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A COMMENT ON THE INTERPRETATION OF ANOMALOUS ENHANCEMENTS IN THE REACTION p + d → d + MISSING MASS

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Difficulties in interpreting the reaction p + d → d + missing mass are discussed. Treating this reaction as a quasi-two-nucleon process, absolute calculations are presented using the OPE model. Comparison is made with other recent calculations.

In a recent contribution [1] the authors with Risser presented absolute calculations of the reaction NN → dππ in the double-resonance region ($E_{cm} \sim 2M_\Delta c^2$). These calculations employed a one-pion-exchange model which was an improvement of an earlier proposed by Risser and Shuster [2] and also by Bar-Nir et al. [3] in a simplified version. The Feynman graph for this model is given in fig. 1.

This one-pion-exchange (OPE) model of ref. [1] reproduced without any adjustable parameter:

(i) The absolute differential cross section for the reaction n + p → d + missing mass at an incident (neutron) beam momentum of 1.9 GeV/c (data of ref. [4]).

(ii) The absolute total cross section for the reaction n + p → d + π^+ + π^- for incident (neutron) beam momenta from 1.5 to 3.2 GeV/c (data of ref. [3]).

These were the only data which existed at that time for the reaction np → dππ in the double-resonance region. (The situation has not changed at this writing.) For that reason the comparison with experiment was limited to those two cases. One might

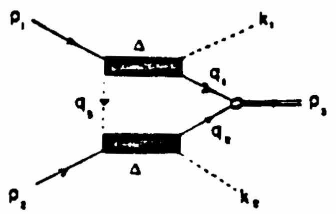

Fig. 1. One-pion-exchange model for the reaction NN → dππ.

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well ask, however, to what extent other data exist which may be used to inder further information on this reaction. It is to this question that the first part of this note is addressed. In chronological order these data are:

(a) The data of Hall et al. [5] for the reaction p + d → d + missing mass at an incident (proton) beam momentum of 1.69 GeV/c. Interpreted as p + N → d + missing mass this corresponds to a total energy in the center-of-mass system of 2.32 GeV or 1.16 GeV/nucleon. These data are thus near the borderline of the region of applicability of a model which limits the pion-nucleon interaction to the $(\frac{3}{2}, \frac{3}{2}^+)$ partial wave. At the same time it should be pointed out that the interpretation of the reaction p + d → d + missing mass as p + N → d + missing mass is complicated by the presence of other "contanimating" processes, especially those processes involving coherent production. We will return often to this point.

(b) The data of the Caen–Saclay collaboration [6,7] for the reaction d + p → d + missing mass, which employed a deuteron beam with momenta from 3.25 to 3.76 GeV/c. The analysis of such data follows the same lines with the same caveats. The early calculation of Risser and Shuster [2] used data from ref. [7] for an incident (deuteron) beam momentum of 3.76 GeV/c. This was at that time the data which possessed the best statistics as well as being closest to the double-resonance energy ($2M_\Delta c^2 = 2.472$ GeV).

An appreciation of the contribution of "contaminating" processes of the reaction d + p → d + missing mass can be obtained from an examination of ref. [4], which displays the data for this reaction at an incident (deuteron) beam momentum of 3.82 GeV/c alongside data for the reaction n + p → d + missing mass at an (almost) corresponding incident (neutron) beam momentum of 1.88 GeV/c. Much of the ABC peak in the backward hemisphere (in the center-of-mass system) is obscured by this "background" leaving only a shoulder compared to the prominent peak seen in the same experiment performed with a neutron beam.

The problems posed by these coherent processes are well known to experimentalists. It is for this reason, for instance, that studies by the Caen–Saclay collaboration of the reaction d + p → d + missing mass were always confined to the backward hemisphere (in the center-of-mass system) where owing to the large momentum transfers the contribution of coherent processes would be minimised.

