Editorial of 20 July 1964 [Phys. Rev. Lett. 13, 79 (1964)].

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Evidence for a Non-Hulthén Impulse-Model Component in $K^+d \to K^{*0}(890)pp$ at 2.0 GeV/c*

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In a study of $K^+d \to K^{*0}(890)pp$ at 2.0 GeV/c, evidence is found for the occurence of the single-pion virtual state $d \to \pi^-(pp)$ associated with the high-momentum tail of the deuteron.

Attempts to use deuterium as a source of quasi-free neutrons in high-energy scattering experiments have been surprisingly successful. The impulse model, wherein the interacting nucleon is regarded as free with a momentum distribution given by the internal wave function for the deuteron, is able to account for most of the events in such experiments. In these events, the momentum distribution of the slowest nucleon (i.e., the "spectator") closely resembles the momentum transform of this wave function. However, about 8% of the events in such experiments have a slow-proton momentum $p_{\rm slow} > 300$ MeV/c, compared with 1–2% expected from a typical wave function (e.g., Hulthén). The production mechanism of this class of events is not fully understood. The presence of these events is generally attributed to one or the other (or both) of the following hypotheses: (a) Initial- or final-state particles scatter on the spectator nucleon; or (b) the Hulthén wave function is inadequate, especially in the high–spectator-momentum region.

In the present Letter we report a study of the properties of the events with $p_{\rm slow} > 300$ MeV/c in the reaction

$$K^+d \to K^{*0}(890)pp\,, \qquad (1)$$

at 2.0 GeV/c.[1] In particular, we investigate the question of whether these events result from double-scattering processes or whether, as seems to be the case, they arise predominantly from a simpler, more direct, production mechanism.

A sample of 24 000 events of $K^+d \to K^+\pi^-pp$ with $\lesssim 3\%$ background was obtained in a 780 000-picture exposure of the Lawrence Berkeley Laboratory 25-in. deuterium-filled bubble chamber to a 2.0-GeV/c K^+ beam. Details of the exposure and data reduction are to be found elsewhere.[2] From fits to the $K^+\pi^-$ invariant-mass spectrum, we find that ~55% of the events contain $K^{*0}(890)$. A working sample of Reaction (1) is selected by using the criterion $0.84 < m_{K\pi} < 0.94$ GeV. This cut yields 11 885 events, of which 85% are examples of Reaction (1); in the remaining 15%, the $K\pi$ system is in a $J^P = 0^+$ state.[2]

A convenient representation of these data is the Chew-Low plot shown in Fig. 1(a). The momentum transfer t between the incident K^+ and the outgoing K^* is plotted as a function of the pp invariant mass M_{pp}. The striking diagonal band of events is due to the fact that the incident K^+ scatters only on a component of the deuteron (the neutron). It can be shown that if the deuteron Fermi motion is ignored, and the incident K^+ scatters only on the neutron, then t and M_{pp} are uniquely related by $-t = M_{pp}^2 - 4m_p^2$. This equation passes through the center of the diagonal band in Fig. 1(a) (not plotted to avoid obscuring the data). The

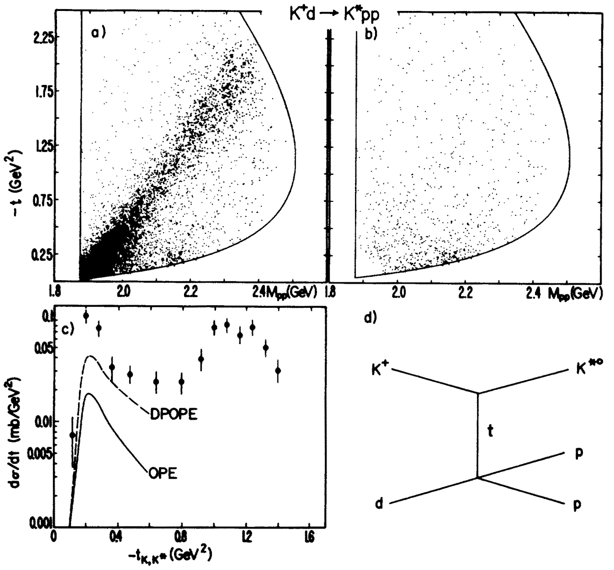

FIG. 1. Chew-Low plot of $t(K^+ \to K^{*0})$ versus M_{pp} for (a) all events and (b) those with $p_{slow} > 300$ MeV/c. (c) $d\sigma/dt$ for events with $2.13 < M_{pp} < 2.19$ GeV. Solid and dashed curves are absolute-cross-section predictions. (d) K^+d π-exchange diagram.

