THE "MISSING" GAMOW-TELLER STRENGTH AND THE CONTINUOUS (p,n) SPECTRA

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Abstract

Microscopic analyses of complete forward angle intermediate energy (p,n)-spectra are presented for the reactions ${}^{90}Zr(p,n)$, ${}^{208}pb(p,n)$ and ${}^{42}Ca(p,n)$. It is shown that the whole spectra up to an excitation energy of $E_x = 70$ MeV are the result of correlated one-particle-one-hole (lplh) spin-isospin transitions only. The spectra reflect, therefore, the linear spin-isospin response of the target nucleus to the probing (p,n) field. We find a large amount of the "missing" Gamow-Teller strength in the continuum part of the 0° spectrum. Then the total amount of Gamow-Teller strength observed in these nuclei is close to the lower sum rule limit of 3(N-Z).

I. Introduction

Recent (p,n) experiments on many nuclei throughout the periodic table¹⁻⁶⁾ have led to the discovery that systematically a large fraction of the minimum Gamow-Teller (GT) strength of 3(N-Z) is missing in the excitation energy region where the shell model would predict it to be. Three physically different mechanisms have been discussed to explain this so-called quenching of the total GT strength. The first is that $\Delta(1232)$ -isobar-nucleon-hole (ΔN^{-1}) states couple into the proton-particleneutron-hole (pn⁻¹) GT states and remove strength from the low-lying excitation spectrum⁷⁾. Here the internal degrees of freedom of the nucleon, specifically the Δ , are made responsible for the quenching of the GT strength. The second mechanism is ordinary nuclear configuration mixing $^{8-10}$, where energetically high-lying twoparticle-two-hole (2p2h) states mix with the low-lying one-particle-one-hole (lplh) GT state and shift GT strength into the energy region far beyond the GTR. The third possibility 11-14, closely connected with the second mechanism, is that a large fraction of GT strength is actually located in the physical background below and beyond the giant GT state and is therefore escaping experimental detection.

In this contribution, we discuss the question of the missing GT strength by starting from the measured (p,n)-spectra at different scattering angles θ . We develop a microscopic model which permits us to calculate the spectra at all scattering angles in a consistent way. The model wave functions for the nuclear excited states are generated from microscopic random phase approximation (RPA) calculations. Two different configuration spaces are used: in the first one we consider the nucleus to consist of nucleons only, whereas in the second one Δ isobars are also included explicitly. Using these two different sets of wave functions we analyze 90 Zr(p,n)-and 208 Pb(p,n)-data at 200 MeV incident energy as well as 42 Ca(p,n)-data at 160 MeV. We show that essentially all the measured cross sections up to an excitation energy of E_X = 70 MeV are produced by 1p1h spin-isospin excitations. Our calculations describe not only the peaks in the spectra but also the continuous parts which are usually termed background.

Since we analyze the experimental spectra in the whole excitation range from $E_x = 0$ to 70 MeV and in the whole angle range from 0 to 18.7 deg, we are in a good position to make reliable statements about the total amount of spin-isospin transition strength observed in the (p,n) reactions and about the question of whether or not there is need for quenching of GT strength (or generally spin-isospin strength) due to Δ isobars. By considering the whole spectra we exclude two major uncertainties which usually occur in the analysis of the data. First, we have no background problem because we calculate the whole spectra. Second, uncertainties in the strength extraction which are produced by the 2p2h nuclear configuration mixing mechanism are minimized because we investigate the spectra up to very high excitation energies. If there should exist a strong shift of lp1h transition strength to high excitation energies (due to the 2p2h configuration mixing effect), we will see this directly from the analysis of the data.

II. The Structure Calculations

To analyze the experimental spectra we have to make assumptions about the nuclear excitation spectrum and about the reaction mechanism. In our calculations we assumed that the nuclear excited states can be described reasonably well by microscopic RPA wave functions. The RPA calculations were performed in a large model space which included all $3\hbar\omega$ ($4\hbar\omega$) ph excitations in case of 90 Zr (208 Pb) and all $6\hbar\omega$ ph excitations in case of 42 Ca. For 90 Zr we also performed a calculation with explicit Δ isobar degrees of freedom¹³). The ΔN^{-1} configurations included all orbits from 1s to 1j.

