Importance of nonanalog nucleon charge exchange transitions in pion knockout reactions

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(Received 17 July 1978)

Complete analog dominance in the nucleon charge exchange transitions affecting ratios of $(\pi,\pi N)$ cross sections near the (3,3) resonance is experimentally unfounded. No dramatic jumps with neutron number in neutron removal ratios are now expected. There may be a vestige of analog dominance in the deviation of $\sigma(\pi^+,\pi^+p)/\sigma(\pi^+\pi^0p)$ from the impulse approximation. Disagreement of an intranuclear cascade calculation with the nucleon charge exchange model (and experiment) is also discussed.

[NUCLEAR REACTIONS $\sigma(\pi,\pi N)$ ratios, T_π near 180 MeV: analog and nonanalog nucleon charge exchange; ^{11}B, ^{12}C, ^{7}Li, ^{19}F, ^{4}He, and emulsion targets; intranuclear cascade model discrepancy.]

In recent years there has been considerable interest in the knockout of nucleons from nuclei by pions with energies near the (3,3) resonance.[1-5] The ratios of the cross sections $\sigma(\pi^-)/\sigma(\pi^+)$ generally differ markedly from the impulse approximation (IA) predictions. Part and possibly the bulk of this difference is apparently due to the fact that the struck nucleons can charge exchange as they exit the nucleus.[6-8] An easy way to estimate these charge exchange effects is to employ a simple semiclassical transport model[7] (N-CEX model). There appear, however, to be some problems with this model; for example, Karol has suggested that its prediction for $\sigma(\pi^+ + {}^{11}\text{B} \rightarrow {}^{10}\text{C} + \pi^0 + n)$ is too large.[9] In view of these problems, we recently proposed a "refined" model which assumes that isobaric analog states play a dominant role in the nucleon charge exchange effects.[10] For certain elements, this refined model predicts that as the neutron number is increased, dramatic changes will occur in the total cross section ratio $\sigma(\pi^-)/\sigma(\pi^+)$ for neutron knockout, R_n.[10,13] Furthermore, the refined model predicts that the corresponding ratio for neutron knockout to a specific final state of the residual nucleus will depend strongly on the particular state. However, since recent experiments[13,14] on ^{13}C and ^{197}Au fail to confirm the latter predictions, we must reconsider the basic premise of analog dominance.

In this communication we discuss four things. First, the still unexplained lack of agreement between an intranuclear cascade model calculation and the N-CEX model is considered. Then the assumption of *complete* analog dominance for N-CEX transitions is shown, on experimental grounds, to be inappropriate. Since nearly all the available pion knockout data are in good qualitative agreement with the simple N-CEX model,[7] it is, we feel, a better description of the physical situation. Finally, we note that the preliminary data on one sort of experiment do suggest some remnant of analog dominance in the nucleon charge exchange effects.

Before looking at the problems with the analog dominance concept, we consider a difficulty which we have not yet resolved: the disagreement of intranuclear cascade (ISOBAR code[15]) and N-CEX calculations[7] for the neutron knockout ratio, R_n. Both models appear to have the same semiclassical basis, but the cascade model includes effects such as a realistic nuclear density and evaporation, and it avoids the simplifying assumptions used in the N-CEX model to find the nucleon charge exchange probability, P. For ^{12}C at 180 MeV, ISOBAR gives $R_n = 2.4$, which is closer to the IA value, 3.0, than to the experimental (and N-CEX model) value, 1.6. ISOBAR correctly predicts the total cross section $\sigma(\pi^-)$, but $\sigma(\pi^+)$ is too small. The evaporation contribution turns out to be very small, so the cross sections are almost entirely due to the direct knockout of a nucleon. Apparently the code does not give a large enough value for P:

$$P_{\text{ISOBAR}} \simeq 0.09\,, \quad P_{N\text{-CEX}} \simeq 0.24 \tag{1}$$

at 180 MeV. Similar troubles hold at other pion energies.

It may be that, for the relatively simple situation of one-nucleon removal, the intranuclear cascade approach misses some important quantum mechanical coherence in the charge exchange process. We have used ISOBAR to calculate cross sections for the reaction $^{11}B(p,n)^{11}C$, summing over all particle-stable final states. Comparing with experiment,[16] we found the ISOBAR cross section at 40 MeV to be about a factor of 3 too small, but at 155 MeV there was good agreement. This supports the possiblity that coherence is a necessity in calculating P correctly at the nucleon energies of interest.

If this is so, we may ask why the N-CEX calculation[7] of P does not also suffer from the same lack of coherence. Here the result $P \simeq 0.24$ was obtained using a value of the $np \rightarrow pn$ forward charge exchange cross section reduced by a Pauli principle factor corresponding to a nuclear surface region density; it agrees with an estimate of P made using a nucleon-nucleus optical potential.[6,17] The lack of coherence in the N-CEX calculation of P may turn out to be offset by other approximations. One of these is the neglect of quasielastic nucleon-nucleon scattering; this process could decrease the mean path length of the recoil nucleon in the nucleus, thereby decreasing P. Energy degradation in the quasielastic collisions would have the opposite effect,[18] i.e., it would increase P; however, the intranuclear cascade calculations[15] indicate this is not important. It is not yet clear why the cascade and transport models disagree on the charge exchange probability P and hence the knockout ratio, R_n. We are continuing to study this question.

