Isovector Couplings for Nucleon Charge-Exchange Reactions at Intermediate Energies

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The isovector parts of the effective nucleon-nucleon interaction are studied by examination of the reaction $^{14}C(p,n)$ at intermediate energies near zero momentum transfer with use of recently developed G-matrix and free-t-matrix interactions. The spin-independent coupling (V_τ) exhibits a strong energy and density dependence which, in the case of the G matrix based on the Bonn potential, significantly improves the agreement between calculated values of $|V_{\sigma\tau}/V_\tau|^2$ at $q=0$ and those recently extracted from the reaction $^{14}C(p,n)$.

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The measurement of zero-degree charge-exchange [e.g., (p,n)] cross sections at intermediate energies[1-3] has proven to be a powerful technique for studying the isovector part of the effective nucleon-nucleon (NN) interaction at small momentum transfer, as well as for extracting Gamow-Teller (GT) strengths[4] and strength distributions. A knowledge of these GT strength distributions is important both for understanding nuclear structure and for calibrating neutrino detectors[3] for use in solar-neutrino spectroscopy. The (p,n) measurements are usually interpreted in a distorted-wave approximation[1-3] in which the charge-exchange cross section at 0° is given approximately by

$$\frac{d\sigma}{d\omega}(0°) \simeq \left(\frac{\mu}{\pi\hbar^2}\right)^2 \frac{k_f}{k_i}\{N_\tau|V_\tau(0)|^2 B(\mathrm{F}) + N_{\sigma\tau}|V_{\sigma\tau}(0)|^2 B(\mathrm{GT})\}, \tag{1}$$

where $B(\mathrm{F})$ and $B(\mathrm{GT})$ are the squared Fermi and GT matrix elements,[1] $V_\alpha(0)$ is the interaction strength at zero momentum transfer, k_i (k_f) is the momentum of the incident (scattered) particle, and N_α is a distortion factor[5] at $\theta=0°$ for a transition of type α. Equation (1) neglects the noncentral parts of the interaction and is for a mixed (F and GT) transition such as occurs in odd-A nuclei. For a pure transition (of type α), only one of the terms contributes, giving

$$\sigma(\alpha) = \frac{d\sigma}{d\omega}(0°,\alpha) = K_\alpha N_\alpha B(\alpha)|V_\alpha(0)|^2, \quad K_\alpha = \left(\frac{\mu}{\pi\hbar^2}\right)^2 \frac{k_f}{k_i}. \tag{2}$$

When the ratio $B(\mathrm{GT})/B(\mathrm{F})$ for two transitions is known from β decay and the ratio of the corresponding zero-degree (p,n) cross sections is measured, the ratio $R^2=|V_{\sigma\tau}/V_\tau|^2$ may be extracted from

$$\frac{B(\alpha)}{B(\beta)}\left|\frac{V_\alpha}{V_\beta}\right|^2 = \frac{\sigma_\alpha}{\sigma_\beta}\frac{K_\beta N_\beta}{K_\alpha N_\alpha}, \tag{3}$$

provided one can make a reasonable estimate of the *ratio* of the distortion factors N_β/N_α. Values of R^2 extracted this way may also be compared with different NN effective interactions. When density-dependent G-matrix interactions are used, $V_{\sigma\tau}$ and V_τ should be interpreted as average values determined by the ground-state density where the transition takes place.

Once the ratio $|V_{\sigma\tau}/V_\tau|$ is known, Eq. (3) may be used to extract $B(\mathrm{GT})$ strengths from measurements of 0° cross-section ratios provided one knows $B(\mathrm{F})$ and the distortion-factor ratio $N_{\sigma\tau}/N_\tau$. It is usually assumed that the isobaric analog state exhausts 100% of the Fermi strength[4] and that $N_{\sigma\tau}/N_\tau$ is adequately given by distorted-wave calculations.