For the residual ph interaction we used a realistic interaction which includes the one-pion (π) and one-rho (ρ) exchange potentials in the $\sigma\tau$ -channel explicitly. The effects of the other mesons were summarized in a two-body correlation function and an additional zero-range term. The explicit form of the ph interaction is given in Ref. 13.

The generalized RPA wave functions including ΔN^{-1} configurations are then given by

$$\Psi^{J} = \left[\sum_{ph} \chi^{J}(ph)a_{p}^{+}a_{h} + \sum_{\Delta h} \chi^{J}(\Delta h)a_{\Delta}^{+}a_{h}\right]|g.s.$$
(1)

where $x^J(ph)$ and $x^J(\Delta h)$ are the RPA transition amplitudes of the $|NN^{-1}\rangle$ and $|\Delta N^{-1}\rangle$ configurations, respectively.

III. The Reaction Calculations

From the wave functions of eq. (1) we calculated the (p,n) cross sections with the fast speed DWIA code FROST-MARS which includes knock-out exchange amplitudes ex $actly^{15}$. For the effective projectile-target nucleon interaction we used the free nucleon-nucleon (NN) t-matrix in the parametrization of Love and Franey 16). For the effective projectile-isobar interaction we employed the one-pion and one-rho exchange potentials assuming the Chew-Low¹⁷⁾ values $f_{\pi N\Delta} = 2f_{\pi NN}$ and $f_{\rho N\Delta} = 2f_{\rho NN}$ for the nucleon-isobar coupling constants. In either case of using RPA or RPA+ Δ wave functions the effective projectile-target nucleon interaction was calibrated to the β -decay in order to guarantee a force independent analysis of the (p,n)spectra. For the calibration procedure we chose the transition 42Ca(0⁺)+42Sc(1⁺, $E_v = 0.61$ MeV) which possesses a B(GT) value of 2.57 (log ft = 3.17) and a large 0° (p,n) cross section. (For details of the calibration procedure see Ref. 13.) The same transition is also used by the experimentalists $^{4-6}$ to normalize measured zero degree (p,n) cross sections to β -decay. We remark that by this normalisation procedure one calibrates only the absolute magnitude of the effective interaction at q=0, but not yet its q dependence. The latter can be checked, however, by analyzing angular distributions of inelastic or charge exchange reactions to states with known nuclear structure. The q dependence of the $\sigma\sigma\tau\tau$ central and tensor components of the Love-Franey interaction¹⁶⁾ has been tested, for instance in Ref. 18, and found to be essentially in agreement with experiment.

Using the calibrated effective interaction, we can now go and analyze (p,n)-spectra taken for other target nuclei. The only uncertainty in going from 42 Ca to another target nucleus is the distortion of the projectile wave functions which changes with the target nucleus. It turns out, however, that in going from 42 Ca to 90 Zr, for instance, the uncertainty is not larger than 10 %. We checked this point by testing various sets of optical potential parameters $^{19-21}$ including those of wine bottle shape 21 . After all we decided to use the global parameter set of Nadasen et al. 19 which is given as a function of the incident energy E and the target mass number A. This choice gives us the possibility to employ optical parameters of the same potential family for different target nuclei. We want to point out, however, that at 200 MeV incident energy these parameters lead to a 10 % larger GT cross section in 90 Zr(p,n) than those determined from 200 MeV 90 Zr(p,p) elastic scattering data 20). Therefore, all our final conclusions in the next sec-

tion might include such an uncertainty. Unfortunately, there exist no experimentally determined optical model parameters for 42 Ca which would help to rule out this uncertainty. We also mention that there exists another uncertainty of the order of 10 % which is connected with the normalization of the 90 Zr(p,n) and 208 Pb(p,n) data relative to the 42 Ca(p,n) data 22 .

