THE ISOSPIN-VIOLATING DECAY $\eta' \rightarrow 3\pi^0$

IHEP¹-IISN²-LAPP³ Collaboration

F. Binon², S.V. Donskov¹, P. Duteil⁴, M. Gouanère³,
A.V. Inyakin¹, V.A. Kachanov¹, D.B. Kakauridze¹, G.V. Khaustov¹,
A.V. Kulik¹, J.P. Lagnaux², A.A. Lednev¹, Yu.V. Mikhailov¹,
Th. Mouthuy², J.P. Peigneux³, A. Possoz⁴, Yu. D. Prokoshkin¹,
Yu.V. Rodnov¹, S.A. Sadovsky¹, P.M. Shagin¹, D. Sillou³,
A.V. Singovsky¹, J.P. Stroot² and V.P. Sugonyaev¹

Joint Experiment of IHEP, Serpukhov, USSR

and

CERN, Geneva, Switzerland

ABSTRACT

In an experiment performed at the 70 GeV IHEP accelerator the rare decay $\eta'(958) \rightarrow 3\pi^0$, which violates isospin conservation, has been observed. The six final decay gamma rays are detected in the hodoscope spectrometer GAMS-2000. The branching ratio of this decay is $BR(\eta' \rightarrow 3\pi^0) = (1.6 \pm 0.4) 10^{-3}$. An estimate of the ratio of the masses of u and d quarks is given.

Submitted to Physics Letters

-
1. Institute for High Energy Physics, Serpukhov, USSR.
 2. Institut Interuniversitaire des Sciences Nucléaires, Brussels, Belgium.
 3. Laboratoire d'Annecy de Physique des Particules, France.
 4. CERN, Geneva, Switzerland.

The interest of the experimental study of the $\eta'(958)$ -meson decay channel into three pions, which does not conserve G-parity, lies with the well known U(1)-problem of QCD, which long ago appeared in current algebra and which is connected with the mass spectrum and the dynamics of pseudoscalar mesons [1-3 (review articles) and 4-18]. The mechanism of the 3π decay of η' as well as that of the similar η decay finally rests on the fact that the masses of current (bare) u and d quarks are not equal. This is why the study of these decays might allow to evaluate such an important constant as the u to d quark mass ratio m_u/m_d .

The low intensity process $\eta' \rightarrow 3\pi$ may be considered to come from $\eta\pi^0$ mixing in the course of the dominating decay $\eta' \rightarrow \eta\pi\pi$. The simultaneous study of these two channels is one of the few ways to make a direct determination of this isospin violating mixing [9,11,17].

The same physical properties are much more difficult to extract from the $\eta \rightarrow 3\pi$ decay because in this case large model corrections (up to 300%) add to the uncertainty of the measurement of the η width [3]. These are absent for $\eta' \rightarrow 3\pi$ which may be normalised to the favoured $\eta' \rightarrow \eta\pi\pi$ decay.

The experimental study of $\eta' \rightarrow 3\pi$ is a long time pending problem. This rare process had not been observed up to now. An upper limit $BR(\eta' \rightarrow \pi^+\pi^-\pi^0) < 5\%$ has been established for the charged decay mode [19]. A similar limit for $\eta' \rightarrow 3\pi^0$ may be evaluated from the existing data on η' neutral decay modes. Theoretical predictions for $BR(\eta' \rightarrow 3\pi^0)$ range from $3 \cdot 10^{-4}$ up to $9 \cdot 10^{-3}$ [9,15,16,18].

The search for the decay

$$\begin{array}{l} \eta' \rightarrow 3\pi^0 \\ \quad \searrow 6\gamma \end{array} \quad (1)$$

has been performed at the 70 GeV IHEP accelerator. The charge exchange reaction

$$\pi^- p \rightarrow \eta' n \quad (2)$$

has been used as a source of monoenergetic η' mesons. This reaction has been thoroughly studied before at Serpukhov energies [20]. The measurements have been performed in a 30 to 40 GeV/c π^- beam between 1980 and 1982.