Extracted values of the ratio R^2 have been published earlier[3] for incident energies $T_p < 200$ MeV which agree reasonably well with the free NN t matrix (see Fig. 1). However, Alford *et al.*[2] and King *et al.*[5] have recently extended the empirical determination of R^2 to energies above 200 MeV where there are striking discrepancies with the free-t-matrix values, as illustrated in Fig. 1.

Here we examine these discrepancies by considering both R^2 and $\bar{R}^2 \equiv \sigma(\mathrm{GT},0°)/\sigma(\mathrm{F},0°)$ for the reaction $^{14}C(p,n)$ between 60 and 450 MeV where measurements of $\bar{R}^2$ (and extractions of R^2) exist. The pure Fermi

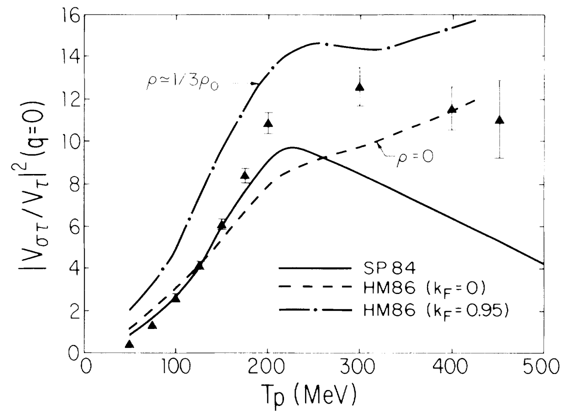

FIG. 1. Calculated and extracted values of R^2. The extracted values were obtained from the reaction $^{14}C(p,n)$ for $T_p \geq 200$ MeV; below 200 MeV the average values of Ref. 3 were used. Calculated values are described in the text.

(GT) transition is to the 0^+ (1^+) state at 2.31 (3.95) MeV. These particular transitions are especially important for the determination of R^2 and $\bar{R}^2$ because *both* $B(\mathrm{F})=2.0$ and $B(\mathrm{GT})=2.8$ are known[6] for the $A=14$ system from β decay. We consider three recently developed NN interactions: (a) a free-t-matrix interaction[7] based on the SP84 phases of Arndt and coworkers,[8] (b) a density-dependent G-matrix interaction[9] based on the Paris potential,[10] and (c) a density-dependent G-matrix interaction (HM86)[11] based on the most recent Bonn potential.[12] Differences in these interactions arise not only from nonequivalent fits to the NN data but also from different treatments of the nuclear medium in the construction of the G matrices. The (p,n) calculations were made in the nonrelativistic distorted-wave approximation; both direct and exchange terms were calculated explicitly.

Our motivation for considering G-matrix interactions as a means of resolving the discrepancy between values of R^2 extracted from (p,n) reactions and those calculated from the free NN t matrix stems from the fact that when V_τ is derived from a nuclear-matter G matrix, it is predicted to be strongly density dependent, whereas $V_{\sigma\tau}$ is predicted to depend very weakly on the local density. The predicted strong density dependence of V_τ has been known for some time[13] and is a common feature of all realistic NN potentials. Indeed, each component of the central interaction *except* $V_{\sigma\tau}$ exhibits[14] a strong density dependence below $\simeq 450$ MeV. Like the energy dependence,[15] this can be understood qualitatively in terms of the short- and long-range parts of the NN *potential*. In particular, the density dependence of the G matrices arises from short-range correlations and only $V_{\sigma\tau}$ is dominated by the long-range one-pion-exchange process; V_0, V_σ, and V_τ are dominated by short-range processes such as the exchange of heavier mesons, multiple pion exchange, etc. In addition to the above considerations, recent analyzing-power *data* for the isobaric analog transition in the reaction $^{48}Ca(p,n)$ suggest the need for a density-dependent V_τ.[14,16]

