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# ON THE POSSIBILITY OF THE $X^0$(958) MESON SPIN DETERMINATION IN THE REACTION $\pi^- p \to X^0 n$

$$\pi^- p \to X^0 n, \quad X^0 \to \gamma\gamma$$

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# ON THE POSSIBILITY OF THE $X^0$(958) MESON SPIN DETERMINATION IN THE REACTION $\pi^- p \to X^0 n$, $X^0 \to \gamma\gamma$

Submitted to ЯФ

Ледницки Р., Шафранов М.Д. **E1 - 8452**

О возможности определения спина $X^\circ(958)$ мезона в реакции
$\pi^- p \to X^\circ n$, $X^\circ \to \gamma\gamma$

Показано, что для детектора фотонов с углом раствора ~ $20^\circ$ нужен пучок $\pi^-$-мезонов с импульсом около 30 ГэВ/с, чтобы однозначно решить проблему спина $X^\circ(958)$ мезона. При интенсивности пучка $10^6$ $\pi^-$ /цикл необходимое время работы ускорителя не превышает 10 суток.

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**Дубна, 1974**

Lednický R., Shafranov M.D. **E1 - 8452**

On the Possibility of the $X^\circ(958)$ Meson Spin Determination in the Reaction $\pi^- p \to X^\circ n$, $X^\circ \to \gamma\gamma$

It is shown that the $X^\circ(958)$ spin problem can be unambiguously solved by studying the Adair distribution in the reaction $\pi^- p \to X^\circ n$ in a wide angular range including very asymmetric $X^\circ \to 2\gamma$ decays. It then follows that for the detector with an opening angle of $\sim 20^\circ$ the beam momentum should be about 30 GeV/c. If the beam intensity is $10^6$ $\pi^-$ per cycle, the accelerator time needed is expected to be about 10 days.

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**Dubna, 1974**

1. At present the ambiguity in the $X^\circ(958)$ meson spin still exists $J^P(X^\circ) = 0^-$ or $2^-$ /1/ although this question emerged more than 7 years ago /2/. The majority of physicists prefer spin parity $0^-$ rather than $2^-$; in different kinds of theoretical estimates the $X^\circ$ meson is supposed to be the ninth pseudoscalar meson, it is even called the $\eta'$ meson. At the same time there exist the symmetry formulae /3/ predicting the $\eta'$ mass near the mass of another ninth pseudoscalar candidate - $E(1420)$ meson. Furthermore, the hypothesis $J^P(X^\circ) = 2^-$ needs special attention because in this case the $X^\circ$ meson Regge trajectory has the intercept near 1 and can play a serious role in spin forces at high energies /4/.

It is now well-known that only the analysis of the correlations between $X^\circ$-meson decay and production can resolve the spin alternatives $0^-$ and $2^-$ *. Such correlations were studied in the reaction

$$K^- p \to X^\circ \Lambda \tag{1}$$

at 2.18 GeV/c /6, 7/. The deviations from the isotropy in the Adair distributions were observed strongly support-

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* The Dalitz plot analysis of the $X^\circ \to \eta\pi\pi$ and $X^\circ \to \gamma\pi^+\pi^-$ decays cannot distinguish between the $0^-$ and $2^-$ hypotheses.

ing the $2^-$ assignment. Note that the anisotropy was seen for a very small perpendicular X° meson momentum*

$$p_T < 100 \text{ MeV/c} . \quad (2)$$

Thus, it appears that in other studies /8-11/ of the reaction (1), where the statistics was not enough to make such a $p_T$ cut, the deviation from the isotropy was not found**.

It is however dangerous to conclude that $J^P(X^\circ) = 2^-$ basing on the $3\sigma$ effect found in the only experiment /6,7/. Further studies of the Adair distributions are needed. Unfortunately, a high statistics bubble chamber experiment cannot be done over a reasonably short period of time. Therefore we suggest to study the Adair distributions with the aid of electronics in the reaction similar to (1)

$$\pi^- p \to X^\circ n . \quad (3)$$

The reaction (3) was studied in many experiments with a detector after a target, see /1/. In this arrangement, however (if the incoming momentum is not high), it is not practically possible to study the decay-production correlations in a wide angular range. For such a study the incoming momentum should be increased ($p_{\pi^-} >$ $> 10$ GeV/c) or a $4\pi$ detector should be used.