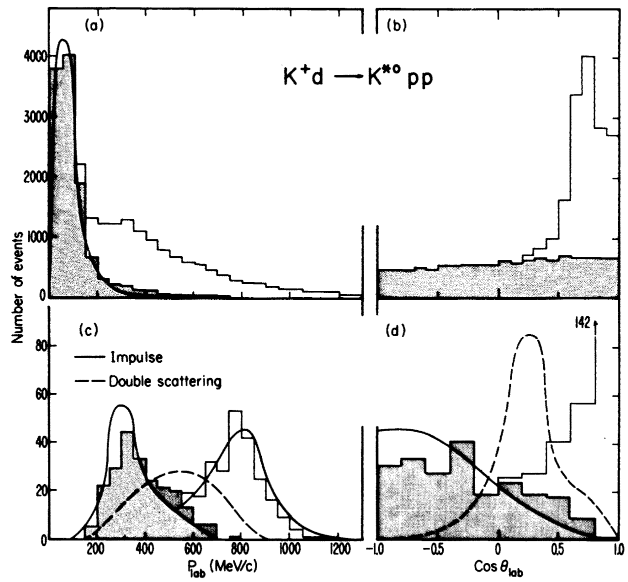

FIG. 2. Laboratory momentum (p_{lab}) and angular distributions ($\cos\theta_{lab}$) for slower (shaded) and faster (unshaded) protons. (a), (b) All 11 885 examples of Reaction (1); (c), (d) 224 events which satisfy Eq. (2). Curves in (c) and (d) are results of Monte Carlo calculations for the slower proton except for the right-most curve in (c) which is for the sum of both protons.

spread of this band is caused by the Fermi motion and can be accounted for with this model.

In addition to the dominant impulse-model band, a second enhancement is seen at low t along the Chew-Low boundary. This is shown more clearly in Fig. 1(c) which shows the distribution in t for events in the arbitrarily chosen region $2.13 \leq M_{pp} \leq 2.19$ GeV. The two regions of enhancement are clearly seen. The one centered at $-t \approx 1.1$ GeV^2 arises from the diagonal or impulse-model band; the second, peaking at $-t \approx 0.2$ GeV^2, corresponds to the events clustered along the t_{min} boundary in Fig. 1(a). The slowest proton associated with these low-t, high-M_{pp} events has a momentum distribution well above the Hulthén distribution. To illustrate this point, Fig. 1(b) shows the Chew-Low distribution for those 883 events with $p_{slow} > 300$ MeV/c. The diagonal band all but disappears and there is a tendency for the remaining events to concentrate along the t_{min} boundary of the Chew-Low plot. This character of the distribution in Fig. 1(b) suggests that a generalized exchange process of the type shown in Fig. 1(d) might be responsible.

The two types of mechanisms considered in this Letter lead to quite different distributions in laboratory momenta (p_{lab}) and angles ($\cos\theta_{lab}$) of the protons in Reaction (1). These distributions are shown in Figs. 2(a) and 2(b) for the entire 11 885-event sample of Reaction (1). In each case both protons from a given event are plotted, with the slower of the two being shaded. The dominant impulse-model properties of the slowest proton are seen; namely, its momentum distribution agrees fairly well with the Hulthén distribution (for $p_{slow} > 250$ MeV/c), and its $\cos\theta_{lab}$ distribution is nearly flat.[3] The faster-proton distribution is as expected from the quasi-two-body process: $K^+n \to K^{*0}p$. Figures 2(c) and 2(d) contain these distributions for those 224 events which fall in the following low-t, high-M_{pp} region of the Chew-Low plane:

$$-t < 0.40 \text{ GeV}^2; \quad M_{pp} < 2.09 \text{ GeV}. \qquad (2)$$

These events have the two remarkable properties that (i) the momentum distribution is double-peaked (at ~300 and ~800 MeV/c, respectively), and (ii) the slowest-proton distribution in $\cos\theta_{lab}$ is fore-aft asymmetric with a pronounced preference for the backward hemisphere.