The experimental layout has been described earlier [21,22]. The trigger system selects exclusive processes of the type $\pi^-p \rightarrow M^0 n$. The neutral states M^0 finally decay into gammas; they include neutral decays of η' produced in reaction (2). The coordinates and energies of the six gammas from decay (1) have been measured in the hodoscope spectrometer GAMS-2000.

Out of the two possible $\eta' \rightarrow 3\pi$ decays the neutral one (1) may be better singled out than the charged one $\eta' \rightarrow \pi^+\pi^-\pi^0$ because of more favourable background conditions.

One of the main processes contributing to background is the non-resonant production of $3\pi^0$ which has the same final topology

The cross-section of this reaction calculated in the one-pion exchange model [23], over a mass interval ΔM of the $3\pi^0$ system at 40 GeV/c is $\Delta\sigma \approx 15\Delta M$ nb/GeV. The mass resolution of GAMS in the region of η' being $\sigma_M/M \approx 1.5\%$, one gets $\Delta\sigma \approx 0.5$ nb. Comparing this value with the cross-section of reaction (2) (2 μ b) the minimum level of $BR(\eta' \rightarrow 3\pi^0)$ which may be measured is about $2 \cdot 10^{-4}$.

On the other hand, the experimental study of decay (1) requires to efficiently detect six gammas and from them to reconstruct the kinematics of the decay particles. The event reconstruction is complicated by the large combinatorial background (15 possible pair combinations of gammas per each event).

The detection of the other 3-pion decay $\eta' \rightarrow \pi^+\pi^-\pi^0$ would be free of these difficulties. However, the cross-section of the corresponding background reaction $\pi^-p \rightarrow \pi^+\pi^-\pi^0 n$ going mainly through the intermediate $\rho\pi$ states which do not appear in reaction (3) is much larger than that of reaction (3). This background prevents the detection of $\eta' \rightarrow \pi^+\pi^-\pi^0$ at a level below one percent.

A total of twenty million events have been analysed with existing reconstruction programs [21,22]. Events with six gammas in GAMS are selected. Kinematical analysis is used to separate unwanted processes with the same topology.

The dominant neutral decay channel of

$$\eta' \rightarrow \eta \pi^0 \pi^0 \rightarrow 6\gamma \quad (4)$$

is the most abundant background process. It is identified through a 4C-fit (fixing the η , π^0 and n masses) satisfying the criterium $\chi^2 < 12$ (98.5% confidence level) (fig. 1). Events which still have one gamma pair combination with a mass in the η range between 500 and 600 MeV are also rejected.

A second source of background is the reaction

$$\pi^- p \rightarrow K_S^0 \pi^0 \Lambda \rightarrow 2\pi^0 \quad (5)$$

which appears as a $3\pi^0$ final state and may be confused when the K_S^0 decays rather near the target. It is enhanced because of the proximity of the $K^*(890)$ resonance. The system of guard counters around the target helps to reduce the contribution of the background. After a 4C-fit of reaction (5) with fixed masses for all particles but leaving the distance between the target and the decay point of the K_S^0 as a free parameter, all events with $\chi^2 < 12$ (98.5% level) are rejected.

The remaining events have finally to satisfy the 4C-fit of reaction (3) with a $\chi^2 < 6$ (80% level) in order to be retained as $3\pi^0$ candidates. Cuts on momentum transfer ($-t > 0.06$ (GeV/c)²), on single gamma energy ($E_\gamma > E_{thr} = 0.5$ GeV) and on π^0 c.m. decay angle ($(\cos\theta_0)^{max} = 0.8$) further suppress the background [21].

The geometry of the experiment results from a compromise between contradicting requirements: a large distance L between the target and GAMS is needed to reduce to a minimum the overlapping of showers in GAMS, but, on the other hand, a small L is required to provide a good geometrical acceptance for the decay (1).

The data have been obtained in three different sets of measurements, which are summarized in Table I. (The total amount of η' recorded in this experiment is more than twice the previous world statistics). After the first measurement a peak in the mass spectrum of $3\pi^0$ events was already visible at the η' mass with a width equal to that of the instrumental resolution but a 3.5 standard deviations statistical significance only.