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* For the Adair analysis the average orbital momentum projection on the beam direction $\langle \ell_z \rangle \simeq p_T / m_R$ should be near zero. In the reaction $K^- p \to X^\circ \Lambda$ the characteristic distance R is determined by the mass of the K*(898) meson. In the reaction $\pi^- p \to X^\circ n$ the nearest possible poles are $A_1(1080)$ and $A_2(1310)$ so that the $p_T <$ $< 100$ MeV/c cut provides $\langle \ell_z \rangle \ll 1$ in both the relations $K^- p \to X^\circ \Lambda$ and $\pi^- p \to X^\circ n$.

** Note that in the recent near threshold experiment at 1.75 GeV/c /11/ only the cut $p_T < 200$ MeV/c could be done.



2. Concerning the X° meson spin determination the dominating 3-particle decays $X^\circ \to \eta \pi\pi$ (72%) and $X^\circ \to \gamma \pi^+ \pi^-$ (26%) are rather complicated since the decay mechanisms depend on free parameters*, the

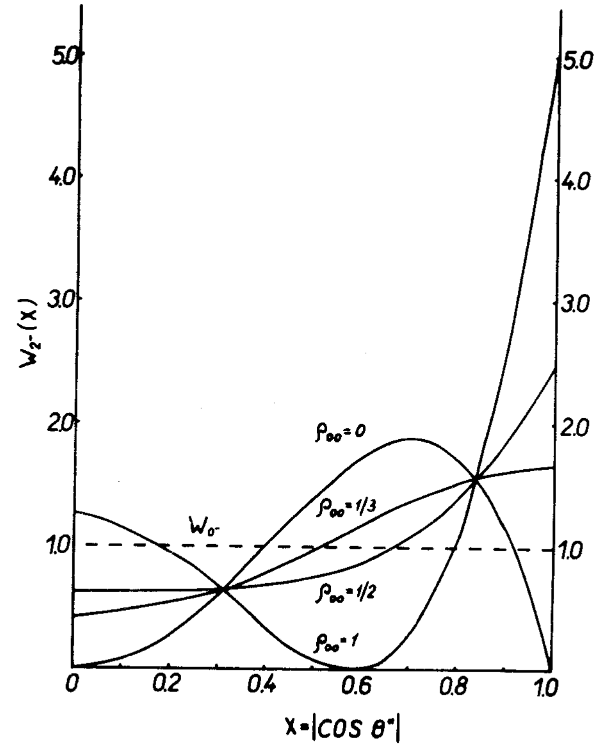


Fig. 1. The distributions of the cosine of the $\gamma$ polar angle in the X° meson rest frame for the $X^\circ \to \gamma\gamma$ decay providing $J^P(X^\circ) = 2^-$, $\rho_{22} = 0$ and $\rho_{00} = 0, 1/3, 1/2$ and 1.

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* In the $X^\circ \to \eta\pi\pi$ decay (in a low orbital momentum approximation) a free parameter is the complex mixing parameter of the amplitudes with $\ell_\eta = 0$, $\ell_{\pi\pi} = 2$ and $\ell_\eta = 2$, $\ell_{\pi\pi} = 0$. In the $X^\circ \to \gamma \pi^+ \pi^-$ decay such a parameter comes from the mixing of the E2 and M1 transition amplitudes.

question of the best decay analyzer arises [13,14,15]. At the same time the matrix element of the $X^\circ \to \gamma\gamma$ decay (2%) is determined unambiguously and yields the strongest anisotropy in the Adair distribution for spin $2^-$ [13,15]. A relative simplicity of the experimental study of the reaction

$$\pi^- p \to X^\circ n, \quad X^\circ \to \gamma\gamma \tag{4}$$

is also attractive.

Let us therefore discuss the reaction (4) in more detail for $J^P(X^\circ)=2^-$. Requiring the Adair condition (2) the decay angular distribution in the $X^\circ$ rest frame with respect to the beam direction in the c.m.s. depends on the $\rho_{00}$ -spin density matrix of the $X^\circ$ meson ($\rho_{22} = 0$) [5,13]

$$W(x) = \frac{15}{2}\left[\frac{1}{6}\rho_{00} + (1-2\rho_{00})x^2 - \left(1-\frac{5}{2}\rho_{00}\right)x^4\right], \tag{5}$$

$x = \cos\theta^*$, $0 \le \rho_{00} \le 1$. In fig. 1 this distribution is plotted for different $\rho_{00}$ -values. We see that the most unfavourable case for differentiating the distribution (5) from the isotropic distributions $W_{0^-}(x) = 1$ occurs at $\rho_{00}$ close to 0.5. In this case the $x$ values should be measured up to $x^{max}$ near 1, i.e., very asymmetric $X^\circ \to \gamma\gamma$ decays should be detected*. This question is analysed in more detail in the Appendix. It is shown that for $x^{max} \ge 0.94$ and $N = 100$ events the confidence level of the wrong hypothesis is expected to be smaller than $CL = 0.2\%$. With decreasing $x^{max}$ the high bound on the CL value of the wrong hypothesis rapidly increases, see fig. 2.