IV. Results and Discussion

IV.1 Analysis of 200 MeV ⁹⁰Zr(p,n)-spectra

In the microscopic model already described we have calculated energy spectra at various scattering angles for the reaction 90Zr(p,n) at 200 MeV incident energy. In Fig. 1 we show the results for the 0° and 4.5° spectra. The 0° spectrum in Fig. 1a is dominated by the GT 1⁺ transitions. Two different theoretical spectra are compared to the data⁴). One is calculated with usual RPA wave functions (full curve) and the other with generalized RPA wave functions which include \triangle isobar degrees of freedom (dashed curve). Both spectra are incoherent sums of cross sections with multipolarities L=0 through L=4 (J^T = 0⁺,0⁻,1⁺,1⁻,2⁺,2⁻,3⁺,3⁻,4⁻,4⁺,5⁺). From these states, the 0⁻,1⁻,2⁻ and 1⁺,2⁺,3⁺ states were calculated either with RPA or with RPA+ \triangle , while the 3⁻,4⁻,4⁺,5⁺ states were treated within the unperturbed 1p1h doorway model of Ref. 11 which includes the nuclear continuum exactly. The RPA model space included all 3ħ ω excitations so that the RPA states extend in excitation energies up to a Q value of Q = -40 MeV. The cross section beyond Q = -40 MeV is mainly due to states with E_X > 3ħ ω which were again treated within the unperturbed 1p1h doorway model of Ref. 11.

The continuous spectra in Fig. 1 were obtained by folding the cross sections to the discrete states into a Breit-Wigner form with a width taken from experiment. The width was assumed to be 1 MeV for states with excitation energies E_x smaller or equal to the energy of the IAS, to be 6 MeV for the GT resonance and other states with $E_x < 15$ MeV, and to be 10 MeV for states with $E_x > 15$ MeV. The width of the GT resonance had to be chosen asymmetrically in order to obtain a reasonably good fit to the experimental resonance shape. A total width of $\Gamma = 6$ MeV was needed and split into two parts $\Gamma = \Gamma_{1eft} + \Gamma_{right}$ with $\Gamma_{1eft} = 2$ MeV and $\Gamma_{right} = 4$ MeV. Then these widths were used in an asymmetric Breit-Wigner form. For the states with $E_x > 15$ MeV, we employed the widths $\Gamma_{1eft} = 2$ MeV and $\Gamma_{right} = 8$ MeV, respectively. By applying the described folding procedure to our cross section calculations we effectively simulate the damping (spreading) of the 1plh RPA doorway states due to their coupling to 2p2h and more complicated configurations.

From Fig. 1a, we see that the 0° spectrum calculated with RPA reproduces the shape of the experimental spectrum rather well, but that it slightly overestimates the

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Fig. 1: Neutron spectra from the reaction ${}^{90}Zr(p,n){}^{90}Nb$ at angles of $\theta = 0^{\circ}$ (a) and (b), and $\theta = 4.5^{\circ}$ (c) and (d). The data (thin full line) were taken from Ref. 4. The complete theoretical spectra in (a) and (c) were calculated either with usual RPA wave functions (thick full line) or with generalized RPA+ Δ wave functions (dashed line)¹³). In the latter case the Δ isobar admixtures were adjusted such that the total GT strength is quenched by 30 % (see the text). (b) and (d) show backgrounds (BGR) with respect to the GT resonance. The full line represents the result obtained with RPA, and the dashed line the one obtained with RPA+ Δ .

data in the low excitation energy region, while it underestimates them in the high excitation energy region. In order to bring theory and experiment into agreement in the low excitation energy region, one apparently has to introduce a quenching mechanism which reduces the amount of GT strength in the Q-value range -8 MeV>Q>-22 MeV. Two different quenching mechanisms have been proposed. In the first case the ΔN^{-1} states couple into the low-lying GT states and move part of the strength⁷) into the Δ resonance region. In the second case energetically high-lying 2p2h states mix into the lplh GT states and shift GT strength from the low (0 MeV>Q>-20 MeV) to the high (-20 MeV>Q>-70 MeV) excitation energy region⁸⁻¹⁰).

