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A MEASUREMENT OF THE BRANCHING RATIO $\omega \rightarrow \text{neutrals}/\omega \rightarrow \text{total}$

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ABSTRACT

The results of a counter experiment on the branching ratio

$$R = \frac{I(\omega \rightarrow \text{neutrals})}{I(\omega \rightarrow \text{total})}$$

are presented. The masses of particles produced in the reaction $\pi^- + p \rightarrow n + (\text{missing mass})$ at 2.12 GeV/c were determined with an uncertainty of ± 15 MeV by using counter techniques to measure the time-of-flight and emission angle of the neutrons. Veto counters around the hydrogen target selected neutral decay modes. The peak values of $\omega/\text{background}$ were 0.4 for the neutral mode and 0.55 for the total decay.

Corrections to the experimental value are discussed.

The value of the branching ratio was found to be $(8.4 \pm 1.5)\%$. This result is compared with various theoretical predictions.

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1. INTRODUCTION

To date, the only known dominant decay modes of the ω meson are the charged mode $\omega^0 \rightarrow \pi^+ + \pi^- + \pi^0$ and the neutral mode $\omega^0 \rightarrow \pi^0 + \gamma$ *).

A measurement of the branching ratio

$$R = \frac{\Gamma(\omega \rightarrow \text{neutrals})}{\Gamma(\omega \rightarrow \text{total})} \quad (1)$$

corresponds therefore to a measurement of

$$R' = \frac{\Gamma(\omega \rightarrow \pi^0 + \gamma)}{\Gamma(\omega \rightarrow \pi^+ \pi^- \pi^0 + \pi^0 + \gamma)} \quad (2)$$

The branching ratio (2) can be predicted on the basis of different theoretical models, to be discussed in the last section.

The experimental results obtained in various laboratories can be classified according to the degree of identification of the individual decay products in the neutral and charged channels. Thus:

- i) a series of measurements have been performed, using hydrogen and deuterium bubble chambers¹⁻⁸⁾ and counter techniques⁹⁾ on the branching ratio

$$\frac{\Gamma(\omega \rightarrow \text{neutrals})}{\Gamma(\omega \rightarrow \pi^+ + \pi^- + \pi^0)} ;$$

- ii) two heavy-liquid bubble chamber experiments^{10,11)} have produced results on the branching ratio

$$\frac{\Gamma(\omega \rightarrow \pi^0 + \gamma)}{\Gamma(\omega \rightarrow \pi^+ + \pi^- + \pi^0)} ;$$

*) $\omega \rightarrow 2\pi^0$ is forbidden by: (a) Bose statistics and angular momentum conservation, (b) C-invariance, (c) Isospin conservation. $\omega \rightarrow 3\pi^0$ is forbidden by: (a) C-invariance, (b) Isospin conservation.

iii) an experiment performed using counter techniques¹²⁾ has given a result on

$$\frac{\Gamma(\omega \rightarrow \text{neutrals})}{\Gamma(\omega \rightarrow \text{charged})} .$$

Other experiments which presented evidence for the $\omega \rightarrow \pi^0 + \gamma$ decay mode, using a heavy-liquid bubble chamber¹³⁾ and spark chambers^{12,14)} were not conclusive enough to produce results on the branching ratio $\Gamma(\omega \rightarrow \pi^0 + \gamma)/\Gamma(\omega \rightarrow \text{total})$.

A summary of the experimental data on the neutral branching ratios of the ω meson is given in Table 1. We present here the results of a counter experiment on the measurement of the branching ratio

$$R = \frac{\Gamma(\omega^0 \rightarrow \text{neutrals})}{\Gamma(\omega^0 \rightarrow \text{total})} .$$

2. EXPERIMENTAL SET-UP AND TRIGGER CONDITIONS

2.1 Principle

The production reaction is

$$\pi^- + p \rightarrow n + X^0 , \quad (3)$$

where X^0 may be any neutral state with a mass between 650 and 950 MeV/c². The mass of the X^0 in an event is identified to ± 15 MeV by measuring the velocity and direction of the neutron. The partial decay channel

$$X^0 \rightarrow \text{neutrals} \quad (4)$$

is selected by a system of veto counters, and is compared with the total production rate.