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*Such a problem is absent in the reaction of the $X^\circ$ photoproduction on the zero spin nucleus, for example, $\gamma He^4 \to X^\circ He^4$ [15], where $\rho_{00} = 0$ as well, so that the Adair distribution (5) is determined unambiguously $W(x) = 15/2\, x^2(1-x^2)$ and strongly differs from the isotropic distribution even at small $x$ values (see fig. 1, $\rho_{00} = 0$).



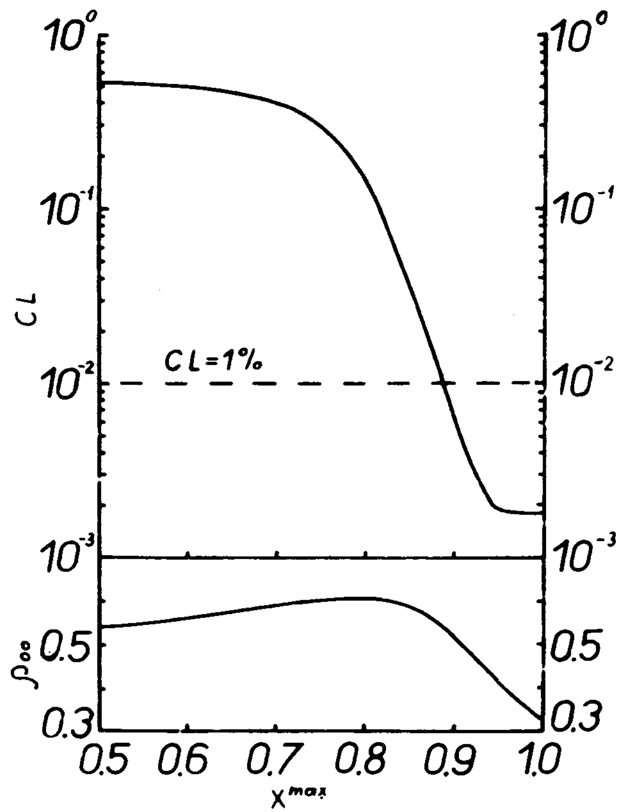


Fig. 2. The maximal confidence level CL of the false hypothesis $J^P(X^\circ) = 0^-$ or $2^-$ for $N = 100$ events and the corresponding $\rho_{00}$ value as functions of $x^{max}$.

3. The reaction (4) was studied at incoming momenta 1.6 [16], 1.9 [17], 3.65 [18], 3.8 [19] and 30-50 GeV/c [12]. In all the experiments $\gamma$'s were detected by means of an optical spark spectrometer. For increasing the signal-background ratio both the $\gamma$'s were detected, and different kinds of neutron detectors were used. The number of $X^\circ \to \gamma\gamma$ decays found in these experiments was typically 20 ÷ 50 events.

Because the cross section of the reaction (4) linearly decreases with increasing the $\pi^-$ laboratory beam momentum [12]

$$\sigma_{2\gamma}(\pi^- p \to X^\circ n) = (3.3 \pm 1.1)\left(\frac{p}{p_0}\right)^{-1.11 \pm 0.12} \mu b, \; p_0 = 1 \text{ GeV/c}, \quad (6)$$

the beam momentum should be chosen as small as possible. In Table 1 the fractions and corresponding cross sections (in nanobars) of the events expected under conditions $p_T < 100$ MeV/c and $T_n > 2$ MeV, $p_T < 100$ MeV/c ( $T_n$ is the neutron kinetic energy, $T_n = 2$ MeV is the neutron detector threshold) are listed for beam momenta from 1.5 GeV/c up to 40 GeV/c. In the calculations we supposed the differential cross section of the reaction (3) to be of the same form as for the reaction $\pi^- p \to \eta^\circ n$, i.e./20/

$$\frac{d\sigma}{dt} = A(1 - gct)e^{ct} \; ,$$

$$(7)$$

$$c = 5.2 + 1.3 \ln \frac{s}{s_1}, \; s_1 = 10 \text{ GeV}^2, \; g = 1.5 .$$

Note that, near threshold, the Adair condition (2) is fulfilled almost for all the events of the reaction (3) and that for $p_{\pi^-} > 2$ GeV/c the fraction of the events satisfying this condition is $\sim 3\%$.

