New Upper Limit on the Width of the X^0(958)

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An upper limit $\Gamma_{X^0} < 0.8$ MeV/c^2 (95% confidence level) is deduced from the missing-mass spectrum near 958 MeV/c^2 in the reaction $\pi^- + p \to \mathrm{MM} + n$ close to threshold. Measurement of those missing masses which decay to 2γ shows a single peak with a central mass of 957.4 ± 0.5 MeV/c^2 close to the value of 957.46 ± 0.33 MeV/c^2 deduced from the total missing-mass spectrum.

The X^0(958) is the only firmly established meson whose width has not yet been measured. Assuming, however, that only one state is present,[1] the branching ratios into the three main decay channels are fairly well known. Theoretical predictions have been made for all these partial widths.[2] All have to take into account singlet-octet mixing, the mixing angle usually being deduced from the Gell-Mann–Okubo mass formula. The most reliable prediction is probably that based on the 2γ decays of the π^0, η, and X^0.[3] In a recent paper,[4] using the reaction $\pi^- + p \to X^0 + n$, we set an upper limit on Γ_{X^0} of 1.9 MeV/c^2, which at the time came close to being inconsistent with quadratic mixing. Since then a new measurement[5] of $\eta \to 2\gamma$ has, if accepted, removed this inconsistency. We report here a new experiment with improved resolution which has significantly lowered the upper limit on Γ_{X^0} and has verified that the 2γ decay has the same mass as the X^0.

The experiment was performed at the Rutherford Laboratory using an improved form of the threshold spectrometer described in detail elsewhere.[6] To increase the resolution, we reduced the target length from 29.4 to 10.0 cm, increased the neutron counter distance from 6.15 to 8.15 m, and measured the incident beam momentum and angle with multiwire proportional chambers. Neutron-counter shielding was modified to reduce the probability for large-angle neutrons to scatter back into the counters. The momentum spectrometer was monitored more thoroughly, and floating-wire calibrations made before and after data collection were now consistent to better than 0.02%.

Missing masses (MM) were measured in the process

$$\pi^- + p \to \mathrm{MM} + n \ (1 + 2 \to 3 + 4).$$

The final-state center-of-mass momentum p^* was constrained to lie within the range $13 \leq p^* \leq 43$ MeV/c by restricting the range of neutron momentum p_4 accepted, so that the missing-mass could be essentially determined[6] from the value of incident momentum p_1. (Unless otherwise indicated, quantities are those measured in the laboratory.) p_1 was measured with standard deviation 0.07% for each event and with an uncertainty in absolute value of $\pm 0.05\%$. At the X^0 the expected missing-mass resolution, determined by Monte Carlo simulation, had a full width at half-maximum of 2.01 MeV/c^2 compared to about 5 MeV/c^2 in Ref. 6.

Figure 1 shows the missing-mass spectrum for all events in which particle 4 was uncharged and had a velocity in the range $0.586 \leq \beta_4 \leq 0.615$. By observing the relation between p_1 and β_4 for the peak in the cross section, it could be confirmed that particle 4 was a neutron. The peak in the mass spectrum is then at 957.46 ± 0.33 MeV/c^2 (calibration errors included). This value for m_3 is taken as evidence that the peak is due to the X^0(958).

As a check on the equipment, in particular the mass resolution, data were also accumulated at regular intervals at the η meson. The resulting mass spectrum is shown in Fig. 2 for events with an all-neutral final state. For the η mass we find 547.45 ± 0.25 MeV/c^2. The width of the spectrum agrees with the predicted width for $\Gamma_\eta = 0$ but there is a small discrepancy in the high-mass tail. Before attempting a fit to these data,