Let us now turn to the validity of our assumption that only analog charge exchange transitions are important. Experimental evidence from (p,n) reactions shows that nonanalog transitions cannot be neglected. Consider first $^{11}B(p,n)^{11}C$. The transition to the ^{11}C ground state is analog, but those to excited states are not. Experimentally,[19]

T_N	σ (g.s)	$\sigma(1.44+4.5)$
30 MeV	24.9 mb	20.4 mb
50 MeV	9.3 mb	11.0 mb

(2)

which means the nonanalog states of ^{11}C (with the same isospin as the ^{11}B ground state) are indeed strongly populated. In the same experiment[19] the isospin changing reaction $^{12}C(p,n)^{12}N$ was also measured, with the results

T_N	σ (g.s. + 1.0)
30 MeV	8.4 mb
50 MeV	5.5 mb .

(3)

These cross sections are not as large as those in Eq. (2) but are sufficiently large that they probably ought not to be neglected.

For a medium-weight nucleus with the appropriate conditions for the pion knockout case we can look, e.g., at the work of Doering *et al.*[20] on the reaction $^{90}Zr(p,n)^{90}Nb$ at $T_p = 45$ MeV and $\theta_n = 0°$. The neutron spectrum has a prominent peak corresponding to the analog transition, but this sits on a large background due to nonanalog transitions. Roughly integrating the areas under the curve, as is appropriate for calculating P, we find

$$\frac{d\sigma}{d\Omega}\,\text{analog} = 2\ \text{mb/sr},$$
$$\frac{d\sigma}{d\Omega}\,\text{nonanalog} = 30\ \text{mb/sr}. \tag{4}$$

Much of the 30 mb cross section may involve transitions to states with the same isospin as the ^{90}Zr ground state. Nevertheless, this hardly corresponds to "analog dominance" in any sense.

We conclude, therefore, that the use of complete analog dominance in the N-CEX model is not justified. Including nonanalog transitions in the model, however, brings us more or less back to the simpler situation of Ref. 7. In particular, we do not now expect to see "dramatic jumps" in R_n when N is varied as predicted in Ref. 10.

What about the other experimental knockout ratios previously considered in the light of the "refined" N-CEX model? Are they consistent with the simpler version? We believe they are, although the experimental facts are not always as clear-cut as one would like. For the $^7Li \rightarrow {}^6Li$ case,[4] interpretation with the original model implies $P \simeq 0.2$ for T_π from 150 to 200 MeV. This is not much different from the P value used for the $^{12}C \rightarrow {}^{11}C$ data[1,2] and is probably not unreasonable. We might have expected P to be somewhat smaller for ^7Li, however, in view of the smaller nuclear density and the smaller particle separation energies.[11]

For $^{19}F \rightarrow {}^{18}F$ ($T = \frac{1}{2}$ target), the measured ratio $R_n(T_\pi)$ is very similar to that for the $T = 0$ targets ^{12}C, ^{14}N, and ^{16}O. This is no longer as disturbing as it was, since the isospin dependence of the simpler model is small. The experiment[5] on the deexcitation γ ray from the first $T = 1$ state of ^{18}F (and ^{26}Al) will need both π^+ and π^- information before any definite statements can be made. The concept of a "fragility factor" introduced[12] to account for differences in the final residual nuclei in certain ratios we believe remains a useful concept.

Indeed, the problem raised by Karol[9] of the π^+

$+{}^{11}B \to {}^{10}C + \pi^0 + n$ reaction involves a ratio with two different residual nuclei, ${}^{10}C$ and ${}^{10}B$. Since ${}^{10}C$ is more "fragile" than ${}^{10}B$, we now attribute the experimentally small ${}^{10}C$ cross section to that fact, rather than to the smallness of nonanalog transitions. In any case, the denominator of the ratio involves the cross section for $\pi^+ + {}^{11}B \to {}^{10}B + (\pi^+ n$ or $\pi^0 p)$. This has not been measured (${}^{10}B$ is stable), so we do not consider this case a difficulty of the N-CEX model.

Thus, we feel that there is no outstanding evidence against the *simple* N-CEX model. In fact, the results of Ref. 13 which contradict the "refined" model are in fine agreement with the simple model, despite the impression those authors have given.

