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Continuum charge-exchange spectra and the quenching of Gamow-Teller strength

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Charge-exchange spectra for the $^{90}Zr(p,n)$ reaction at 200 MeV are calculated over the range $-70 \leq Q_{pn}$ (MeV) ≤ 0, in an effort to assess the degree of quenching and/or redistribution of Gamow-Teller strength. Comparison with the data suggests that the mixing of 1p-1h with 2p-2h states provides the most plausible explanation of the missing Gamow-Teller strength. Predicted spectra for anticipated (n,p) data are also presented and it is indicated how such data may provide additional insight into the issue of missing Gamow-Teller strength.

One of the most exciting recent developements in nuclear physics has been the systematic observation of isovector spin-flip excitations in the (p,n) reaction[1] which has spawned an intriguing problem related to the Gamow-Teller (GT) resonance. At incident-proton energies above ~ 100 MeV this resonance is seen clearly in the forward angle spectrum near the isobaric analog state (IAS). Although the location of these GT resonances are reasonably well described by theory,[2] the total GT transition strengths, deduced from analyses of (p,n) data, are significantly smaller than those predicted by nearly model independent sum rules.[1]

The two mechanisms which have been most often suggested for the suppression of the observed GT strength are (a) Δ-hole admixtures in the GT region of the spectrum resulting in some GT strength being shifted to about 300 MeV excitation energy[3] and (b) the coupling of high-lying two-particle-two-hole (2p-2h) configurations to the low-lying 1p-1h configurations which can result in the GT strength being fragmented and spread over a large energy interval.[4–6] Bertsch and Hamamoto[6] have estimated that this type of configuration mixing may account for the removal of as much as 50% of the GT strength to the energy region of 15–45 MeV for the nucleus ^{90}Zr. In this higher energy region other resonances can contribute significantly to the (p,n) cross section. To assess the importance of the suggested quenching mechanisms (a) and (b) it is extremely important to calculate the (p,n) cross sections as reliably as possible over a wide range of excitation energy and to compare them with the experimental ones. In previous calculations,[7,8] a direct reaction mechanism has been assumed. In Ref. 7, random phase approximation (RPA) wave functions have been used, but a very schematic nucleon-nucleon force has been used to obtain the charge exchange cross sections. In Ref. 8 the effects of ground state correlations and of the residual interaction on the nuclear excited states have been neglected; these effects are important for calculating excitation energies and strengths.[2,9] In the present work both correlated 1p-1h states and a realistic projectile-target nucleon interaction are used in the detailed evaluation of (p,n) cross sections for that part of the spectrum near the GT resonance and several tens of MeV above.

Here, we consider the $^{90}Zr(p,n)$ reaction at 200 MeV incident energy where experimental data[10] already exist. The reaction calculations are made within the single-scattering distorted-wave approximation which should be reasonable for negative Q values up to several tens of MeV at forward angles.[11] The effective nucleon-nucleon interaction used in the scattering calculations is an updated version of that in Ref. 12, and provides a quantitative description of experimental cross sections at small momentum transfer for reactions in which isovector spin-flip states are excited.[12,13] The knock-on exchange terms associated with the central parts of the effective interaction are included in a well-established short-range approximation.[14] The knock-on exchange term arising from the tensor force is neglected. It has been verified by explicit calculations that the contribution of this term to the total cross section and to the spin-flip probability is small at the small momentum transfers considered. The very small[12] isovector spin-orbit term is also omitted from our calculations. Empirical optical model parameters were taken from Ref. 15 for the entrance channel at $E_p = 200$ MeV; for the exit channel at all excitation energies the parameters were taken from Ref. 16. The reaction calculations were made using the codes ALLWRLD[17] and DWBA70.[18]

The basic element of nuclear structure in the single-scattering approximation is the transition density as a function of the excitation energy. We obtain the transition density by using the charge-exchange Hartree-Fock random-phase-approximation (HF-RPA) framework,[19] which has been quite successful in calculations of other charge-exchange processes.[19] The Skyrme III (SIII) force[20] is used to generate the HF single-particle potential. The residual interaction used is of zero range; its form follows from the general form of the self-consistent residual interaction corresponding to forces of the Skyrme-type[21] when the density-dependent and velocity-dependent terms are dropped. The omission of such terms is expected to be best in the vector-isovector channel[22] where the exchange of π and ρ mesons dominates. The strength of the interaction is taken to be $t = -934$ MeV fm^3 and the value of the neutron-proton asymmetry coefficient is $x = 0.5$. HF-RPA calculations using this residual interaction reproduce reasonably well the experimental energies[23] of known isovector spin-flip states,[9] which are preferentially excited near 200 MeV by the nucleon projectile.[12] The single-particle continuum is discretized by using box-boundary conditions for positive energy states, the size of the box being 15 fm. The 1p-1h configuration space is truncated at 200 MeV, and, to compensate for the escape and spreading widths, we smooth the strength distribution with a Lorentzian function whose full width at half maximum is taken to be 2 MeV. The RPA average excitation energies and transition strengths calculated within the framework described above are nearly identical with the results obtained in Ref. 9, where the continuum HF-RPA has been used. The transition densities are calculated using a technique described in Refs. 9 and 19. For natural parity states, both $S=0,1$ amplitudes are calculated. For unnatural parity excitations ($S=1$ only), amplitudes corresponding to orbital angular momentum transfer to the target of $L=J\pm1$, and the interference caused by the tensor force is included.