Figure 1 shows the values of R^2 extracted from data for the reaction $^{14}C(p,n)$ with use of Eq. (3) together with the SP84 t-matrix and HM86 G-matrix values at $\rho=0$ and $\rho \simeq \frac{1}{3}\times$normal density (ρ_0). By comparing the calculated cross-section ratios with R^2, we have verified that the transitions considered here take place near $\rho=\frac{1}{3}\rho_0$. The density-dependent effects are large; in particular, the increase in $R^2(\rho)$ with increasing ρ is primarily due to the suppression[13,14] of $G_\tau(\rho)$ at small momentum transfer as ρ increases. Horowitz[17] has also found a similar energy and density dependence of R^2 by including only Pauli-blocking effects. The differences between $G(\rho=0)$ and the SP84 t matrix are shown in Fig. 1. For $100 \lesssim T_p \lesssim 350$ MeV, the HM86 amplitudes provide a somewhat better description of the $n+p$ cross-section data near 180° than do the SP84 amplitudes.[18]

Although it is more transparent to compare R^2 (theory) with R^2 (experiment) as in Fig. 1, a comparison of measured and calculated *cross-section* ratios $(\bar{R}^2)$ is more direct and is shown in Fig. 2. The distorted-wave (p,n) calculations include the central, spin-orbit (V_τ^{LS}), and tensor (V_τ^T) parts of the three interactions mentioned earlier. In each case, the optical potential has been calculated in a folding model[14] with use of the corresponding t- or G-matrix interaction. The p-shell density for the GT transition is that labeled CKPOT of Taddeucci, Doering, Galonsky, and Austin[19] scaled to give $B(\mathrm{GT})=2.8$; the p-shell density (CKPOT) for the Fermi transition was provided by Taddeucci.[19] The G-matrix interaction based on the Bonn potential is seen to provide a considerably better description of the cross-section ratio than the other two interactions, especially below $\simeq 300$ MeV where the Paris and Bonn *potentials* were fitted to the NN data. Figure 2 also shows the measured[19] and calculated cross sections for the Fermi and GT 0° cross sections separately. In addition to the error bars shown, there is a systematic uncertainty[19] of $\simeq 10\%$ in the overall normalization of the absolute cross sections. The relatively slowly changing values of $\bar{R}^2$ for the Paris-Hamburg G matrix are seen to result from the nearly energy-independent values of the calculated Fermi *and* GT cross sections; the calculated GT cross sections using the Paris-Hamburg G-matrix interaction are in reasonable agreement with the data below 200 MeV where absolute cross-section data are available.[19] Overall, the G matrix based on the Bonn potential (HM86) yields the best agreement with the absolute and relative cross sections, especially below $\simeq 350$ MeV where its use is best justified.

The open circles correspond to the use of phenomenological optical potentials[20] with the isovector part of the HM86 interaction at 200 MeV and below where the re-