Let us first discuss the assumption that only the 2p2h effect is responsible for the quenching of the GT strength by shifting strength from the low to the high excitation energy region. This effect is to a large extent already included in our calculation since we folded the discrete RPA cross sections into an asymmetric strength distribution function of Breit-Wigner form. Note, however, that these

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strength distribution functions lead to much less shift (spreading) of strength microscopic 2p2h configuration mixing calculathan those obtained in tions 10, 23-26). The 2p2h strength distribution functions have a long high energy tail which falls off only gradually. To that respect we assume a minimal spreading of strength in our calculations. It is interesting to know up to which excitation energy the GT strength is extending under this assumption of minimal spreading. To show this we first determine the background with respect to the GT states in the measured spectra. The cross section area in the spectrum not described by the background calculations should then be GT strength. The result for the GT background of the O^O spectrum is shown in Fig. 1b. The full curve represents the result obtained with RPA and the dashed curve the one obtained with RPA+ ${f \Delta}$ (quenched background). The peak at Q = -12 MeV is due to the IAS and all the rest of the background cross section up to Q = -70 MeV is mainly due to the lhw L=1 and 2hw L=2 resonances whose angular distributions, although peaking at larger scattering angles (see Figs. 1c and 2), are extending forward to 0° . The full curve in Fig. 1b shows that there is only very little background just below the GT states. It shows furthermore that there has to be GT strength in the Q-value region -20 MeV>Q>-30 MeV which means that the GT strength indeed is extending beyond the main peak. Comparing the calculated spectrum in Fig. 1a with the background cross section in Fig. 1b, one notices that the extension of GT strength beyond the main peak actually follows in a very natural way from the line shape of the experimental GT resonance. With our assumption of minimal spreading the GT strength extends only up to Q = -40 MeV, which is a much smaller value than that derived from 2p2h configuration mixing calculations^{10,23-26)}.

The theoretical spectrum in Fig. 1a calculated with RPA slightly overestimates the experimental one in the Q-value range, O MeV>Q>-40 MeV. Considering this Q-value range we need a quenching of 15 % of the theoretical spectrum in order to bring experiment and theory into agreement. Unfortunately, we cannot decide whether this quenching should be due to the Δ isobar effect or due to additional spreading of both the GT strength and the L=1 and L=2 strength. A larger asymmetric spreading as required by 2p2h calculations would shift more strength to higher excitation energies. Such an additional shift would actually be welcome since the theory is underestimating the data at high negative Q values with the present widths.

We can, however, show that the Δ isobar effect cannot be very large, i.e., not 30 % or 50 % of the minimal sum rule limit $S_{\beta_{a}} = 3(N-Z)$ as was required by several authors⁷⁾. This can be seen from the dashed curve in Fig. 1a which is the result of a calculation performed with generalized RPA wave functions which include Δ isobar-nucleon hole components explicitly. The Δ isobar admixtures were adjusted such that the total B(GT) strength is quenched by 30 %. In spreading the strength, the same widths were used as in the RPA result. The spectrum calculated with RPA+ Δ underestimates the data everywhere and particularly strongly in the GT resonance region. Within the framework of our 1p1h model (RPA) where we neglect 2p2h admixtures into the ground state of 90 Zr there is obviously no need for such a large Δ isobar-nucleon hole quenching. Actually we underestimate the experimental zero degree (p,n) cross section by approximately 37 mb if we consider the whole Q-value range from 0 MeV>Q>-70 MeV. However, we also point out that the inclusion of ground state correlations of the 2p2h-type might modify this conclusion¹⁰.



Fig. 2: Same as in Figs. 1a and 1c, but now for the scattering angles $\theta = 9.5^{\circ}$, 12.8°, and 18.7°.