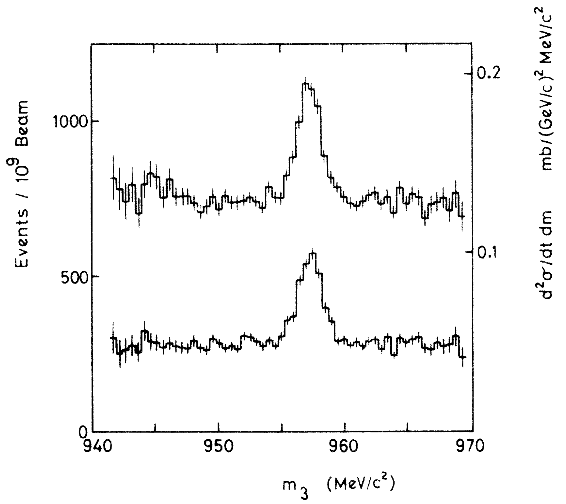

FIG. 1. The mass spectra from which Γ_{X^0} is extracted. The bin width is 0.49 MeV/c^2. No decay selection has been applied for events in the upper histogram; the relatively large signal-to-background ratio is a result of the high mass resolution. In the lower histogram a limited decay selection, mainly designed to suppress non-X^0 backgrounds, has been applied.

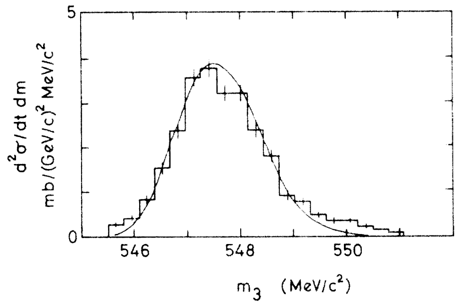

FIG. 2. Missing-mass spectra for all-neutral final states in the region of the $\eta(549)$. The bin width is 0.295 MeV/c^2. The full line is the prediction for zero width.

the statistical errors in the wings and background points were increased so as to resemble the situation at the X^0. Allowing for a straight-line background we found an upper limit for Γ_η of 0.15 MeV/c^2 (statistical errors only), with a good fit at $\Gamma_\eta = 0$. Systematic errors therefore appear to be small, however it should be noted that the relative importance of the various contributions to the mass resolution changes significantly between the η and the X^0.

The data shown in Fig. 1 were fitted with a linear background and predictions for the convolution of the resolution function with various X^0 widths, with the result shown in Table I. A quadratic background gave an almost identical result. The resolution function is predicted in terms of the basic parameters of the experiment: hydrogen-target length, effective neutron-counter diameter, and so on. It is therefore much harder to set a lower rather than an upper limit to the width, as any effect not included will almost certainly widen the function. Thus, although the table shows a best fit near $\Gamma = 0.3$ MeV/c^2, we consider this too small a fraction of the width of the resolution function for us to set a lower limit to Γ.

There are two aspects to the setting of an upper limit from our data. First we consider the purely statistical aspect. $\Delta\chi^2$, the difference of the minimum value of χ^2 and the value at an assumed true value of Γ, has a χ^2 distribution with *one* degree of freedom[7] and the 95% point of this distribution occurs at a value $\Delta\chi^2 \approx 4$. Thus we can deduce a 95% confidence interval for Γ by finding the values of Γ where $\Delta\chi^2 = 4$. This gives $\Gamma < 0.65$ MeV/c^2. The second aspect concerns the reliability of our estimate of the resolution function. As mentioned above, our checks of this at the η cannot be directly extrapolated to the X^0. Our procedure was to calculate a "minimal" resolution function by altering the value of each parameter affecting the resolution in a direction leading to a narrower resolution (as is appropriate for setting an upper limit) and by an amount corresponding to the maximum uncertainty in the parameter. This resolution function was convoluted with a Breit-Wigner amplitude, as before, to establish an upper limit incorporating our systematic uncertainties. This upper limit is 0.8 MeV/c^2 at the 95% confidence level, which is therefore our preferred value.

TABLE I. Fit to all mass bins (53 degrees of freedom) of Fig. 1.

	χ^2	
Γ (MeV/c^2)	No selection	Background suppressed selection
0	42.1	50.7
0.21	39.9	46.1
0.41	40.3	45.2
0.62	43.2	47.7
0.82	48.1	53.0
1.03	54.7	60.7
1.23	62.8	70.3