With these misgivings in mind we have calculated using the model of ref. [1] the recoil momentum spectrum for the process p + d → d + missing mass interpreting it as p + N → d + missing mass. Only one complete recoil-momentum spectrum anywhere near the double-resonance energy exists for this reaction, the data of Hall et al. [5] for an incident (proton) beam momentum of 1.69 GeV/c. Hall et al. studied both this reaction and also the reaction p + p → d + missing mass and made a decomposition of the cross section into channels of definite isospin. By this is meant that in terms of channels of definite isospin we may write

$$\sigma(\mathrm{pp} \to \mathrm{d}\pi\pi) = \sigma(T = 1)\,,$$

$$\sigma(\mathrm{pd} \to \mathrm{dN}\pi\pi) = \tfrac{3}{2}\sigma(T = 1) + \tfrac{1}{2}\sigma(T = 0)\,,$$

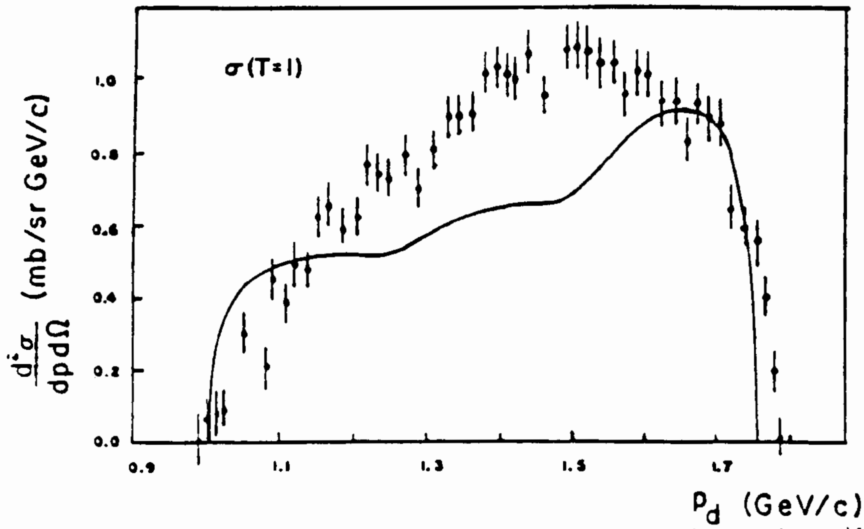

Fig. 2. Predicted differential cross section for the reaction pp → dππ. The data are those of Hall et al.

provided that we interpret the second process as quasi-two-nucleon.

In figs. 2 and 3 we display the recoil momentum spectra $\sigma(T = 1)$ and $\sigma(T = 0)$ at an incident (proton) beam momentum of 1.69 GeV/c along with the experimental data. The agreement is not extraordinary but reflects the trend of the data. The re-