The two next series of data were taken with an improved apparatus in better background conditions, with improved data handling methods [21]. The sum of data I and data II, the data III and the overall spectrum are shown on fig. 2.

Sixty events are observed in the total η' -peak, with a statistical significance of 10 standard deviations above the background. The background level itself is close to the expected contribution from (3). When stronger cuts are applied to suppress background processes (4) and (5) the peak to noise ratio is improved without significant decrease of the number of η' in the peak. The small contribution of (4) and (5) to the background is also confirmed by a simulation with a data base of real showers [21].

The t (four-momentum transfer squared) distribution of events in the η' peak is in good agreement with that measured for η' production in reaction (2) [20].

The G-parity violating decay of η' in three neutral pions being thus experimentally observed, the branching ratio $BR(\eta' \rightarrow 3\pi^0) = \Gamma(\eta' \rightarrow 3\pi^0)/\Gamma(\eta' \rightarrow \text{all})$ is evaluated in two steps. First the number of $\eta' \rightarrow 3\pi^0$ events is normalized to that of the intense $\eta' \rightarrow \eta\pi^0\pi^0$ channel (fig.1) which has been simultaneously detected in the set-up (the η through its 2γ decay mode only). The ratio $\Gamma(\eta' \rightarrow 3\pi^0)/\Gamma(\eta' \rightarrow \eta\pi^0\pi^0)$ depends on the ratio of detection efficiencies for the two processes, $\epsilon_{\eta\pi^0\pi^0}/\epsilon_{3\pi^0}$, which is close to one (*) as both decay channels have a similar topology. A simulation with real showers shows that $\epsilon_{\eta\pi^0\pi^0}/\epsilon_{3\pi^0}$ is not sensitive to changes in selection criteria nor to the acceptance of the spectrometer.

The measured value is

$$\frac{\Gamma(\eta' \rightarrow 3\pi^0)}{\Gamma(\eta' \rightarrow \eta\pi^0\pi^0)} = (7.5 \pm 1.8)10^{-3} \quad (6)$$

Using the tabulated value $BR(\eta' \rightarrow \eta\pi^0\pi^0) = BR(\eta' \rightarrow \eta\pi^+\pi^-)/2 = 0.218 \pm 0.005$ one obtains

$$BR(\eta' \rightarrow 3\pi^0) = (1.6 \pm 0.4)10^{-3} \quad (7)$$

This measured value may be compared with the theoretical evaluations of Roiesnel and Truong [16] ($6 \cdot 10^{-4}$ with more than 50% uncertainty), of Veneziano et al., [15] ($6 \cdot 10^{-3}$) (see also [18]), and of Gross et al., [9] (10^{-3}).

The total η' width evaluated from recent data on the two-photon decay width $\Gamma(\eta' \rightarrow 2\gamma) = (5.2 \pm 0.5) \text{ keV}$ [24] and from the branching ratio $BR(\eta' \rightarrow 2\gamma) = (0.019 \pm 0.002)$ [19] is $\Gamma(\eta' \rightarrow \text{all}) = (274 \pm 40) \text{ keV}$. Normalising to this value, one finally gets

$$\Gamma(\eta' \rightarrow 3\pi^0) = (0.44 \pm 0.12) \text{ keV} \quad (8)$$

(*) $\epsilon_{3\pi^0}$ and $\epsilon_{\eta\pi^0\pi^0}$ themselves largely differ from unity due to the high final state multiplicity. They include a factor $\cos^2 \theta_{\text{max}} \approx 0.5$ and also a factor connected with the detection threshold of gammas [21] (≈ 0.3 with $E_{\text{thr}} = 1 \text{ GeV}$).