2.2 Beam telescope

The incident beam momentum is 2.12 GeV/c, with a spread $\Delta p/p = \pm 1\%$. The beam is defined by three counters U, $\bar{R}$, and S (see Fig. 1): U ($10 \times 6 \times 1$ cm³) provides the zero time for the neutron time-of-flight and is made up of three elements in order to handle the high rate of the primary beam (2×10^6 π /sec); $\bar{R}$ is an anticoincidence counter

($20 \times 20 \times 1 \text{ cm}^3$) with a 4 cm diameter hole in its centre; S ($4 \times 4 \times 0.05 \text{ cm}^3$) is a thin scintillation counter which, in association with U and $\bar{R}$, provides a parallel beam, well centred on the H_2 target. The hydrogen target is 10 cm long and 4 cm diameter. The quantity of material in the beam, including counters and mylar windows, but excluding the hydrogen in the target, is 0.2 g/cm^2 .

2.3 Selection of the neutral modes

A system of anticoincidence counters $\bar{T}$, $\bar{T}_3$, and $\bar{T}_4$ surrounds the target and provides the selection of the neutral decay modes of the X^0 particle. $\bar{T}$ is a plane counter, $35 \times 35 \times 1.5 \text{ cm}^3$ placed after the target, perpendicular to the beam. $\bar{T}_3$ and $\bar{T}_4$ are two Y-shaped counters, each arm of the Y having dimensions $12 \times 35 \times 1.5 \text{ cm}^3$. These are placed so as to form a tube of veto counters around the target. During the study of the production rate, $\bar{T}$ is removed physically, whilst $\bar{T}_3$ and $\bar{T}_4$ are switched off electronically.

Beam particles not interacting in the target are rejected by $\bar{Q}$ ($5 \times 5 \times 0.5 \text{ cm}^3$). The dimensions and the position of $\bar{Q}$ (35 cm distant from the target centre) have been chosen to minimize the vetoing of the charged pions coming from an $\omega \rightarrow \pi^+ + \pi^- + \pi^0$ decay^{*}, whilst still covering the whole beam profile.

2.4 The neutron detector

Neutrons are detected in 12 plastic scintillators, each having the dimensions $100 \times 18 \times 18 \text{ cm}^3$, arranged in two banks to give a detection area of 1.08 m^2 and a total scintillator thickness of 36 cm along the neutron line of flight. A set of large anticoincidence counters, $\bar{G}_1^R$, $\bar{G}_2^R$, $\bar{G}_3^R$, each with dimensions $120 \times 50 \times 2.5 \text{ cm}^3$, is placed 50 cm in front of the neutron counter and ensures, with better than 99.95% efficiency, that no charged particle coming from the target area is detected by the neutron counter.

Each element of the neutron counter is viewed by two XP 1040 photomultipliers, one at each end. They are used for the time-of-flight measurements and for position identification of the neutron¹⁵⁾. The simultaneous measurement of neutron time-of-flight and emission angle yields

^{*}) See later for the evaluation of this effect.

the value of the missing mass. For the electronic trigger, only the information coming from one end of the scintillator (side 1) is used: this has the effect of distorting the shape of the missing-mass curves, as shown in Fig. 2.

Typical results obtained with our set-up are 3 cm positional resolution with minimum ionizing particles, and 0.7 nsec time resolution, full widths at half-height. The stability of the electronics is 0.1 nsec over a period of a week. The 12 elements constituting the neutron detector were periodically checked and calibrated in the direct beam in order to be sure of their correct performance. Details of the technique used to achieve the wanted stability and resolution are described fully elsewhere¹⁶⁾.

2.5 Electronic logic (Fig. 3)

The mixed signals from the members of the front and back stacks of counters are denoted by R_1^F and R_1^B , R_2^F and R_2^B (see Fig. 1). Dynode signals are used with high-level pulse-height discrimination to provide the gating signals R_1^F , H , etc. The anode signals with low threshold triggers (25% of the high level) provide the timing signals R_1^F , L , etc. The L signals gated by the H signals and by $\bar{G}^R$ *) give the timing signals N_1 and N_2 from the two 'ends' of the neutron counter.