The *dashed* curves in Figs. 2(c) and 2(d) show the slow-proton distributions resulting from a Monte Carlo calculation in which the impulse model is assumed for $K^+n \to K^{*0}p$ (the experimental t distribution is assumed), with the spectator momentum given by the Hulthén function, *but* with the final-state K^{*0} elastically scattering on the spectator proton (similar results are obtained if, instead, the incident K^+ first elastically scatters on the spectator proton).[2] The t dependence for the $K^*p \to K^*p$ process is assumed to be the same as in K^+p elastic scattering at 2 GeV/c. It is seen that neither the $p_{\rm lab}$ nor $\cos\theta_{\rm lab}$ distributions for the slower proton can be understood with this model. [The t dependence is also found to be much flatter than that observed in Fig. 1(c).] Finally, we remark that only 8.5% of the Monte Carlo events with $p_{\rm slow} > 300$ MeV/c generated with this double-scatter model fall in the Chew-Low region defined by Eq. (2), compared with 19% of the data in Fig. 1(b). Alternatively, we may remark that if the observed 224 events in this region were all examples of double scattering, this would require that 22% of the events in Reaction (1) underwent double scattering, a value which is considerably larger than allowed by the data or which is expected from theoretical estimates.[4] *We conclude that double scattering is not the main source of the low-t enhancement seen in Fig. 1(b).*

In contrast with the difficulty in understanding these events in terms of a double-scattering picture, it is found that they arise quite naturally from an impulse model in which a high–spectator-momentum tail is assumed as input to the calculation. The solid curves in Figs. 2(c) and 2(d) result from such a calculation in which the experimental $p_{\rm slow}$ distribution of Fig. 2(a) is assumed. The essential features of the $p_{\rm lab}$ and $\cos\theta_{\rm lab}$ distributions for both the slow and fast protons are seen to be reproduced by this impulse-model picture. (The distribution in t_{K,K^*}, not shown, also agrees, since it is not modified from the input values by initial- or final-state scattering as in the previous calculation.)

We now consider the generalized exchange process shown in Fig. 1(d), in which some exchange meson from the K^+-K^* vertex scatters on the deuteron leading to the pp final state. With an exchanged pion (this is likely since it is the closest pole and both vertex couplings are large), both the breakup angular distribution in the pp rest frame and the absolute magnitude of Reaction (1) would be related to the known cross section[5] for

$$\pi^+ d \to pp. \tag{3}$$

Since the major component of Reaction (3) is of an impulse-model type,[6] these considerations are quite compatible with the good impulse-model agreement in Figs. 2(c) and 2(d). The differential cross section for Reaction (3) at a pp invariant mass of 2.16 GeV[5] (i.e., approx $1+4\cos^2\theta+\cos^4\theta$) is found to agree well in shape with the breakup angular distribution in the pp rest frame for those events which satisfy Eq. (2).

The Chew-Low equation for a deuteron target[2] may be used to test whether the absolute cross section for the low-t, high-M_{pp} component of Reaction (1) is governed by Reaction (3):

$$\frac{d^3\sigma}{dt\,dm\,dM} = \frac{1}{4\pi^3 m_d^{\,2} p_{\rm lab}^{\,2}}\, m^2 q\sigma(m) \times \frac{1}{(t-\mu^2)^2} M^2 Q\sigma(M). \tag{4}$$

Here M and Q (m and q) are the pp ($K^+\pi^-$) invariant mass and momenta in their rest frames, respectively, $\sigma(m)$ is the cross section for $K^+\pi^-$ elastic scattering in the K^* region, and $\sigma(M)$ is the known cross section[5] for Reaction (3). Figure 1(c) contains absolute-magnitude $d\sigma/dt$ curves which are calculated from Eq. (4) with no form factors at either vertex (solid curve) and with the known Durr-Pilkuhn[7] form factor for the K^* vertex[8] (dashed curve). The absolute magnitude and shape of the dashed curve are in fair agreement with the data given the low statistics and unknown t dependence at the deuteron vertex. For example, if the same form factor used at the K^* vertex is also used at the deuteron vertex, the calculated cross section is brought into agreement with our observed cross section.