Particularly important for our discussion of the quenching of the total GT strength are the results for the high scattering angles at $\theta = 9.5^{\circ}$, $\theta = 12.8^{\circ}$, and $\theta = 18.7^{\circ}$ which are shown in Fig. 2. At these scattering angles the GT resonance gives a comparatively small contribution to the total (p,n)-spectrum. The

shape and magnitude of these spectra are therefore mainly determined by states of other multipolarities. Note that the theoretical spectra calculated with RPA provide in all cases a good description of the experimental data while the spectra calculated with RPA+ Δ tend to be too small in magnitude at small scattering angles ($\theta < 9.5^{\circ}$).

This good description of the small and large angle scattering data by our model calculations leads us to the following important conclusion: At 200 MeV incident energy the whole (p,n) spectra up to $E_x = 70$ MeV are a result of one-step processes only. Two-step processes with explicit excitation of 2p2h states are suppressed. This conclusion has important consequences for the interpretation of the forward angle (θ = 0°, 4.5°, and 9.5°) spectra. It implies that the experimental cross section area at large negative Q values in Figs. 1 and 2, which is not yet described by our calculations, should also be the result of one-step processes. This is, however, only possible if there exists additional lplh transition strength in the high Q-value region -40 MeV>Q>-70 MeV which produces forward peaked angular distributions, i.e., the latter have to be of L=O, L=1, or L=2 shape. All strength of this type, however, is already included in our calculations, but it is dominantly located in the low excitation energy region where it actually leads to too large theoretical cross sections. A simple and consistent solution to this problem can be obtained if we assume an even stronger spreading of the L=O, L=1, and L=2 strength to higher excitation energies than we have done so far. With this assumption the overestimate of the data by the theory at low excitation energies and small angles and the underestimate at high excitation energies would disappear, while the results for the large angle spectra remain essentially unchanged.

In view of the problems concerning the spreading of GT strength (and those of other resonances) due to the 2p2h configuration mixing effect, it seems to be advisable for a careful discussion of the Δ isobar quenching effect to work with energy integrated cross sections. In Table 1 we list the energy integrated experimental cross sections (second column) and the calculated ones (third column) as a function of the scattering angle 0. The integration interval extends from zero to Q = -70 MeV. The theoretical cross sections were calculated either with RPA or RPA+ Δ (numbers in parentheses). The RPA result reproduces the measured cross sections calculated with RPA+ Δ underestimate the corresponding experimental values at forward angles ($\theta = 0^0$, 4.5^0 , and 9.5^0) by about 20 % to 25 %. At $\theta = 18.7^0$ the cross sections based on RPA and RPA+ Δ are essentially the same and agree with experiment. From the results in Table 1 one might be tempted to conclude that there should be no quenching due to Δ isobars. This conclusion is, however, daring since we have so far not included the following important effect in our analysis of the

^e c.m. (deg)	σ _{exp} (mb/sr) O MeV>Q>-70 MeV	σ _{cal} (mb/sr) Ο MeV>Q>-70 MeV
0.0	215	232 (178)
4.5	212	211 (164)
9.5	203	192 (156)
12.8	150	164 (144)
18.7	102	102 (104)

<u>Table 1:</u> Energy integrated experimental and theoretical cross sections of 90Zr(p,n) spectra for different scattering angles θ . The theoretical cross sections were calculated either with RPA wave functions or generalized RPA+ Δ wave functions (numbers in parentheses). All numbers are subject to ~ 10 % uncertainty due to the choice of optical potential parameters.

data. Bertsch and Hamamoto 10 have pointed out that by shifting strength from the low to the high excitation energy region one simultaneously creates new strength at low excitations energies. This is due to the fact that a strong spreading of the lplh strength due to the admixture of 2p2h configurations also implies the presence of strong 2p2h correlations in the target nucleus ground state. From the point of view of perturbation theory both processes are of the same order in the residual ph interaction. The presence of strong ground state correlations, on the other hand, gives the possibility to create new GT strength which adds to the 3(N-Z) limit¹³). How much new strength is really created depends sensitively on the interference of the ground state correlations with the final state correlations. This interference is a coherent process making an estimate of the created strength rather difficult. In view of these problems we are led to draw the following conclusions with respect to the Δ isobar quenching effect in 90 Zr: Quenching due to A isobars is only needed if there exist large ground state correlations of 2p2h-type in 90Zr which create additional GT strength above the 3(N-Z) limit. Otherwise, the (p,n) cross sections are compatible with the strength predictions as obtained from the usual RPA. The strength has to be spread out, however, over a relatively large energy range.