The signal U from the beam counter is gated by the coincidence requirement $\overline{SR}_1 \bar{Q}$ in the production experiment, and by $\overline{SR} \overline{QT} \bar{T}_3 \bar{T}_4$ in the neutral mode measurements. The gated signal is split to form the two timing signals B_L and B_R .

Three analogue signals are formed: $t_1 = B_L N_1$, $t_2 = B_R N_2$, and $\vartheta = N_1 N_2$. The first two give independent measurements of the time-of-flight and the latter gives the position in the counter. A rough selection of minimum and maximum values of t , removes prompt events and low missing-mass events. A selected t_i signal in coincidence with a ϑ signal provides the final trigger for recording the analogue information. The pattern of neutron counters which are struck is also recorded on magnetic tape.

A continuous monitor of the number of incident pions is given by an independent coincidence $US\bar{R}$, not shown on the diagram.

*) $\bar{G}^R$ is a signal obtained by mixing $\bar{G}_1^R$, $\bar{G}_2^R$, and $\bar{G}_3^R$.

2.6 Total acceptance of the neutron detector

The neutron counter, which can be moved horizontally and vertically for calibration purposes, is set at 400 cm from the target and is positioned at 47.5° with respect to the beam line. In this position, the neutron counter has 14° polar and 21° azimuthal angular acceptances in the lab. system.

The angular and time acceptances of the neutron detector are shown by the shaded area on the kinematic curves in Fig. 2. The time window is set so as to accept neutrons arriving between 6 and 45 nsec after the prompt events. (Prompt events are those with a time-of-flight from the H_2 target to the neutron counter equal to that of γ -rays.) The energy of these neutrons is between 400 MeV and 35 MeV.

Under these conditions, ω events with $-0.40 > \cos \vartheta_n^{c.m.} > -0.97$ are accepted, where $\vartheta_n^{c.m.}$ is the angle of emission of the neutron in the centre-of-mass system in reaction (3). The discrimination levels on the neutron counter pulses were set at a value corresponding to 18 MeV recoil protons. Notice that the branching ratio is independent of the neutron counter efficiency.

3. DATA ANALYSIS

3.1 Event selection

Inspection of the missing mass curves (Fig. 2) shows that, for fixed accuracy of time measurements, the error on the mass decreases as the time-of-flight increases. It is thus possible to choose time-of-flight limits so as to optimize the ratio of peak-to-background. This corresponds to a neutron angular acceptance in the centre-of-mass system of $-0.60 > \cos \vartheta_n^{c.m.} > -0.97$. The missing-mass spectra for these events are shown in Figs. 4a and 4b. The ratios of signal-to-background at the peak values are 0.4 and 0.55 for the neutral and the total mode, respectively.

3.2 Method of analysis

The branching ratio of $\rho^0 \rightarrow \text{neutrals} / \rho^0 \rightarrow \text{charged}$ has as experimental upper limit a value of $\lesssim 10^{-3}$ ¹⁷⁾. Consequently, the mass spectra (Figs. 4a and 4b) differ because a background of ρ^0 's is present in Fig. 4b. Using known production cross-sections ¹⁸⁾ we can estimate this contribution, which is shown by the dotted curve in Fig. 4b. After

subtraction of this background, the two spectra were fitted by the method of least squares to a superposition of a Gaussian function, describing the ω peak, and a smooth background function which was a third-order polynomial in the missing mass. The width of the Gaussian was held fixed at the calculated value of 33 MeV FWHH, which was obtained by taking into account the ω width and the experimental resolution. So the free parameters in the fit were the four coefficients of the polynomial, the height and the centre of the Gaussian.

The background slope was studied by varying the position of the neutron detector, between 47° and 49° in the lab. system, without changing the beam energy. This changed the position of the ω peak relative to the mass cuts due to the electronic and angular windows by ~ 40 MeV. The background slope due to kinematical, geometrical, and instrumental effects was estimated by Monte Carlo calculations in which the production cross-section was assumed independent of the missing mass, and was isotropic in the centre-of-mass system. The result of these investigations is that our background varies smoothly and by only 15% in the mass region ranging from 720 to 870 MeV.