Gross et al.[9] evaluate the ratio of $\Gamma(\eta' \rightarrow \pi^0 \pi^+ \pi^-)$ to $\Gamma(\eta' \rightarrow \eta \pi^+ \pi^-)$ as a function of the mass difference between u and d quarks. For neutral channels their relation becomes

$$\frac{\Gamma(\eta' \rightarrow 3\pi^0)}{\Gamma(\eta' \rightarrow \eta \pi^0 \pi^0)} = 9.4 \left(\frac{m_d - m_u}{m_s} \right)^2 \quad (9)$$

or

$$\text{BR}(\eta' \rightarrow 3\pi^0) = 2.1 \left(\frac{m_d}{m_s} \right)^2 \left(1 - \frac{m_u}{m_d} \right)^2 \quad (10)$$

The mass formula for the nonet of pseudoscalar mesons [3,11,25] gives a reliable estimate of the ratio m_d/m_s

$$\frac{m_d}{m_s} = \frac{m_{K^0}^2 - m_{K^+}^2 + m_{\pi^+}^2}{m_{K^0}^2 + m_{K^+}^2 - m_{\pi^+}^2} = 0.050 \quad (11)$$

This value would not change by more than 10% through radiative corrections and deviations from SU(3) symmetry [26,27]. Using it in (10) one gets

$$\text{BR}(\eta' \rightarrow 3\pi^0) = 5.2 \left(1 - \frac{m_u}{m_d} \right)^2 10^{-3} \quad (12)$$

The theoretically attractive possibility for the u quark to have a zero mass [28,29,11] seems to be ruled out if the calculations of Gross et al., [9] are valid. In this case (12) gives a BR value exceeding the experimental one (7) by a factor three.

According to (9) and (11) it follows from the data (7) of the present experiment that

$$\frac{m_u}{m_d} = 0.44 \pm 0.07. \quad (13)$$

The quoted uncertainty takes into account the experimental error only.

This value may be compared with other evaluations: (0.6 ± 0.2) based on $\rho\omega$ mixing [30], $(0.2 \div 0.4)$ from Weinberg analysis [1], 0.43 from [15], 0.40 from [27], and 0.57 from [31].

We would like to thank S.S. Gershtein, B.L. Ioffe, V.F. Obraztsov and T.N. Truong for useful discussions. We thank the IHEP and CERN directorates for their support of the GAMS program.

REFERENCES

- [1] S. Weinberg - The problem of mass. In Festschrift for I.I. Rabi ed. L. Motz (New York Academy of Science, N.Y. 1977). Also for further references.
- [2] P. Langacker and H. Pagels, Phys. Rev., D19 (1979) 2070.
- [3] S. Weinberg, Phys. Rev., D11 (1975) 3583.
- [4] M. Gell-Mann et al., Phys. Rev., 175 (1968) 2195.
- [5] S. Glashow and S. Weinberg, Phys. Rev. Lett., 20 (1968) 224.
- [6] N. Cabibbo and L. Maiani, in Evolution of particle physics (Academic Press, 1970).
- [7] G. Parisi and M. Testa, Nuovo Cimento, 67A (1970) 13.
- [8] S. Raby, Phys. Rev., D13 (1976) 2594.
- [9] D.J. Gross, S.B. Treiman and F. Wilczek, Phys. Rev., D19 (1979) 2188.
- [10] G. 't'Hooft, Phys. Lett., 85B (1979) 357.
- [11] B.L. Ioffe, Yad. Fyz., 29 (1979) 1611.
- [12] G. Veneziano, Nucl. Phys., B159 (1979) 213;
Phys. Lett., 95B (1980) 90.
- [13] S. Coleman and B. Witten, Phys. Rev. Lett., 45 (1980) 100.
- [14] R. Aaron, H. Goldberg, Phys. Rev. Lett., 45 (1980) 1752.
- [15] P. Di Vecchia et al., Nucl. Phys., B181 (1981) 318.
- [16] C. Roiesnel and T.N. Truong, Nucl. Phys., B187 (1981) 293;
Preprint Ecole Polytechnique A515.0982, 1982.
- [17] A. Lachiri and B. Bagchi, Phys. Lett., 101B (1981) 287.
- [18] G.W. Intemann and G.K. Greenhut, Phys. Rev., D22 (1980) 1669.
- [19] Rev. Part. Prop. Phys. Lett., 111B (1982) 3.
- [20] W.D. Apel et al., Yad. Fyz., 30 (1979) 366;
Phys. Lett., 83B (1979) 131.
- [21] F. Binon et al., Yad. Fyz., 36 (1982) 670;
Nuovo Cimento, 71A (1982) 497. Also for further references.
- [22] F. Binon et al., Yad. Fyz., 38 (1983) 934;
Yad. Fyz., 38 (1983) 1199; Nuovo Cimento, 78A (1983) 313;
Lett. Nuovo Cimento, 39 (1984) 41.
- [23] L.A. Ponomarev, Elem. Part. and Atomic Nucl., 7 (1976) 186.