The (p,n) spectrum was calculated by summing the contributions due to transitions involving $J^\pi \leq 5^+$ (excluding 5^-). The convergence achieved is good for $\theta \lesssim 10°$. For example, the 5^+ transitions contribute less than 1% of the cross section at 0° and about 2% at 10°. As illustrative examples, the theoretical and the experimental[10] double differential cross sections are shown in Fig. 1 as a function of the reaction Q value for $\theta = 0.2°$, 4.5°, 9.5°. The cross section for the narrow IAS (only 5.2 mb/sr at 0.2°) is not shown. Essentially all of the theoretical GT strength is located in the two large peaks in the $\theta = 0.2°$ spectrum at $Q_{pn} = -17$ and -8 MeV. Experimentally these peaks are located at -15.6 and -9.2 MeV, respectively. The peak in the calculated spectrum at $Q_{pn} = -29$ MeV is due to $L=1$ ($J^\pi = 0^-, 1^-, 2^-$) transitions, and the structure in the theoretical spectra for $\theta = 0.2°$ and $\theta = 4.5°$ around $Q_{pn} = -40$ MeV is mainly due to the spin-isovector monopole resonance,[9] which is a $J^\pi = 1^+$, $L=0$ transition of a non-GT character. Of course, the widths of the calculated peaks, but not their strengths, depend upon the magnitude of the averaging interval used.

We find that the low energy [$-23 \lesssim Q_{pn}(\mathrm{MeV}) < 0$] part of the excitation spectrum at very forward angles is strongly dominated by the GT resonance. This feature has been noted in previous calculations.[7,8] It is, therefore, convenient to discuss the Q-value regions $-23 \leq Q_{pn}(\mathrm{MeV}) \leq 0$ and $-70 \leq Q_{pn}(\mathrm{MeV}) \leq -23$ separately. In the former region, the GT resonance contributes about 94% of the theoretical energy-integrated cross section at 0°, while in the latter region, its contribution is negligible. The value of Q_{pn} used to separate the two regions is somewhat arbitrary, as it depends on the magnitude of the averaging interval used in the RPA calculations. In Table I we show the theoretical and the experimental cross sections integrated over the two energy intervals. Examination of the

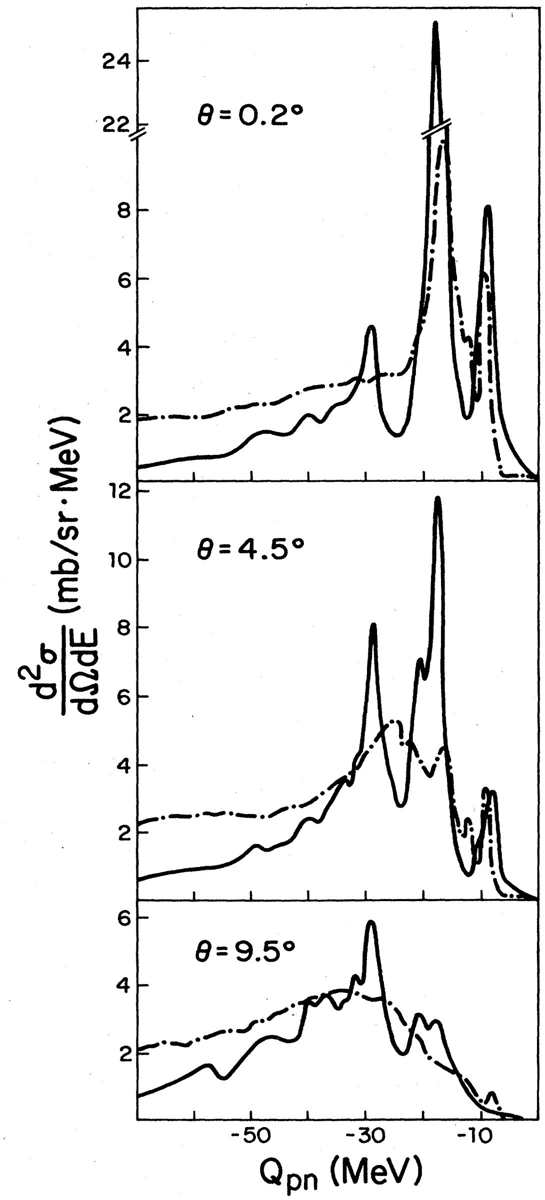

FIG. 1. Spectra for the reaction ^{90}Zr(p,n) at $E_p = 200$ MeV. The continuous lines represent the calculated cross sections, and the dot-dashed lines the data (Ref. 10).