The missing mass spectra, after background subtraction, are shown in Fig. 5. They yield

(723 ± 107) events of the type ' $\omega \rightarrow$ neutrals'

and

(1214 ± 104) events of the type ' $\omega \rightarrow$ total'

for 50.8×10^8 and 5.8×10^8 incident pions, respectively.

3.3 Corrections

In order to evaluate the branching ratio it is necessary to take into account the following corrections:

- i) Random vetoing at high rates. This effect was measured by adding 100 nsec to the signals of the anticoincidences, and by studying the rate dependence of 'neutral' and 'total' ω triggers under these conditions. The resultant correction factor to the branching ratio is 1.14 ± 0.02 .

ii) Loss of 'neutral' events.

This loss has two origins:

- a) Conversion of γ -rays from the decay mode $\omega \rightarrow \pi^0 + \gamma$, in the target, in the anticoincidence counters ($\bar{T}$, $\bar{T}_3$, $\bar{T}_4$, $\bar{R}$), and by Dalitz conversion. This loss has been calculated with a Monte Carlo method, assuming the measured ω -production angular distribution¹⁹⁾, and yields a $(9 \pm 0.5)\%$ depression of ' $\omega \rightarrow$ neutral' events.
- b) Interaction of the neutron in the anticoincidence counter $\bar{T}$. Using known neutron cross-sections²⁰⁾ in carbon and hydrogen, and taking into account the ω angular distribution¹⁹⁾, we calculate that 6% of the neutrons are lost in counter $\bar{T}$, thus producing a $(6 \pm 1)\%$ depression on the ' $\omega \rightarrow$ neutral' events.
- iii) Loss of 'charged' events. This is due to those charged pions from the decay $\omega \rightarrow \pi^+\pi^-\pi^0$, which are detected in the anticoincidence counters $\bar{Q}$, $\bar{R}$ and $\bar{G}^R$. (90% of the effect comes from $\bar{Q}$.) Monte Carlo calculations, using the ω -production angular distribution¹⁹⁾, give a $(7 \pm 0.5)\%$ depression of the ' $\omega \rightarrow$ total' events.
- iv) Simulation of 'neutral' events. If the charged pions from the decay $\omega \rightarrow \pi^+\pi^-\pi^0$ are able to escape all anticoincidence counters $\bar{T}$, $\bar{T}_3$, $\bar{T}_4$, $\bar{R}$, then the 'charged' event becomes 'neutral'. The probability of this happening has been estimated to be less than 10^{-3} .

3.4 Result and discussion

Normalizing the events to the same number of incident pions and taking into account all the above-mentioned effects and their uncertainties, the final result is:

$$\frac{\Gamma(\omega \rightarrow \text{neutrals})}{\Gamma(\omega \rightarrow \text{total})} = (8.4 \pm 1.5)\% .$$

A summary of the world data on the neutral ω branching ratios, all expressed in terms of $\Gamma(\omega \rightarrow \text{neutral})/\Gamma(\omega \rightarrow \text{total})$ is presented in Fig. 6. The new world average is now $(9.2 \pm 0.8)\%$.

This result should be compared with the various theoretical models which predict the partial width $\Gamma(\omega \rightarrow \pi^0 \gamma)$ and/or the branching ratio

$$R = \frac{\Gamma(\omega \rightarrow \pi^0 \gamma)}{\Gamma(\omega \rightarrow \pi^+ \pi^- \pi^0)} \quad (5)$$

The first theoretical prediction is due to Gell-Mann, Sharp and Wagner²¹⁾ (GM-S-W), who suggested that the ω -decay proceeds via ρ -dominance; thus the conversion of a ρ into a γ -ray or into a $\pi\pi$ -pair describes the two ω -decay modes. Notice that in this model the unknown coupling constant $g_{\omega\rho\pi}$, needed in order to calculate the partial widths $\Gamma(\omega \rightarrow \pi^0 \gamma)$ and $\Gamma(\omega \rightarrow \pi^+ \pi^- \pi^0)$, cancels in the evaluation of the branching ratio (5). Other models have used the ρ -dominance idea together with other assumptions such as Unitary Symmetry²²⁾ and Current Algebra Commutators plus PCAC²³⁾.