We interpret these results as evidence for the occurrence of the single-pion virtual state $d \to \pi^-(pp)$ associated with the high-momentum tail of the deuteron. In processes where pion exchange is excluded, such as $K^+d \to K^0pp$, effects of the $d \to \rho^- pp$ virtual state may be observable.

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Experimental Search for a Low-Mass Scalar Boson*

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Two experiments are reported in which a search was made for the scalar boson predicted to be produced in the ^{16}O(6.05 MeV) to ground state and ^{4}He(20.2 MeV) to ground state 0^+ to 0^+ transitions with subsequent in-flight decay into electron-positron pairs. Taken together, our results show that the light scalar boson proposed by Sundaresan and Watson to account for certain muonic x-ray energy discrepancies cannot have a mass in the range $1.030 \leq m \leq 18.2$ MeV.

One of the characteristic features of the currently developing unified gauge theories of electromagnetic and weak interactions is the prediction of the existence of, as yet, undiscovered particles. The new particles predicted by these gauge theories are typically very massive (many GeV/c^2) and, hence, are expected to be very difficult to observe. Almost all of these theories, in particular the prototype Weinberg-Salam theory,[1] require the existence of a scalar particle, φ (the Higgs scalar), with well-defined coupling constants for the lepton-scalar interaction but unfortunately with a completely unspecified mass. For the φ, however, it has been pointed out[1-4] that even a very low mass cannot be excluded by observations to date. In fact, experimental evidence suggestive of a low-mass scalar particle has been accumulated in muonic x-ray studies. Dixit *et al.*,[5] and also Walter *et al.*,[6] have found certain discrepancies between measured and theoretically calculated muonic x-ray energies in several transitions among high-Z elements. Sundaresan and Watson[4] and Resnick, Sundaresan, and Watson[3] have shown that these discrepancies can be removed by assuming the φ particle with coupling constants consistent with the Weinberg-Salam theory and with $m_\varphi \leq 22$ MeV. Resnick, Sundaresan, and Watson[3] suggest several experimental possibilities for production and study of these hypothetical particles. Among these, one promising approach follows from the relatively large branching ratios expected for the production of the scalar particle in 0^+ to 0^+ nuclear decays; for example the decay of the ^{16}O(6.05 MeV) 0^+ excited state would have a φ branching ratio up to a few percent if m_φ was not too close to the 6.05-MeV production threshold.

Based on these considerations a search for the φ branching mode in the decay of the ^{16}O 6.05-MeV level was carried out with negative results. Since the upper bound for m_φ was limited by $E_x(^{16}\mathrm{O})$, the investigation was extended to a search for φ production in the decay of the ^{4}He 20.2-MeV level, again with negative results. Thus, almost the entire mass region for m_φ suggested from the muonic x-ray anomalies[3,4] is now excluded. Details of the experiment are given below.

The experiment on the ^{16}O(6.05 MeV) state will be described first. The φ should, according to the Weinberg theory, decay via the weak interaction into an electron-positron pair provided that $m_\varphi \geq 1.022$ MeV. The lifetime[3] for the decay ranges from approximately 0.7 nsec near $m_\varphi = 6.05$ MeV to many microseconds near $m_\varphi = 1.022$ MeV (below 1.022 MeV only the two-photon decay mode is available with a lifetime expected[3] to be $\gtrsim 10^{-4}$ sec). Since the particle possesses only the weak interactions, it would readily penetrate[3] matter much as does the neutrino. A heavily shielded scintillation detector placed near a target in which the ^{16}O(6.05 MeV) state is produced should suffice to detect φ's which decayed within the volume of the detector; the signal from such a decay would approximate that of a 6.05-MeV γ ray.