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SPIN-FLIP VERSUS NON-SPIN-FLIP INTERACTION IN FORWARD (p,n) REACTIONS

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ABSTRACT

The ratio of the probabilities for triggering Gamow-Teller or Fermi transitions in forward (p,n) reactions is evaluated, using total and forward nucleon-nucleon cross-sections. Our results indicate that the ratio extracted from the (p,n) reaction is not consistent with the free nucleon-nucleon data.

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Forward (p,n) reactions at intermediate energies ($100 \div 200$ MeV) have been extensively used to measure the Gamow-Teller (GT) strength in nuclei^{1),2)}. Because the process does not have the kinematic limitations of β decay, a wide excitation energy range is accessible. This allows one to set bounds on sum rules which are sensitive to the non-nucleonic content of the nuclear ground state. This has been studied in the standard approach of isobar mixing³⁾, but it has also been suggested⁴⁾ that quark degrees of freedom may be relevant. In this letter, we point out that the analysis of forward (p,n) reactions leading to the determination of the GT strength may not be consistent with nucleon-nucleon (N,N) scattering.

The extraction of GT strength from forward (p,n) cross-sections proceeds through the distorted wave Born impulse approximation (DWBIA). The reaction amplitude is computed from the free (N,N) scattering operator sandwiched between distorted waves generated by a phenomenological optical potential. In the forward direction, the inelastic cross-section comes out as the GT or Fermi strength (B_{GT} or B_F) of the transition multiplied by a distortion factor (N_{GT} or N_T), and by the probability ($|V_{GT}|^2$ or $|V_T|^2$) of inducing a GT or Fermi transition²⁾. The distortion factors vary little from state to state and can be related to each other by the DW calculation with confidence, thus allowing a determination of the unknown B_{GT} if one of the states has its B_{GT} measured in β decay. If this is not the case, the GT strength can be related to the Fermi strength provided the ratio $R = |V_{GT}/V_T|$ is known.

The ratio R is of utmost importance since, on the one hand, it is a consequence of the working hypothesis that it can be computed from the free (N,N) scattering operator and, on the other hand, it can be measured⁵⁾ from the few cases where both B_{GT} and B_F are known from β decay. Agreement between the computed ratio and the experimental one must be considered as a necessity for the consistency of the approach. A sizeable discrepancy should be the signal that something is going wrong, be it the renormalization of the (N,N) interaction or of the scattering operator in nuclear matter, multiple scattering or anything else. Whatever the origin of a discrepancy, its existence would indicate that one is not able to measure B_{GT} or B_F . Instead, one is obtaining something more complicated which embodies other effects. Therefore, it is crucial to settle this point.

The ratio R has been measured⁵⁾ from threshold to an incident proton energy of 200 MeV. Its energy dependence turns out to be linear with small fluctuations in value from nucleus to nucleus. The straight line is shown in Fig. 1, together with a few experimental points to indicate the accuracy. We have also

plotted the value of R as obtained by Love and Franey⁶⁾ from a parametrization of (N,N) scattering fitted to phase shifts. The agreement between data and Love and Franey's results breaks down above 150 MeV, but one may invoke a caveat either in the parametrization or in the phase shifts, which may fail for this particular observable. For instance, it has been shown⁷⁾ that the use of another set of phase shifts suppresses the discrepancy between the theoretical and experimental R . For proton-neutron forward amplitudes, phase shifts are in severe difficulties⁸⁾ so that, ideally, one should compute R directly from experimental charge exchange data. Unfortunately, this requires difficult polarization experiments⁷⁾, which have not been carried out with sufficient accuracy. However, making use of dispersion relations, it is possible to express R in terms of quantities either measurable, such as forward and total (N,N) cross-sections, or calculable.

As is well known⁷⁾, R can be written in terms of Hoshizaki's amplitudes a, m, h ⁹⁾, evaluated for the forward direction:

$$R = \left[\frac{1}{3} \frac{2 |m^{cex}|^2 + |m^{cex}| + 2 |h^{cex}|^2}{|a^{cex}|^2} \right]^{\frac{1}{2}} \quad (1)$$

where the charge exchange amplitudes are related to the elastic (p,p) and (p,n) ones by (T stands for a, m , or h):

$$T^{cex} = T^{pp} - T^{pn} \quad (2)$$

Expression (1) is obtained from the forward nuclear (p,n) reaction cross-section computed in plane wave impulse approximation and neglecting Fermi motion. The difference with respect to the full DWBIA calculation goes into the distortion factor, which has already been taken into account in the experimental curve for R . The neglect of Fermi motion is consistent with the DWBIA analysis leading to the determination of R because it takes the (N,N) amplitudes at the momenta corresponding to a fixed nucleon target¹⁰⁾. Anyway, it has been shown⁷⁾ that the Fermi motion effect on R is very moderate and becomes negligible above 200 MeV.