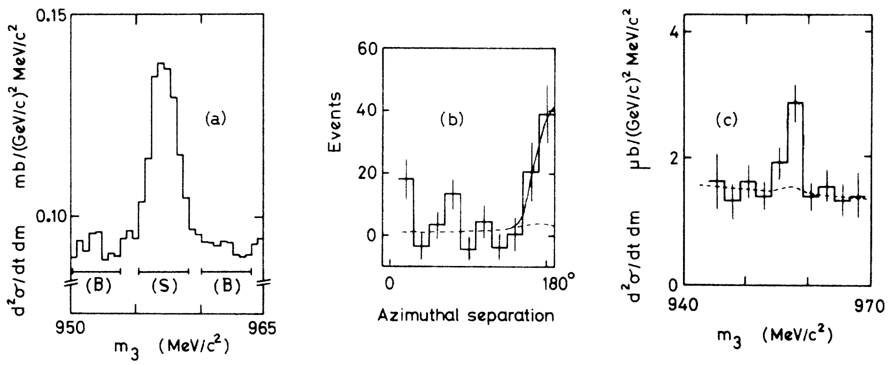

FIG. 3. The 2γ decay mode. (a) Missing-mass spectrum showing the regions used to sample the signal (S) and background (B). (b) Events with two showers are then selected and after background subtraction a plot is made of their azimuthal separation. This shows a clear peak near 180° which cannot be explained in terms of the other X^0 decays (dashed line). The full line shows the fitted 2γ contribution. (c) Mass spectrum selecting events with an azimuthal separation of $>144°$, and correcting for the selection efficiency $(31\pm3)\%$. Mass bins have been grouped in fives. The dashed line includes the predicted background from the other X^0 decays.

Information from the counter array surrounding the hydrogen target was used to suppress non-X^0 background, following the method of Ref. 4. The lower histogram of Fig. 1 shows the resulting sample of data and Table I contains values of χ^2 for the corresponding fit. Although χ^2 as a function of Γ is somewhat sharper than for the missing-mass spectrum, the upper limit to Γ is hardly affected.

Evidence that the X^0 detected has a 2γ decay is shown in Fig. 3. To increase the number of events the neutron gate has been widened to $0.573 \leq \beta_4 \leq 0.630$. This gate somewhat worsens the resolution [Fig. 3(a)]. Events in which 2γ's were indicated by the decay counters were then selected and the azimuthal separation of the two γ's examined. Real 2γ events should have a separation close to 180°. The separation found is shown in Fig. 3(b) where we have subtracted background from the X^0 signal using the regions shown in Fig. 3(a). The predicted background for non-2γ decays of the X^0 is indicated. Finally, with no background subtracted, we show the mass spectrum for 2γ events having an azimuthal separation of $>144°$. The peak observed has a central mass of 957.4 ± 0.5 MeV/c^2, in close agreement with that of the X^0. Lack of events prevents a useful limit being set on the width. Correcting for the estimated selection efficiency of $(31\pm3)\%$, we find a branching ratio $X^0\to2\gamma/X^0\to$total of $(3.4\pm0.9)\%$. An isotropic decay distribution has been assumed.

The branching ratio can be directly compared with that of $(1.0\pm1.2)\%$ obtained in our earlier experiment.[4,8] We attribute the difference to a statistical fluctuation. The best value from the two experiments together is $(2.5\pm0.7)\%$. These numbers are in line with the other results[9] on $X^0\to2\gamma$. The significance of our new result lies in the accurate identification of the central mass together with the good mass resolution.

We comment briefly on the implication of the new limit on Γ_{X^0} for pseudoscalar mixing. Updating the conclusions in Ref. 4, we find that simple quadratic mixing is now incompatible with a partial width $\eta\to2\gamma$ of about 1 keV.[10] However the new measurement[5] of this quantity gives 374 ±60 eV which implies $\Gamma_{X^0}\approx0.27$ MeV/c^2 for quadratic and 0.05 MeV/c^2 for linear mixing, both still compatible with our result. The positive sign can still be excluded.

Finally we note that the very high resolution must make it very unlikely that more than one meson is present in our mass spectra.

[1]More than one state may be present, in particular see M. Aguilar-Benitez *et al.*, Phys. Rev. Lett. 23, 1635 (1970); T. A. Lasinski *et al.*, Rev. Mod. Phys. 45, S1 (1973).