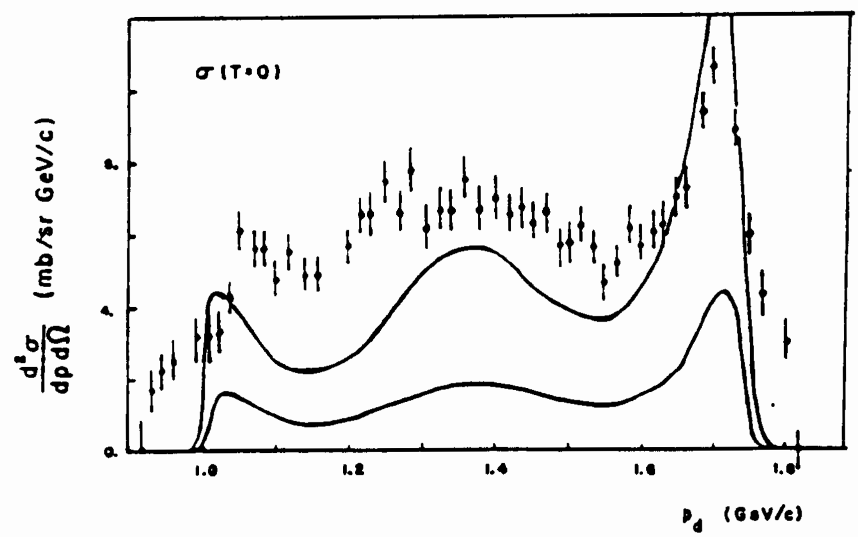

Fig. 3. Predicted differential cross section for the $T = 0$ channel of the reaction NN → dππ. The upper curve is this same calculation multiplied by a factor of 3. The data are those of Hall et al. for the reaction d + p → d + p + $(\pi\pi)^{T=0}$.

coil-momentum spectrum in the $T = 1$ channel is fairly well reproduced both in shape and in magnitude. The general shape of the recoil-momentum spectrum in the $T = 0$ channel is well reproduced but the absolute cross section is too small by a factor of about three. This level of agreement in the magnitude of the $T = 0$ channel is not surprising following our remarks at the beginning of this article.

We are supported in this conclusion, namely, that "contaminating" processes are largely responsible for the poor agreement in the magnitude of the $T = 0$ cross section, by two facts: first, the $T = 1$ cross section, which is more sensitive to details of the model is well reproduced. Secondly, the model reproduces the total cross section for the process np → dππ at this beam momentum. The data of Hall et al. are consistent with Saclay data at similar beam momenta [6] so that it is very unlikely that the disagreement could be attributed to the data taking. The data, however, do not appear to be consistent with that for the reactoin np → dππ, if we are willing to accept the model of ref. [1], at least as a device for interpolation.

We must conclude, therefore, that the contribution from "contaminating" coherent processes to the reaction p + d → d + missing mass must be at least as large as the two-nucleon processes at this beam momentum and that it is largely because the former processes lack structure in the ABC region that the ABC effect is so clearly visible in this reaction. There is even some experimental indication of this [8].

Since experimental data now exist for the reaction n + p → d + missing mass, there might have been little interest in such a lengthy discussion of the reaction p + d → d + missing mass. However, these data have been used in a reappraisal [9] of the OPE model in which every conceivable reaction involving no more than four nucleons is examined. These are:

$$\mathrm{N + N \to d + missing\ mass}, \qquad \mathrm{p + d \to {}^3He, {}^3H + missing\ mass},$$

$$\mathrm{p + d \to d + missing\ mass}, \qquad \mathrm{d + d \to {}^4He + missing\ mass}.$$

Ref. [9] suggests that the OPE model fails badly at beam momenta below those studied by refs. [1,2]. We should, therefore, examine its result in some detail. We confine our discussion to the first two reactions.

In the analysis of ref. [9] a slightly altered version of the old OPE model of Risser and Shuster [2] has been used. As in that model only the $\frac{3}{2}, \frac{3}{2}^+$ πN partial-wave amplitude is taken to be non-vanishing and the nucleons and deuteron are treated as scalar particles. However, the p-wave nature of this partial wave is taken partially into account by including a factor $\cos\theta^*_{\pi N}$. This is equivalent in a world with scalar nucleons to having vector ($J = 1$) Δ's. The approximation for the deuteron vetrex function in ref. [9] is identical to that of ref. [2]. Likewise, neither ref. [2] nor ref. [9] included any vertex correction for the off-shell pion. (The fixed-θ^* prescription only states that θ^* is the angle between the (on-shell) incoming nucleon and the (on-shell) outgoing pion in the πN center-of-mass frame.) Both ref. [2] and ref. [9] suffer from the drawback that the normalization of the cross section is an adjustable parameter. Unlike the model of ref. [2] that of ref. [9] has not taken the energy dependence of the Δ width into account. As a consequence the πN amplitudes used there do not have the correct threshold behavior. Thus, we see that the OPE models of ref. [2] and ref. [9] are identical in every detail except that ref. [9] includes an additional factor $(\cos\theta_1^*)(\cos\theta_2^*)$ while neglecting the correct threshold behavior of the πN amplitude.