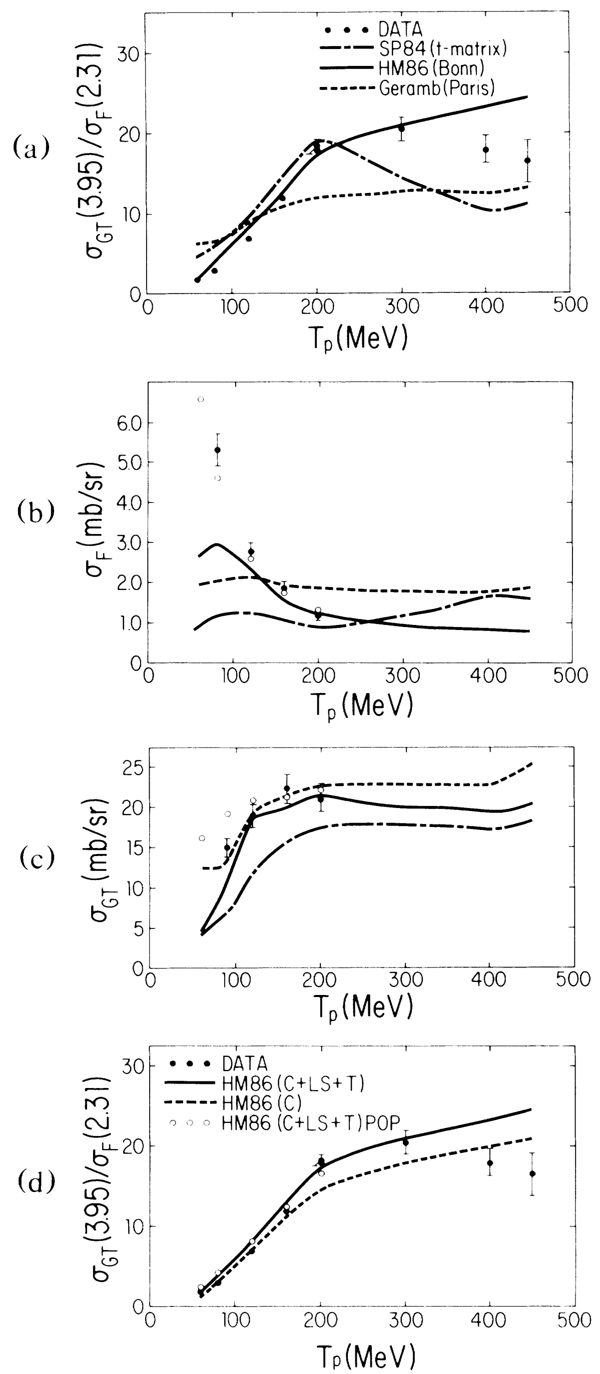

FIG. 2. (a) Measured and calculated ratios ($\bar{R}^2$) of the 0° cross sections for GT and Fermi transitions in the reaction $^{14}C(p,n)$. (b) Measured and calculated values of the 0° Fermi cross sections for the reaction $^{14}C(p,n)$. The curves (open circles) correspond to the use of folded (phenomenological, POP) optical potentials. (c) Measured and calculated values of the 0° GT cross sections for the reaction $^{14}C(p,n)$. (d) Measured and calculated values of $\bar{R}^2$ for the reaction $^{14}C(p,n)$. *C*, *LS*, and *T* denote central, spin-orbit, and tensor parts of the *NN* force.

sults are most sensitive to the type of optical potential used. The use of phenomenological optical potentials improves the agreement with the data for the Fermi transition significantly and slightly improves the agreement with the measured GT cross sections. The tendency of *G*-matrix calculations of the optical potential to overestimate the absorption below $\simeq 200$ MeV has been noted earlier.[14]

Figure 2(d) illustrates the role of the spin-orbit and tensor parts of the HM86 interaction and thus provides a measure of the uncertainties in the use of Eq. (3) for extracting R^2. In particular, the inclusion of V_τ^{LS} and V_τ^T increases the calculated values of $\bar{R}^2$ by $\simeq 15\%$ above $\simeq 120$ MeV. A similar increase in $\bar{R}^2$ also occurs for the other interactions. This increase in $\bar{R}^2$ is due to a *decrease* in the calculated values of $\sigma_F(0°)$ when V_τ^{LS} and V_τ^T are included; the corresponding change in $\sigma_{GT}(0°)$ is typically $\simeq 2\%$ above 100 MeV. The decrease in the calculated $\sigma_F(0°)$ arises primarily from the interference between V_τ^{LS} and V_τ. This interference depends strongly on the presence of optical-model spin-orbit distortion. The open circles in the bottom part of Fig. 2 illustrate the *insensitivity* of $\bar{R}^2$ to the use of phenomenological instead of folded optical potentials.