IV.2 Analysis of the 208 pb(p,n) reaction at E_n = 200 MeV

For the 208 Pb(p,n) reaction we have performed a similar analysis of the forward angle (p,n)-spectra as for 90 Zr. The case 208 Pb is especially interesting because the RPA works best in this nucleus and describes excitation energies, B(E λ)-values, and transition densities of many low- and high-lying states in a quantita-

tive way. Therefore 208 Pb is an ideal case to study the quenching of the total GT strength.



Fig. 3: Zero degree neutron spectrum from the reaction 208 Pb(p,n) 208 Bi. The data (-----) were taken from Ref. 4. The complete theoretical spectrum was calculated with RPA wave functions (dashed curve). The long-short-dashed curve shows the "background" with respect to the GT resonance.



Fig. 4: Same as in Fig. 3 but now for $\theta = 4.5^{\circ}$. The dashed curve is the complete theoretical spectrum.



Fig. 6: Comparison of the calculated zero degree 1^+ -spectrum with the experimental data⁴.

Our results for the 0° -spectrum are shown in Fig. 3. The theoretical spectrum has been calculated with usual RPA wave functions and is compared with the data of Gaarde et al.⁴⁾. Apparently there is a striking similarity between the results for 208 Pb(p,n) and those for 90 Zr(p,n). This is not only true for the 0° -spectra but

θ (deg) c.m.	σ _{exp} (mb/sr) 0>Q>-70 MeV	° _{calc} (mb/sr) 0>Q>-70 MeV	
0.0	418	421	
2.5	419	391	
4.5	342	339	
7.0	308	287	
9.5	274	242	
12.8	209	181	

<u>Table 2:</u> Energy integrated experimental and theoretical cross sections of $\frac{208pb(p,n)}{208pb(p,n)}$ spectra for different scattering angles 0. The theoretical cross sections were calculated with RPA. All numbers are subject to ~ 10 % uncertainty due to the choice of optical parameters. Note that the theoretical numbers slightly deviate from those given in Ref. 33. This is due to a different choice of optical parameters of the Orsay group³⁴) while in Ref. 33 we used those of Nadasen et al.¹⁹.

holds also for all spectra at higher scattering angles shown in Figs. 4 and 5 (see also Ref. 27). In Fig. 6 we compare the calculated 0° 1⁺-spectrum with the experimental data. The 1⁺ cross section includes all Ofiw (GT)-, 2fiw-, and 4fiw-excitations. The 1⁺ strength distribution possesses a long high energy tail which extends up to a Q-value of ~ -50 MeV. In Table 2 we list the energy integrated experimental and calculated cross sections as a function of the scattering angle 6 for the 208 Pb(p,n) reaction. It can be seen that the theoretical cross sections calculated with RPA reproduce the measured ones at all scattering angles within an accuracy of 10 %. This means that all the conclusions drawn earlier from the analyses of the 90 Zr(p,n) spectra are also valid in case of the 208 Pb(p,n) reaction.

IV.3 The ⁴²Ca(p,n)⁴²Sc reaction at 160 MeV

The ${}^{42}\text{Ca}(p,n){}^{42}\text{Sc}$ reaction is of great importance in the discussion of the missing GT strength for the following two reasons: First, there is a strong low-lying GT state at $\text{E}_{x} = 0.61 \text{ MeV}$ in ${}^{42}\text{Sc}$, the B(GT) value of which is known from ß decay experiments²⁸). Since we use this state to calibrate the effective projectile-target nucleon interaction the uncertainties in our reaction calculations are greatly diminished by analyzing the spectra in the same nucleus (i.e. ${}^{42}\text{Ca}$) where we carry out the calibration. Second, in contrast to the ${}^{48}\text{Ca}(p,n)$ spectrum²⁹ which shows two GT peaks, the ${}^{42}\text{Ca}(p,n)$ exhibits only one low-lying peak at Q = -8 MeV 5). This raises the question whether there exists a high-lying GT state in ${}^{42}\text{Ca}$ or whether it is hidden in the background. To clarify this question we have performed

a similar analysis for the $4^{2}Ca(p,n)$ reaction as described earlier for $9^{0}Zr(p,n)$ and $2^{0}Bpb(p,n)$.