The OPE Feynman graph for the process NN → dππ is given in fig. 1 using the notation of ref. [9].

On the basis of this OPE model ref. [9] arrives for the following results as applied to the first two reactions above:

For the production of a neutral missing mass, the calculated recoil-momentum spectra at 1.88 GeV/*c* and 1.90 GeV/*c* (incident beam momentum/nucleon) show prominent peaks at the edges of phase space and a broad central peak in accord with the data. The data at 1.69 GeV/*c* show these same features. But in the calculation of ref. [9] at this beam momentum the central peak is absent, replaced by a broad central minimum, and the ABC peaks are not near the edges of the phase space but rather where the data show minima. In addition, we note that the calculated cross sections of ref. [9] at 1.88 and 1.90 GeV/*c* follow the behavior of the ππd phase space for values of the deuteron recoil momentum near the extrema, as indeed it must. At 1.69 GeV/*c*, however, this does not seem to be the case suggesting that the analytic structure of the phase-space factors is different in the two cases.

For the production of positively-charged missing masses the calculation of ref. [9] show some "ABC-like" structure. The deviation from phase space it not so serious at 1.88 GeV/*c* but at 1.69 GeV/*c* it is very serious showing two very prominent peaks.

In short, there are enormous qualitative differences in the predictions of ref. [9] for two beam momenta which differ only by 10%.

This drastic change in the calculated cross sections as the beam momentum is reduced from 1.88 to 1.69 GeV/*c* was not observed in the calculations of ref. [1] nor did Risser and Shuster find such an effect during the course of their calculations. In fact, the calculations of ref. [1] showed the same qualitative structure over the range of beam momenta from 1.3 to 2.5 GeV/*c*. It would be hard to imagine that the inclusion of the $\cos\theta^*$ factors could be responsible for such drastic behavior since the non-spin-flip πN amplitude of ref. [1] is indeed proportional to $\cos\theta^*$. The neglect of a vertex correction for the πN amplitude or the approximation made for the deuteron vertex do not much effect the shape of the cross sections.

We are thus totally unable to account for the anomalies in the calculations of ref. [9] at 1.69 GeV/*c*. Curiously, this anomalous behavior is not present in the calculations in ref. [9] of p + d → ^{3}He + π + π at similar beam momenta. Since ref. [9] treats both of these reactions on a similar footing the anomaly should appear in both or neither reaction.

As regards the normalisation of the results of ref. [9] one might mention that neglecting the vertex correction for the off-shell pion will always overestimate the calculated cross section (because the vertex correction is always less than unity). Likewise, approximating $|\psi_d(x)|^2$ by $|\psi_d(0)|^2$ will also overestimate the cross section because $\psi_d(0)$ is always the largest value attained by the s-wave deuteron wave function. We have found by explicit calculation that these two errors together amount to more than an order of magnitude in the absolute cross sections without much affecting the shape. It is, therefore, interesting to remark that in order to fit data at 1.88 GeV/*c* ref. [9] must choose a value for $|\psi_d(0)|^2$ which is several times *larger* than that given by reasonable models (such as the Hulthén wave function). The calculation of ref. [1], which made none of these approximations, nonetheless reproduced the magnitude of the experimental cross sections within 20%.

In summation: The interpretation of the reaction p + d → d + missing mass at an incident (lab) proton momentum of 1.69 GeV/*c* as p + N → d + missing mass at this same lab beam momentum does not seem to be consistent with data for the reaction N + N → d + missing mass. A recent analysis [9] of the second reaction at this beam momentum is in violant disagreement with more complete calculations [1] using a more realistic model which reproduces all the known data on the reaction NN → dππ and NN → d + missing mass. This recent analysis, however, gives some suggestion of being internally inconsistent, at least as regards the reactions N + N → d + missing mass and p + d → d + missing mass.

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