In summary, we have shown that the extracted ratio $R^2 = |V_{\sigma\tau}/V_\tau|^2$ is a sensitive test of the strong density dependence of V_τ which is a common property of realistic *G*-matrix interactions. Moreover, we find that there are significant differences between three of the most widely used effective *NN* interactions even at $\rho = 0$ and that these differences depend on energy. The HM86 interaction based on the Bonn potential provides the best overall agreement with the measurements of the ratio (and absolute values) of the GT and Fermi cross sections for the reaction $^{14}C(p,n)$. By considering cross-section ratios ($\bar{R}^2$) directly, we have calculated uncertainties in extracting R^2 which arise from the inclusion of spin-orbit and tensor forces as well as those which arise from the use of phenomenological instead of folded optical potentials. Above 100 MeV, the former uncertainty is calculated to be $\simeq 15\%$; the latter is only a few percent for the HM86 interaction. Finally, predictions of the absolute Fermi and GT cross sections for the reaction $^{14}C(p,n)$ at 0° have been provided above 200 MeV for each interaction.

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[1]C. D. Goodman *et al.*, Phys. Rev. Lett. **44**, 1755 (1980); B. D. Anderson *et al.*, Phys. Rev. Lett. **45**, 699 (1980).

[2]W. P. Alford *et al.*, Phys. Lett. B **179**, 20 (1986).

[3]T. N. Taddeucci *et al.*, Phys. Rev. C **25**, 1094 (1981); J. Rapaport *et al.*, Phys. Rev. Lett. **54**, 2325 (1985).

[4]C. D. Goodman, Comments Nucl. Part. Phys. **10**, 117 (1981); G. F. Bertsch, Comments Nucl. Part. Phys. **10**, 91 (1981).

[5]N. S. P. King *et al.*, Phys. Lett. B **175**, 279 (1986).

[6]F. Ajzenberg-Selove, Nucl. Phys. **A449**, 1 (1986).

[7]M. A. Franey and W. G. Love, Phys. Rev. C **31**, 488 (1985).

[8]R. A. Arndt *et al.*, Phys. Rev. D **28**, 97 (1983); R. A. Arndt and L. D. Roper, unpublished.

[9]H. V. von Geramb, in *Interaction Between Medium Energy Nucleons in Nuclei—1982,* edited by H. O. Meyer, AIP Conference Proceedings No. 97 (American Institute of Physics, New York, 1983), p. 44.

[10]M. Lacombe *et al.*, Phys. Rev. C **21**, 861 (1980).

[11]K. Nakayama and W. G. Love, unpublished.

[12]R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149**, 1 (1987).

[13]W. G. Love, Phys. Rev. C **15**, 1261 (1977); W. Bauhoff, Phys. Rev. C **30**, 734 (1984), and in *Medium Energy Nucleon and Antinucleon Scattering,* edited by H. V. von Geramb (Springer-Verlag, Berlin, 1985), p. 191; J. J. Kelly and J. A. Carr, in *Spin Excitations in Nuclei,* edited by F. Petrovich *et al.* (Plenum, New York, 1984), p. 253.

[14]W. G. Love, Amir Klein, and M. A. Franey, in *Antinucleon- and Nucleon-Nucleus Interactions,* edited by G. E. Walker, C. D. Goodman, and C. Olmer (Plenum, New York, 1985), p. 1; W. G. Love and Amir Klein, J. Phys. Soc. Jpn. **55**, 78 (1986).

[15]G. E. Brown, J. Speth, and J. Wambach, Phys. Rev. Lett. **46**, 1057 (1981).

[16]B. D. Anderson *et al.*, Phys. Rev. C **31**, 1147 (1985).

[17]C. Horowitz, to be published.

[18]W. G. Love, Amir Klein, M. A. Franey, and K. Nakayama, in Proceedings of the TRIUMF Workshop on Isovector Excitations in Nuclei, Vancouver, British Columbia, 1986, Can. J. Phys. (to be published).

[19]T. N. Taddeucci, R. R. Doering, A. Galonsky, and S. M. Austin, Phys. Rev. C **29**, 764 (1984); T. N. Taddeucci, private communication; T. N. Taddeucci *et al.*, Nucl. Phys. (to be published); J. Rapaport *et al.*, to be published; S. Cohen and D. Kurath, Nucl. Phys. **73**, 1 (1965).

[20]J. R. Comfort and B. C. Karp, Phys. Rev. C **21**, 2162 (1980).