All the model assumptions made here are the same as described earlier, except that we calculate the nuclear structure wave functions in a somewhat different way. We obtained them by treating 42 Ca as a closed shell nucleus like 48 Ca, but giving the $f_{7/2}$ neutron shell a fractional occupation number of 0.25 to make a total neutron number of N=22. Then we performed an RPA calculation in a large model space which included all < $6\hbar\omega$ (ph) excitations.

In the structure calculations, we neglected 2p2h and more complicated ground state correlations as well as the particle-particle (pp) interaction which is known to be quite attractive in 42 Ca 30). Therefore, we are not able to describe fine details of the nuclear excitation spectrum. This is particularly true for the OMW states which are sensitive to the pp interaction. On the other hand, for calculating the complete spectrum, it is more important to exhaust the total sum rule strength of every multipole transition than to look for details of their strength distributions. Actually the IMW, 2MW, and 3MW states should be quite realistically described in our calculations since they are little affected by the pp interaction.



Fig. 7: Neutron energy spectra for the ${}^{42}Ca(p,n){}^{42}Sc$ reaction at various scattering angle θ . The 0^o data (thin full line) were taken from Ref. 5. The theoretical spectra were calculated with large basis RPA wave functions using the optical parameters of Ref. 19 and the Love-Franey t-matrix¹⁶) which was calibrated to β decay in the cross section calculations¹³).

In Fig. 7 we show the calculated spectra for the $^{42}Ca(p,n)$ reaction at 160 MeV incident energy. These spectra are incoherent sums of cross sections with L=0 through L=3 ($J^{\pi} = 0^+, 0^-, 1^+, 1^-, 2^+, 2^-, 3^+, 3^-, 4^-$). The continuous spectra were ob-



<u>Fig. 8:</u> Zero degree spectrum for the ${}^{42}Ca(p,n){}^{42}Sc$ reaction. The data (thin full line) were taken from Ref. 5. The complete theoretical spectrum (thick full line) was calculated as described in the text. The dashed curve is the background with respect to the GT states in ${}^{42}Ca$. The dotted curve is the calculated 0° ${}^{40}Ca(p,n){}^{40}Sc$ spectrum.

tained by folding the cross sections to the discrete RPA states into an asymmetric Breit-Wigner form using widths which as far as possible were taken from experiment. For the highly excited states we took an average width of $\Gamma = \Gamma_{left} + \Gamma_{right} = 10$ MeV with $\Gamma_{left} = 2$ MeV and $\Gamma_{right} = 8$ MeV.

In the upper left part of Fig. 7 we compare the calculated 0° spectrum (thick full line) with the data of Goodman et al.⁵) (thin full line). The dashed curve denotes the background cross section with respect to the GT states. Most interestingly the background cross section is very small in the energy region 0>Q>-20 MeV. This can be better seen from Fig. 8 where we show a blow up version of the 0° spectrum. The smallness of the background cross section is due to the fact that it has to be produced by $0h\omega$ and $1h\omega$ states with spin-parities $J^{\pi} \neq 1^{+}$. From these states only the 0^{+} state has a forward peaked cross section. All the other $0h\omega$ states with spin-parities $J^{\pi} = 2^{+}, 3^{+}, 4^{+}$, etc. contribute very little at 0° . A similar argument holds for the low-lying 0^{-} , 1^{-} , and 2^{-} states the angular distributions of which possess a L=1 shape and therefore do not contribute to the low energy part of the 0° spectrum. The shape of the background cross section suggests that the experimental 0° spectrum in the Q-value range 0>Q>-20 MeV directly reflects the GT strength function.