For the forward $X^\circ$ production we have calculated a minimal opening angle of $\gamma$'s, $\psi^{min}$, a greater value $a$ of two $\gamma$ production angles corresponding to $x^{max} = 0.9$ and $x^{max}$ at $a = 10^\circ$. Looking at Table 1 we see that the value $x^{max} \gtrsim 0.9$ can be reached if $p_{\pi^-} \geq 10$ GeV/c (we suppose that only the production angles $a < 10 \div 20^\circ$ are measured). For example, for the angle $a = 10^\circ$ the optimal beam momentum is $p_{\pi^-} = 25 \div 30$ GeV/c ($x^{max} \simeq 0.9 \div 0.94$).

We have also calculated the neutron characteristics such as maximal neutron production angle $\theta_n^{max}$ and neutron production angle $\theta_n$, time of flight $\tau$ at the distance 1 m and neutron kinetic energy $T_n$ under boundary conditions $p_T = 10$ MeV/c and $T_n = 2$ MeV. From Table 1 we see that for momenta $p_{\pi^-} > 10$ GeV/c neutrons should be detected in narrow $\theta_n$ intervals, with time of flight $\tau \sim 30 - 50$ nsec/m and kinetic energy 2-7 MeV. Since for the neutrons with a kinetic



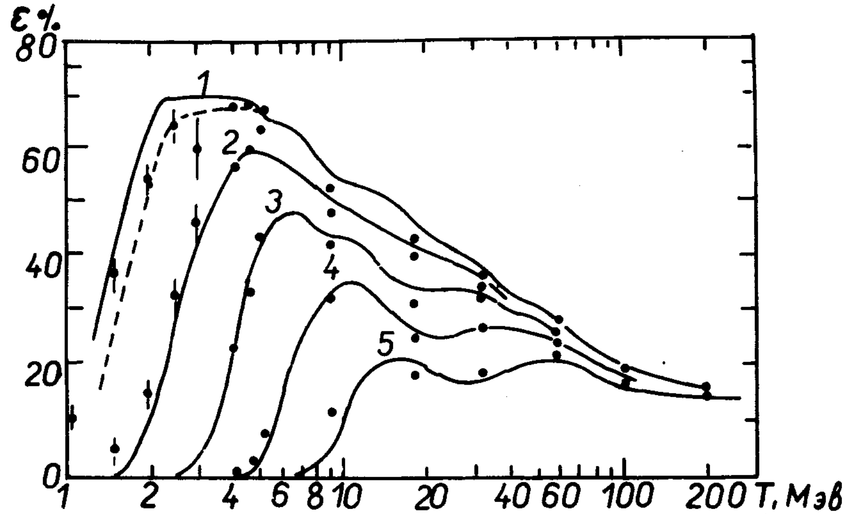


Fig. 3. The dependence of the neutron registration efficiency on the neutron kinetic energy for different neutron detector thresholds /21/.

energy of 2-7 MeV the registration efficiency can reach $\sim 70\%$ /21/ (see fig. 3), a cylindrical neutron detector can be used as an additional trigger. Note in this context that in the experiment /12/ at $p_{\pi^-} = 30$-$50$ GeV/c the squared four-momentum transfer resolution $\sim 2.10^{-3}$ $(\text{GeV/c})^2$ (at $t \sim 0$ ) was obtained without measuring the neutron characteristics. Such a resolution is quite sufficient for separating the events with $p_T < 100$ MeV/c ($|t| < 10^{-2}$ $(\text{GeV/c})^2$ ).

Let us estimate the number of events expected per 10 day accelerator run. For the 30 cm liquid hydrogen target and the beam intensity $10^6 \pi^-/9$ sec we have

$$N = 10^2 \frac{\sigma}{\sigma_0}, \quad \sigma_0 = 1 \text{ nb} \quad (8)$$

which, at $p_{\pi^-} = 30$ GeV/c, corresponds to 230 events with $p_T < 100$ MeV/c (100% registration efficiency supposed).