REFERENCES (cont'd)

- [24] W. Bartel et al., Phys. Lett., 113B (1982) 190. Also for previous data.
- [25] R. Dashen, Phys. Rev., 183 (1969) 1245.
- [26] J. Schechter and Y. Ueda, Phys. Rev., D4 (1971) 733.
- [27] B.L. Ioffe et al., Deep inelastic processes, Atomizdat, Moscow 1983.
- [28] S. Weinberg, Phys. Rev. Lett., 40 (1978) 223.
- [29] F. Wilczek, Phys. Rev. Lett., 40 (1978) 279.
- [30] P. Langacker, Phys. Rev., D20 (1979) 2983.
- [31] C.A. Dominguez, Phys. Lett., 86B (1979) 171.

SUMMARY OF DATA AND RESULTS

Series of measurements	I June 1980	II ^(*) April 1981	III ^(**) December 1982	Summed data
p(GeV/c)	40	30	38	
L(m)	9	12	12	
N_{π^-}	$1.5 \cdot 10^{11}$	$3 \cdot 10^{11}$	$8 \cdot 10^{11}$	$1.3 \cdot 10^{12}$
$N_{\eta'}$	$2 \cdot 10^5$	$4 \cdot 10^5$	$1.4 \cdot 10^6$	$2 \cdot 10^6$
$N_{\eta' \rightarrow \eta \pi^0 \pi^0}$	$2.1 \cdot 10^3$	$2.4 \cdot 10^3$	$5 \cdot 10^3$	10^4
$N_{\eta' \rightarrow 3\pi^0}$	16 ± 6	21 ± 7	26 ± 6	62 ± 12
"Peak/Noise"	0.8	1.4	2.4	1.8
$n_{\text{st.dev.}}$	3.7	5.5	8	10
$\bar{M}_{3\pi^0}$ (MeV)	952 ± 6	960 ± 5	956 ± 4	956 ± 3
$BR(\eta' \rightarrow 3\pi^0) \cdot 10^3$	1.9 ± 0.9	2.4 ± 1.0	1.5 ± 0.4	1.6 ± 0.4

N_{π^-}	Number of negative pions through the H_2 target.
$N_{\eta'}$	Number of η' produced in the target.
$N_{\eta' \rightarrow \eta \pi^0 \pi^0}$	Number of $\eta \pi^0 \pi^0$ decay events.
$N_{\eta' \rightarrow 3\pi^0}$	Number of $3\pi^0$ events in the η' peak above the background.
"Peak/Noise"	Ratio of the number of events in a 40 MeV interval in the peak over the number of background events in the same mass interval.
$n_{\text{st.dev.}}$	Number of standard deviations above the background (statistical significance of the η' peak)
$\bar{M}_{3\pi^0}$	Center of the peak. The width of the peak is equal to the instrumental resolution of GAMS ($\sigma_M/M = 1$ to 1.5%).

(*) Geometry optimized for the observation of $\eta \rightarrow \pi^0 \gamma \gamma$ [21]

(**) Geometry optimized for the observation of $\eta' \rightarrow 3\pi^0$.

FIGURE CAPTIONS

- Fig. 1 Mass spectrum of events identified as $\pi^-p \rightarrow \eta\pi^0\pi^0n$, $\eta \rightarrow 2\gamma$, $\pi^0 \rightarrow 2\gamma$ $\eta' \rightarrow \eta\pi^0\pi^0$ events are in the peak which is centered on the η' tabulated mass.
- Fig. 2 Mass spectrum of $3\pi^0$ events. The dashed curve is the sum of data from the series I and II. The lower curve is the data from series III. The upper curve is the sum of all data. The tabulated η' mass is indicated on the scale.

FIG. 1

FIG. 2