[2]Recent papers and reviews include H. Gentz, J. Katz, and H. Steiner, Phys. Rev. D 7, 2100 (1973); B. G. Kenny, Phys. Rev. D 7, 2156 (1973); A. Bramon and M. Greco, Laboratori Nazionali di Frascati del Comitato Nazionale per l'Energia Nucleare Report No. LNF-73/60 (to be published); F. D. Gault *et al.*, "A review of the η-η' mixing problem" (to be published).

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37, 1777 (1965).
[4]D. M. Binnie *et al.*, Phys. Lett 39B, 275 (1972).
[5]A. Browman *et al.*, Cornell Laboratory for Nuclear Studies Report No. CLNS-242, 1973 (unpublished).
[6]D. M. Binnie *et al.*, Phys. Rev. D 8, 2789 (1973).
[7]See, for example, H. O. Lancaster, *The Chi-Squared Distribution* (Wiley, New York, 1969). We have also verified that $\Delta\chi^2$ has a χ^2 distribution with one degree of freedom explicitly for our nonlinear case by generating a large number of "fake" spectra statistically similar to our data and by inspecting the resultant distribution of $\Delta\chi^2$. The use of the χ^2 versus Γ plot to set an upper limit on Γ is equivalent to the likelihood ratio test of the hypotheses $\Gamma \leq$ upper limit, $\Gamma >$ upper limit. We give the argument in detail in view of a comment on Ref. 4 in G. R. Kalbfleisch *et al.*, Phys. Rev. Lett. 31, 333 (1973). While intended to be conservative, as it would be if describing a data set with 53 degrees of freedom, the prescription suggested in this reference is not satisfactory. For example, if the data outside the X^0 are combined into a few bins, thus greatly reducing the number of degrees of freedom without much loss of information, we find an upper limit to Γ_{X^0} lower than the final figure of 0.8 MeV/c^2 given in the text. Statistical errors and possible systematic effects should be considered separately.
[8]This 2γ branching ratio was originally given as $(0.8 \pm 1.0)\%$.
[9]E. H. Harvey *et al.*, Phys. Rev. Lett. 27, 885 (1971); W. D. Apel *et al.*, Phys. Lett. 40B, 680 (1972); P. Dalpiaz *et al.*, Phys. Lett. 42B, 377 (1972).
[10]C. Bemporad *et al.*, Phys. Lett. 25B, 380 (1967).

Heavy-Particle Production in 300-GeV/*c* Proton/Tungsten Collisions

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A search was made for massive particles produced by 300-GeV/*c* protons, A 1.1-km flight path through a beam transport system permitted the measurement of the production of heavy particles for secondary momenta of 25 to 200 GeV/*c*. No counts were obtained for masses greater than 2 GeV/c^2 among 5.5×10^7 secondary particles. Cross sections are presented for forward production of π^+, π^-, p, $\bar{p}$, d, and $\bar{d}$.

An experiment has been performed to measure the yields of heavy metastable particles produced by 300-GeV/*c* protons at the National Accelerator Laboratory (NAL). Results are given for π^+, π^-, p, $\bar{p}$, d, and $\bar{d}$ rates, and upper limits are set for the production of heavier objects.

Speculations concerning the existence of stable, massive particles outside of the known baryons and their antiparticles have largely been confined to the lowest mass in unitary symmetry triplets.[1] However, the possibility surely exists that there are entirely new families of objects analagous to leptons and baryons with stable ground-state particles. If these have masses >2 GeV/c^2, they could easily have escaped detection in the searches at older accelerators and in the cosmic rays. The high luminosity and energy of the NAL accelerator imposes an obligation to continue these explorations.

The principle of this observation consists of recording the time delay over a 1.1-km flight path (relative to pions of $\beta\simeq1$) for particles of well-defined momentum. The time-delay method is greatly facilitated by the remarkably tight bunching in time of protons extracted from the NAL accelerator when the rf is left on during the extraction period. The rf structure peaks have a full width at half-maximum (FWHM) of 1.0 nsec and are spaced 18.83 nsec apart. This time coherence persists in the low-mass secondaries during the 3-μsec flight path from the target. Heavier particles arrive after the $\beta=1$ bunch. The time-of-flight difference is

$$\Delta t = Lm^2(2cp^2)^{-1},$$

where L is the flight path, c the velocity of light, m the secondary particle mass, and p the secondary momentum.