Finally, we point out some experiments which deviate from the IA in a way which appears difficult to understand unless some vestige of analog dominance remains. These involve measurement of the ratio

$$R_2 = \sigma(\pi^+, \pi^+ p)/\sigma(\pi^+, \pi^0 p). \tag{5}$$

Experiments have been performed using emulsions at 112 MeV (Ref. 21) and 170 MeV,[22] a propane bubble chamber at 130 MeV,[23] and a helium bubble chamber at 110 and 160 MeV.[24] The data taken with different techniques do not appear to be entirely consistent, but in every case the ratio R_2 is *smaller* than the IA value, which is $\frac{9}{2}$ at resonance. In the simple N-CEX model, however, the effect of nucleon charge exchange is to *increase* the ratio over the IA value. For example, at resonance,

$$R_{2,\,\mathrm{Ref.}\,7} = \frac{9(1-P)+P}{2(1-P)} = \frac{9}{2} + \frac{P}{2(1-P)}. \tag{6}$$

For a $T=0$ nucleus, however, the depletion of the denominator due to charge exchange necessarily involves an isospin-changing transition. Consider a ${}^{12}C$ target. Then, in more detail,

$$R_2 = \frac{9[1-P(p+{}^{11}B \to n+{}^{11}C)]+P(n+{}^{11}C \to p+{}^{11}B)}{2[1-P(p+{}^{11}C \to n+{}^{11}N)]}. \tag{7}$$

The P's in the numerator involve mirror nuclei and are presumably equal, but the P in the denominator may be smaller than the others. [Compare Eq. (3) with Eq. (2).] Setting it equal to zero gives

$$R_{2,\,\mathrm{Ref.}\,10} = \frac{9}{2} - 4P. \tag{8}$$

Thus nucleon charge exchange now *decreases* the ratio from the IA value. We should wait, however, until the experimental difficulties in measuring R_2 have been understood[25] before claiming it is less than the IA prediction and consequently returning some amount of analog dominance to the simple N-CEX model.

We wish to thank A. A. Goy, F. Lenz, and G. M. Vagradov for useful conversations. This work was done under the auspices of the Department of Energy and the National Science Foundation, and while R. R. S. was on a long-term exchange visit arranged by the U. S. and U. S. S. R. Academies of Science.

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[1]B. J. Dropesky *et al.*, Phys. Rev. Lett. 34, 821 (1975).
[2]L. H. Batist *et al.*, Nucl. Phys. A254, 480 (1975).
[3]N. P. Jacob and S. S. Markowitz, Phys. Rev. C 13, 754 (1976).
[4]J. R. Bolger *et al.*, Phys. Rev. Lett. 37, 1206 (1976).
[5]B. J. Lieb *et al.*, Phys. Rev. C 14, 1515 (1976).
[6]P. W. Hewson, Nucl. Phys. A133, 659 (1969).
[7]M. M. Sternheim and R. R. Silbar, Phys. Rev. Lett. 34, 824 (1975).
[8]J. Hufner, H. J. Pirner, and M. Thies, Phys. Lett. 59B, 215 (1975).
[9]P. J. Karol, Phys. Rev. Lett. 36, 338 (1976).
[10]R. R. Silbar, J. N. Ginocchio, and M. M. Sternheim, Phys. Rev. C 15, 371 (1977).
[11]R. R. Silbar, Phys. Rev. C 15, 1158 (1977).
[12]M. M. Sternheim and R. R. Silbar, Phys. Rev. C 16, 2059 (1977).
[13]C. L. Morris *et al.*, Phys. Rev. Lett. 39, 1455 (1977).
[14]S. B. Kaufman, E. P. Steinberg, and G. W. Burler, Phys. Rev. C (unpublished).
[15]K. Chen *et al.*, Nucl. Phys. A231, 462 (1974). This code works well for pion reactions removing more than one nucleon; see J. N. Ginocchio, Phys. Rev. C 17, 195 (1978).
[16]L. Valentin, Nucl. Phys. 62, 81 (1965).
[17]G. F. Bertsch (private communication).
[18]P. Varghese, R. R. Silbar, and M. M. Sternheim, Phys. Rev. C 14, 1893 (1976), especially footnote 11.
[19]A. S. Clough *et al.*, Nucl. Phys. A143, 385 (1970).
[20]R. R. Doering *et al.*, Phys. Rev. Lett. 35, 1691 (1975).
[21]Yu. R. Gismatullin, V. I. Ostroumov and V. A. Plyushchev, Yad. Fiz. 13, 478 (1971) [Sov. J. Nucl. Phys. 13, 268 (1971)].
[22]Yu. A. Berdnikov, dissertation, Leningrad Polytechnical Inst., 1977 (unpublished); Ya. A. Berdnikov *et al.*, Yad. Fiz. 27, 599 (1978) [Sov. J. Nucl. Phys. 27, (1978)].
[23]E. Bellotti *et al.*, Nuovo Cimento 14A, 567 (1973).
[24]C. Guaraldo *et al.*, Frascati Report No. LNF-77/27(P), 1977 (unpublished).
[25]Although R_2 involves different final nuclei, the fragility factor may not be too important here. For $T=0$ targets these are mirror muclei. Moreover, the experiments of Refs. 21 to 24 do not necessarily require the residual nuclei to be particle-stable.