All these models^{*)} need as input the experimental values of the ρ -width, Γ_ρ , and of the ρ -mass, m_ρ . The values of Γ_ρ and m_ρ measured in different "strong interaction" experiments fluctuate outside the quoted error limits²⁴⁾ and disagree with the values obtained at Novosibirsk²⁵⁾ with (e^+e^-) colliding beams. For this reason we show in Fig. 7 how the various theoretical predictions^{**) for R depend upon Γ_ρ .}

Theoretical predictions on the partial width $\Gamma(\omega \rightarrow \pi^0 \gamma)$ have also been obtained on the basis of quark models²⁷⁾ and of the SUB model²⁸⁾. These models need as experimental input the magnetic moment of the proton and all give for the partial width the value $\Gamma(\omega \rightarrow \pi^0 \gamma) \simeq 1.2$ MeV. If

*) Those models which use PCAC²³⁾ require as further inputs the experimental value of G_A/G_V , the π -nucleon coupling constant $g_{\pi NN}$ and the nucleon mass m_n , which all appear in the PCAC relation.

**) Notice that in the Gasiorowicz (G) and Cabibbo, Maiani and Preparata (C-M-P) models, the value of G_A/G_V used was $|G_A/G_V|^{\text{old}} = 1.18$. According to a new experimental determination²⁶⁾ of the neutron lifetime this value should be $|G_A/G_V|^{\text{new}} = 1.23 \pm 0.04$. The values reported in Fig. 7 for the above-mentioned models have been recalculated using the new value for G_A/G_V .

we choose for the partial width the value predicted by Becchi and Morpurgo²⁷⁾ and by Van Royen and Weisskopf²⁷⁾, $\Gamma(\omega \rightarrow \pi^0 \gamma) = 1.17 \text{ MeV}$, using for the total width the value²⁴⁾ $\Gamma(\omega \rightarrow \text{total}) = (12.2 \pm 1.3) \text{ MeV}$ it turns out that

$$R = \frac{\Gamma(\omega \rightarrow \pi^0 \gamma)}{\Gamma(\omega \rightarrow \text{total})} = (9.8 \pm 1.1)\% .$$

An interesting point to be noticed is that if we use the currently quoted average values for the mass and width of the ρ ($M_\rho = 774 \text{ MeV}$, $\Gamma_\rho = 128 \text{ MeV}$) all models give remarkably similar results.

With the new Novosibirsk²⁵⁾ data on Γ_ρ and m_ρ ($\Gamma_\rho = 93 \pm 15 \text{ MeV}$; $M_\rho = 764 \pm 11 \text{ MeV}$) this is no longer true and a new interest is revived on the one hand in a deeper theoretical analysis of the various models and of their mutual connections, and on the other in a more precise determination of all the relevant experimental quantities.

* * *

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Table 1

Experimental results on the neutral branching ratio of the ω meson

Experiment	Branching ratio measured (%)	
Armenteros et al.	$\frac{\omega \rightarrow \text{neutrals}}{\omega \rightarrow \pi^+ + \pi^- + \pi^0}$	17 ± 4
Buschbeck-Czapp et al.	"	11 ± 2
Kraemer et al.	"	8 ± 3
Miller	"	13.0 ± 3.5
James and Kraybill	"	$6 \begin{smallmatrix} +5 \\ -2 \end{smallmatrix}$
Flatté et al.	"	9.7 ± 1.6
Alff-Steinberger et al.	"	9.9 ± 4
Barash et al.	"	10 ± 3
Di Giugno et al.	"	13.4 ± 2.6
Barmin et al.	$\frac{\omega \rightarrow \pi^0 + \gamma}{\omega \rightarrow \pi^+ + \pi^- + \pi^0}$	$>12.5 \pm 2.4$
Jacquet et al.	"	13.0 ± 4.0
Feldmann et al.	$\frac{\omega \rightarrow \text{neutrals}}{\omega \rightarrow \text{charged}}$	12.4 ± 2.1
This experiment	$\frac{\omega \rightarrow \text{neutrals}}{\omega \rightarrow \text{total}}$	8.4 ± 1.5

