90% C.L.).
The mass spectrum of \( \pi^*\gamma\gamma \) systems, produced in reaction (9), obtained after suppression of the \( \pi^*\pi^* \), \( \pi\pi^* \) and \( \omega\gamma \) systems, shows no peak corresponding to decay (5). An upper limit of

\[
\Gamma(\eta' \to \pi^*\gamma\gamma) / \Gamma(\eta' \to \pi\pi^*\pi^*) < 3.7 \times 10^{-3}
\]  

(19)

may be estimated. The vector dominance model gives a value between \( 5 \times 10^{-4} \) and \( 5 \times 10^{-5} \) for this ratio.

No statistically significant peak is seen in the invariant mass spectrum of \( 2\pi^* \) systems produced in reaction (9) (3-C fit, 96% C.L., fixing the masses of the \( \pi^* \) mesons and of the recoiling neutron). This gives for the \( \eta' \to 2\pi^* \) decay, forbidden by parity conservation,

\[
\Gamma(\eta' \to 2\pi^*) / \Gamma(\eta' \to \pi\pi^*\pi^*) < 4.5 \times 10^{-3}
\]  

(20)

In the invariant mass spectrum of \( 4\pi^* \) events (5-C fit, 96% C.L., fixing the mass of the \( \pi^* \)'s and of the recoiling neutron) a structure is observed in the region of the \( \eta' \)-meson. It disappears when \( \eta \to 3\pi^* \) are suppressed. The following limit is obtained:

\[
\Gamma(\eta' \to 4\pi^*) / \Gamma(\eta' \to \pi\pi^*\pi^*) < 2.3 \times 10^{-3}
\]  

(21)

The estimated upper limits for the partial widths following from (18)-(21) are given in Table I.

4. MATRIX ELEMENT OF THE DECAY \( \eta' \to 3\pi^* \)

The matrix element of decay (4) has been obtained after a 5-C fit (fixing the mass of all particles, including \( m_{3\pi^*} = m_{\eta'} \)) of the events in the corresponding \( \eta' \)-meson peak (Fig. 6). The Dalitz plot of these events, taking into account the detection efficiency of the setup, is uniformly populated. A similar population is observed for the background events in neighbouring mass intervals of the \( \eta' \) peak.

The matrix element squared of decay (4) can be written

\[
|\mathcal{M}_b(\eta' \to 3\pi^*)|^2 = A(1 + 2\beta Z)
\]  

(22)

(up to second terms in the pion energy \( E_{\pi^*} \)) where \( Z \) is the square of the distance to the center of the Dalitz plot.
\[ Z = \left( \frac{r}{r_{\text{max}}} \right)^2 = \frac{6}{(m_{\pi'} - 3m_{\pi})^2} \sum_{i=1}^{3} \left( E^{(i)}_{\pi'} - \frac{m_{\pi'}}{3} \right)^2 \]  \hspace{1cm} (23)

The obtained value of the slope parameter is

\[ \beta = -0.1 \pm 0.3 \]  \hspace{1cm} (24)

This is the first experimental determination of this matrix element. A theoretical estimate of the slope parameter gives \(|\beta| < 0.03 \) [15].

The study of decay (2) has shown that the slope parameter of the linear matrix element \(|\mathcal{M}(\eta' \rightarrow \eta \pi^+\pi^-)|^2 = B (1 + 2aY)\) (where \(Y\) is one Dalitz variable) is also small, namely \(a = -0.058 \pm 0.013\) [8].

**CONCLUSION**

The relative probabilities of the neutral decay channels of the \(\eta'\)-meson have been determined with greatly improved precision. All neutral decays have been measured in the same set of data. This is essential in order to reduce the influence of systematic errors to a minimum. The measurement of \(\text{BR}(\eta' \rightarrow 2\gamma)\) has allowed the determination of the full width of the \(\eta'\)-meson using the partial width \(\Gamma(\eta' \rightarrow 2\gamma)\) measured in \(e^+e^-\) collisions.

Of all the studied neutral decays of the \(\eta'\), the decays into three particles \(\eta' \rightarrow 3\pi^0\) and \(\eta' \rightarrow \eta \pi^+\pi^-\) present a special interest. A better knowledge of the matrix element of the first decay, which violates isospin conservation, contributes to the understanding of the various processes participating in the mechanism of G-parity violation [15]. Precise measurement of the second decay are important for QCD in the low energy regime as its dynamics is largely influenced by gluon anomalies [16].

We thank the CERN and IHEP directorates for their support to the GAMS program in the framework of which a series of studies have been performed on the neutral decays of light mesons.
REFERENCES


**FIGURE CAPTIONS**

Fig. 1 Invariant mass spectrum of $2\gamma$ events produced in reaction (9). The arrows point to the tabulated values of the $\eta$ and $\eta'$-mass.

Fig. 2 Invariant mass spectra of $\eta\pi^+\pi^-$ systems produced in reaction (9) with six and ten photons in the final state. The arrows point to the tabulated mass value of the $\eta'$-meson. The curve is the instrumental resolution of the spectrometer.

Fig. 3 a) Variation of the number of registered decay (1) and (2a) events with the reduction of the geometrical size of GAMS. $n$-number of rows of counters at the GAMS border not taken into account in the treatment. The curves represent $c_2\gamma$ and $c_{\eta\pi^+\pi^-}$ normalized to the point $n = 2.5$ (arrow).

b) Real number of these decays as a function of the effective size of GAMS.

c), d) Same as a) and b) but for decay (2a); the detection efficiency is normalized to the point $E_{th} = 0.6$ GeV.

Fig. 4 a) Dependence of the number of decay (1) events on the threshold energy $E_{th}$ of the photons in GAMS. Full line: detection efficiency of this decay, normalized to the point $E_{th} = 4$ GeV.

b) Corresponding real numbers of decay (1) events.

c), d) Same as a) and b) but for decay (2a); the detection efficiency is normalized to the point $E_{th} = 0.6$ GeV.

Fig. 5 Same as fig. 4c) and d) but for decay (2b). The efficiency has been normalized to the point $E_{th} = 0.3$ GeV.

Fig. 6 Mass spectra of $3\pi^+$ and $\omega\pi$ systems produced in reaction (9). The arrows point to the tabulated value of the $\eta'$ mass. The dashed peaks correspond to the decay modes (3) and (4).

Fig. 7 Integral $t$-distribution of the events in the $\eta'$ peak of fig.6 (histogram). The curve is this dependence for decay (1) events in reaction (10). This figure and the following one are based on one half of the total statistics gathered for decay (4).

Fig. 8 Number of decay (4) events for different values of the threshold energy $E_{th}$. The curve is the detection efficiency of this decay, normalized to the point $E_{th} = 1.5$ GeV.
Fig. 1
Fig. 2
Fig. 3
Fig. 4
$N_{\eta\pi^0\pi^0}\cdot 10^3$

$\eta' \rightarrow 10\gamma$

$\frac{N_{\eta\pi^0\pi^0}}{E_{\eta\pi^0\pi^0}} \cdot 10^3$

$E_{th}$ [GeV]

Fig. 5
Fig. 8