TABLE I. Calculated and experimental (in parenthesis) cross sections for the ^{90}Zr(p,n) reaction at $E_p = 200$ MeV integrated over selected Q-value ranges for different scattering angles. The uncertainty in the data is 15%.

Angle	$-23 \leq Q_{pn} \leq 0$ MeV		$-70 \leq Q_{pn} \leq -23$ MeV		$-50 \leq Q_{pn} \leq -23$ MeV	
0.2°	129.6	(79.0)	67.1	(112.0)	52.9	(73.0)
2.5°	107.3	(66.0)	81.2	(116.0)	65.9	(80.0)
4.5°	73.1	(49.0)	100.5	(140.0)	83.0	(95.0)
7.0°	38.5	(31.0)	114.9	(144.0)	90.8	(100.0)
9.5°	24.2	(23.0)	111.0	(139.0)	84.9	(91.0)

results for $-23 \leq Q_{pn}(\text{MeV}) \leq 0$ shows that the calculated cross sections are larger than the data by a factor of 1.5–1.6 at very forward angles, where the GT states dominate ($\sim 35\%$ missing GT strength), but are close to the measured cross sections at 7.0° and 9.5°. On the other hand, the calculated strength for $-70 \leq Q_{pn}(\text{MeV}) \leq 23$ is smaller than the experimental one at all angles with the relative difference decreasing with increasing angle. A part of this discrepancy may be attributed to multistep processes, whose contribution for energy losses as large as 60–70 MeV may be important relative to the one-step processes included in our calculations. In Table I are also shown the calculated and measured cross sections integrated over a narrower energy interval $[-50 \leq Q_{pn}(\text{MeV}) \leq -23]$, where the multistep processes are expected to be smaller. In this segment of the spectrum the theoretical results are in reasonable ($\sim 10\%$) agreement with the experimental ones at 4.5°, 7.0°, 9.5°, but at very forward angles the calculations underestimate the data by $\sim 30\%$.

The picture suggested by our analysis is that at least part of the GT strength which is missing from the low energy portion of the experimental spectrum is present at excitation energies well beyond the values predicted by the 1p-1h model. This picture is consistent with the suggestions of Ref. 6. To obtain a more accurate estimate of the total amount of GT strength in the (p,n) continuum would require calculating the (p,n) cross section with nuclear wave functions which include the coupling of 1p-1h configurations to more complicated ones. This is not done here.

It is curious to note that if we remove 12 of the 30 $[3(N-Z)]$ units of GT strength from the theoretical spectrum in the interval $-23 \leq Q_{pn}(\text{MeV}) \leq 0$, which corresponds to 50 mb/sr at 0.2°, 38 mb/sr at 2.5°, etc., and spread this strength over the region $-50 \leq Q_{pn}(\text{MeV}) \leq -23$, about 27 mb/sr will be added to the theoretical cross section in this region at 0.2°, 22 mb/sr at 2.5°, 10 mb/sr at 4.5°, etc., and we would obtain good agreement with experiment even at very forward angles. This suggests that the amount of GT strength removed to very high energies due to Δ-isobar admixtures is likely to be rather small.

If the redistribution of GT strength takes place as described above it should be extremely interesting to examine the (n,p) spectrum at intermediate energies in medium to heavy mass nuclei where little GT strength is expected. If the redistribution of a forward angle cross section involves primarily GT excitations, the measured and calculated (n,p) spectra should be in much better agreement. In anticipation of such measurements at TRIUMF and perhaps IUCF and LAMPF we have also calculated the (n,p) spectrum at $E_n = 200$ MeV. The predictions for $\theta = 0°$ are shown in Fig. 2.

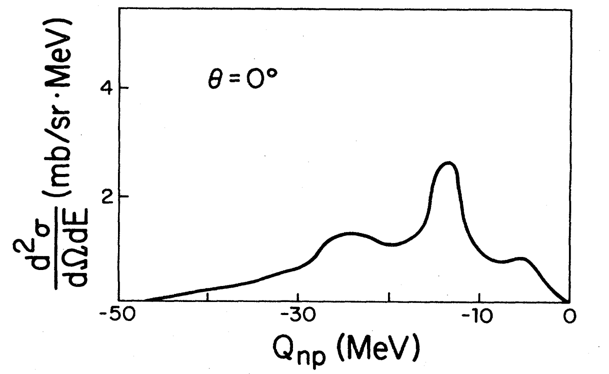

FIG. 2. Calculated zero degree spectrum for the reaction ^{90}Zr(n,p) at $E_n = 200$ MeV.

Although calculations like those reported here are quite tedious, they need to be made and compared with experimental data for different targets and at more than one incident energy in order to get a better understanding of the redistribution of GT strength. The importance of the issue of GT quenching to our understanding of spin degrees of freedom in the nucleus merits such an effort.

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