Figure captions

- Fig. 1 : Top view of the experimental set-up.
- Fig. 2 : Kinematic curves at 2.12 GeV/c for various values of the missing mass, showing the angular and time acceptance of the neutron detector. The straight line represents prompt events. The ordinate is the sum of the time-of-flight of the neutron and the transmission time of the light from the interaction point to side '1' of the counter.
- Fig. 3 : Block diagram of the electronic logic
TR - trigger unit
OR - logical OR circuit
CU - coincidence unit
C - coincidence input
V - veto input
H - high discrimination channel
L - low discrimination channel.
- Fig. 4 : Missing-mass spectra of the events with $-0.60 > \cos \theta_n^{c.m.} > -0.97$:
a) distribution of the 'neutral' triggers, reaction (4);
b) distribution of the triggers in the production reaction (3).
The small dotted curve shows the calculated ρ^0 production.
- Fig. 5 : Missing-mass distributions of the ω events after background subtraction. The solid curves represent the fitted Gaussian functions.
- Fig. 6 : Showing the world data on the neutral branching ratio of the ω meson. For the sake of comparison, all data are translated into the same ratio $\Gamma(\omega \rightarrow \text{neutral})/\Gamma(\omega \rightarrow \text{total})$. The results are arranged in chronological order; the last point represents our result. The world average of experimental results is shown in Fig. 7.

Fig. 7 : Theoretical predictions for R as a function of $\Gamma\rho$. The value of $m\rho$ used is that obtained at Novosibirsk²⁵⁾. The dashed vertical lines indicate the error limits of $\Gamma\rho$ obtained at Novosibirsk²⁵⁾. Note that

- i) As mentioned in the text, the Gasiorowicz and the C-M-P models need an extra input: $|G_A/G_V|$. The curves shown here have been calculated using the latest, most accurate experimental determination: $|G_A/G_V| = 1.23 \pm 0.015$ (see Ref. 26). These models predict only the partial width $\Gamma(\omega \rightarrow \pi^0 \gamma)$ and so the predicted value of R is affected by the experimental uncertainty in $\Gamma(\omega \rightarrow \text{total})$. This uncertainty is²⁴⁾ $\sim 10.7\%$ and is combined with the uncertainty in the mass value and in $|G_A/G_V|$ to obtain the uncertainties indicated by the upper and lower curves.
- ii) The (GM-S-W) model predicts $\Gamma(\omega^0 \rightarrow \pi^0 \gamma)$ and $\Gamma(\omega^0 \rightarrow \pi^+ \pi^- \pi^0)$ and therefore the theoretical prediction of R is not affected by the experimental uncertainty in $\Gamma(\omega \rightarrow \text{total})$.
- iii) The quark models do not need $\Gamma\rho$ and $m\rho$ as input, but the proton magnetic moment. In particular the Becchi and Morpurgo model²⁷⁾ predicts the partial width $\Gamma(\omega \rightarrow \pi^0 \gamma)$, so in order to obtain R, it is necessary to use $\Gamma(\omega \rightarrow \text{total})$. It is the uncertainty in this quantity which gives the uncertainty in R shown in the figure. Van Royen and Weisskopf²⁷⁾ (VR-W) predict also $\Gamma\omega \rightarrow 3\pi$, and their result is $R = 7.3\%$. If the (VR-W) prediction for $\Gamma(\omega \rightarrow 3\pi)$ is ignored the value for R is equal to the previous one.

FIG. 1

FIG. 2 LAB ANGLE OF NEUTRON

FIG.3

FIG. 4a

FIG. 4b

MISSING MASS IN MeV

100

100

100

100

100

100

100

100

100

FIG. 5

FIG.6

FIG.7