Expressing R as far as possible in terms of measurable quantities, one gets:

$$R = \sqrt{\frac{1}{3}} \left[\frac{16 \pi \frac{d\sigma^{cex}}{dt}(t=0)}{(\sigma_{tot}^{pp} - \sigma_{tot}^{pn})^2 (1 + \rho_{cex}^2)} - 1 \right]^{\frac{1}{2}} \quad (3)$$

with

$$\rho_{\text{cex}} = \frac{\rho^{\text{pp}} \sigma_{\text{tot}}^{\text{pp}} - \rho^{\text{pn}} \sigma_{\text{tot}}^{\text{pn}}}{\sigma_{\text{tot}}^{\text{pp}} - \sigma_{\text{tot}}^{\text{pn}}} \quad (4)$$

and ρ^{pp} , ρ^{pn} are the ratios of real to imaginary part of the spin-averaged forward amplitude $a(\theta = 0)$ of (p,p) and (p,n) elastic scattering respectively.

The forward charge exchange differential cross-section is well known above 300 MeV from recent measurements at LAMPF¹¹⁾ and SIN¹²⁾, and above 800 MeV from that of Bizard et al.¹³⁾. Below 300 MeV, the data [refer, for instance, to the compilation of (N,N) scattering data by Bystricky and Lehar¹⁴⁾] are old and subject to normalization uncertainties which we overcome by comparison with the (N,N) forward amplitudes calculated by Grein et al.⁸⁾ via dispersion relations using total cross-sections in pure spin states as input.

The proton-proton total cross-sections are well measured⁸⁾, as are ρ^{pp} , from Coulomb interference measurements. Dispersion, as well as phase shift analyses, are in excellent agreement with the data.

A problem appears with the total neutron-proton cross-sections. Whereas the previous data¹⁵⁾ agree rather well with each other, they differ from a new measurement performed at LAMPF¹⁶⁾ by an amount up to 3 mb around 500 MeV.

The only unmeasured quantity appearing in Eq. (4) is ρ^{pn} , and here we have to make use of the forward amplitudes obtained from the dispersion relation⁸⁾ [tables are given in Ref. 17)]. We would like to stress that ρ^{pn} is a well-defined quantity and in good agreement with values reconstructed from phase shifts analysis.

Using this information, we obtain the results shown in Fig. 1. Above 100 MeV, our values for R are definitively at variance with those obtained from nuclear data. The rapid drop above 300 MeV is a mere reflection of the well-known dispersion shape - the real part of a^{cex} is at its maximum value at the energy where its imaginary part crosses zero ($\sigma_{\text{tot}}^{\text{pp}} = \sigma_{\text{tot}}^{\text{pn}}$ at about 600 MeV). This leads to a minimum in R around 700 MeV. After a slight rise in the region around 1 GeV, R will tend to zero asymptotically.

In order to demonstrate that the observed discrepancy is not due to the calculated ρ^{pn} but is a consequence of (N,N) scattering data, we also show an upper bound for R which is solely fixed by the experimental data, namely:

$$R = \sqrt{\frac{1}{3}} \left[\frac{16\pi \frac{d\sigma^{cex}}{dt}(t=0)}{(\sigma_{tot}^{pp} - \sigma_{tot}^{pn})^2} - 1 \right]^{\frac{1}{2}} \quad (5)$$

This bound is evaluated alternatively with the σ_{tot}^{pn} data of Ref. 15) and with those of Ref. 16). Except for this uncertainty, the bound is well determined, and one can see that the nuclear data are clearly above it. The troubling point is that the discrepancy gets worse as the incident energy increases. At 200 MeV, it would correspond to about a factor 1.6 in a ratio of cross-sections. Knowing that charge exchange transitions occur mainly at the surface of the nucleus, where the density is low, one can hardly invoke renormalization of the scattering matrix due to Pauli blocking or anything else as an obvious explanation for the disease¹⁸⁾. Nevertheless, it may be worth noticing that the worst discrepancy occurs in the region where the real part of a vanishes (in this case, the upper bound and the full calculation coincide: see Fig. 1), so that moderate nuclear matter effects may be magnified. This could be verified by measuring R in a region where the real part of a is non-zero, for instance around 400 MeV. ($^3\text{He}, t$) experiments performed in the corresponding energy range do indicate¹⁹⁾ that at 400 MeV the experimental R is close to the value predicted by (N, N) scattering. However, it is not established that the value of R in (p, n) and in $(^3\text{He}, t)$ reactions is the same. The comparison may then be hazardous.

We have eliminated most of the ambiguities in the calculation of R coming from the (N, N) scattering input. It is now necessary to determine the error in the DWBIA analysis of forward (p, n) reactions. The measurement of R at higher energies would be of great help for this concern.

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FIGURE CAPTION

The parameter R versus proton laboratory energy. The dotted line is the fit of Ref. 5) to nuclear data. The full circles are typical experimental points used for the fit. Distortion correction has been extracted. The open circles are the results of Love and Franey⁶⁾. The solid (dashed) and dashed-dotted lines are the upper bound obtained from free nucleon-nucleon scattering using the $\sigma_{\text{tot}}^{\text{np}}$ data of Ref. 15) [Ref. 16)], and the full result, including the real part of a , respectively. The bars indicate typical errors.

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