In conclusion it seems quite possible to get $\gtrsim 100$ events of the reaction (4) at $p_{\pi^-} \sim 30$ GeV/c with $x^{max} \sim 0.94$

T A B L E I

| $P_{\pi^-}$ GeV/c | $\Theta_n^{max}$ | $T_n = 2$ MeV, $\tau = 52$ nsec: $\Theta_n$ | $P_T = 100$ MeV: $\Theta_n$ | $\tau$ nsec | $T_n$ MeV | $X^\circ$ forward: $\psi^{min}$ | $x^{max}=0.9$: $\alpha$ | $\alpha = 10^\circ$: $x^{max}$ | Fraction of events, $P_T < 100$ MeV/c: % | nbn | $P_T < 100$ MeV/c, $T_n > 2$ MeV: % | nbn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.5 | 14.1° | - | 10.2° | 6.5 | 157.4 | 88.6° | 121.2° | - | 10.3 | 164.8 | 10.3 | 164.8 |
| 2 | 36.3° | - | 18.2° | 10.3 | 52.9 | 58.6° | 97.4° | - | 2.9 | 44.4 | 2.9 | 44.4 |
| 5 | 62.0° | - | 43.8° | 21.9 | 11.0 | 22.2° | 45.7° | - | 2.4 | 13.2 | 2.4 | 13.2 |
| 10 | 71.1° | 37.9° | 61.8° | 27.8 | 6.8 | 11.0° | 23.6° | 0.54 | 2.6 | 6.7 | 2.2 | 5.7 |
| 15 | 74.7° | 57.1° | 69.4° | 29.5 | 6.1 | 7.4° | 15.9° | 0.76 | 2.8 | 4.5 | 2.0 | 3.3 |
| 20 | 76.8° | 65.1° | 73.4° | 30.2 | 5.8 | 5.4° | 11.9° | 0.86 | 2.9 | 3.4 | 2.0 | 2.4 |
| 30 | 79.2° | 72.6° | 77.6° | 30.8 | 5.6 | 3.6° | 8.0° | 0.94 | 3.1 | 2.3 | 2.0 | 1.5 |
| 40 | 80.5° | 76.3° | 79.7° | 31.0 | 5.5 | 2.8° | 6.0° | 0.96 | 3.2 | 1.8 | 2.1 | 1.2 |



satisfying the Adair condition $p_T < 100$ MeV and thus to resolve the $0^-$ and $2^-$ alternatives for the $X^\circ$ meson spin parity.

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## Appendix

Suppose $J^P(X^\circ) = 2^-$. Let $N$ be the number of events of the reaction (4) measured in the interval $\langle 0, x^{max} \rangle$ and satisfying the Adair condition (2). Dividing this interval into $n$ bins of the same length $\Delta x = x^{max}/n$ with $N_i$ events in the $i$-th bin, we can calculate $\chi^2$ for both the hypothesis $0^-$ and $2^-$

$$\chi^2_{J^P} = \sum_{i=1}^{n} \frac{[N_i - \tilde{W}_{J^P}(x_i)\Delta x N]^2}{\tilde{W}_{J^P}(x_i)\Delta x N}, \qquad (A.1)$$

where $\tilde{W}_{J^P}(x) = W_{J^P}(x) / \int_0^{x^{max}} W_{J^P}(\xi)d\xi$, $W_{0^-}(x) = 1$ and $W_{2^-}(x)$ is given by the formula (5). Neglecting the difference between $W_{2^-}$ and $W_{0^-}$ in the denominators of the expressions (A.1), we can write

$$\chi^2_{0^-} \simeq \chi^2_{2^-} + \chi^2_D$$

$$(A.2)$$

$$\chi^2_D = \sum_i [\tilde{W}_{2^-}(x_i) - \tilde{W}_{0^-}(x_i)]^2 \Delta x N \simeq N \int_0^{x^{max}} [\tilde{W}_{2^-}(x) - \tilde{W}_{0^-}(x)]^2 dx .$$

Therefore the expected $\chi^2_{0^-}$ value is

$$\langle \chi^2_{0^-} \rangle \simeq \langle \chi^2_{2^-} \rangle + \chi^2_D = n - 1 + \chi^2_D . \qquad (A.3)$$

In fig. 2 we show the confidence level CL of the maximal $\langle \chi^2_{0^-} \rangle$ value for $N = 100$ and $n = 10$ * and the corresponding $\rho_{00}$ value, coming from the condition $\partial \chi^2_D / \partial \rho_{00} = 0$, as functions of $x^{max}$.

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* $n$ should be chosen as small as possible so far as the approximation $\Sigma \to \int$ in (A.2) allows.

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