Since the RPA provides a poor approximation to the excitation spectrum of 42 Ca but a good approximation to that of 40 Ca we also show the calculated zero degree 40 Ca(p,n)-spectrum in Fig. 8 (dotted curve). The comparison of both calculated spectra gives some hints in the reliability of the 42 Ca(p,n) background calcula-

tion. Note that the ${}^{42}Ca(p,n)$ background cross section is somewhat larger than the ${}^{40}Ca(p,n)$ cross section but otherwise similar in shape. This is what one would expect because of the two additional neutrons in ${}^{42}Ca$.

Our analysis of the 0^{0} ⁴²Ca(p,n) spectrum suggests that the bump centered around Q = -18 MeV in the ⁴²Ca(p,n) spectrum corresponds to the high-lying collective GT peak. The width of this bump is approximately 6 MeV. Note that the high-lying GT state in ⁴⁸Ca possesses a similar width²⁹).

θ _{c.m.} (deg)	σ _{GT} (mb∕sr)	σ _{bgr} (mb/sr)	σ _{GT} +σ _{bgr} (mb/sr)
0.0	13	8	21
5.0	8	19	27
11.5	2	24	26
15.5	1	15	15

<u>Table 3:</u> Energy integrated theoretical cross sections (-15>Q>-25 MeV) as function of the scattering angle θ . Column 2 shows the cross section of the high-lying GT state in 42 Ca, column 3 the corresponding background cross section, and column 4 the sum of both cross sections.

One might then ask why the GT strength around Q = -18 MeV was not detected experimentally so far. The reason can be seen from Table 3 where we list energy integrated GT and background cross sections as function of the scattering angle θ for the energy region in question. One sees that the background cross section in the energy range -15>Q>-25 MeV grows rapidly with angle so that the sum of GT and background cross section has the shape of an L=1 angular distribution rather than an L=0 shape which would be needed to identify the GT strength. Our conclusion that there could be a substantial amount of GT strength around Q = -18 MeV can be directly proven by measuring the transverse spin transfer coefficient D_{NN}. Such an experiment has recently been carried out successfully at the Indiana University for some other target nuclei^{31,32}.

The RPA calculations predict a total GT cross section of 34 mb in 42 Ca. By distributing this GT cross section in the 0° spectrum in a way as suggested by the background calculations we obtained the thick full curves in Figs. 4 and 5. These curves show that there seems to be no problem to "hide" the total GT cross section in the measured 0° (p,n) spectrum.

V. Summary and Conclusions

We have presented microscopic analyses of forward angle 90 Zr(p,n) and 208 Pb(p,n) spectra at E_{n} = 200 MeV and of 42Ca(p,n) spectra at E_{n} = 160 MeV. The analyses show that the whole spectra up to excitation energies of $E_y = 70$ MeV are the result of direct one-step processes only and that the spectra can be regarded as the linear $\sigma\tau$ response of the target nucleus to the probing (p,n) field. The spectra are background-free with the understanding that background stands for a cross section which is produced by complicated multistep processes. Both the peaks and the continuous parts of the spectra are due to lplh excitations of the target nucleus. Therefore, one can decompose the spectra into the various multipoles and obtain in this way information on the strength distribution of final nuclear states with different J^{π} .

Concerning the quenching of the total GT strength, our calculations suggest that the amount of GT strength in the low excitation energy region can be as large as the lower sum rule limit, i.e. $S_{\beta} = 3(N-Z)$, without leading to contradiction with the present (p,n) data. Quenching due to Δ isobars is only needed if $S_{\beta_{A}} \neq 0$. This is the case as soon as there exist 2p2h or other correlations in the ground states of 90 Zr, 208 Pb or 42 Ca which are not included in the RPA. How much S_{B1}-strength is present in these nuclei can be determined from (n,p) experiments. Therefore, (n,p) experiments are very crucial tools to settling the problem on the role of the ${\scriptscriptstyle\Delta}$ isobar in nuclei.

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