COLLECTIVE ISOSPIN-SPIN EXCITATIONS AND GAMOW-TELLER STRENGTH

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Abstract

The (p,n) reaction at intermediate energies is a sensitive tool for the study of isospin-spin correlations in nuclei. For heavy nuclei the neutron-spectra are at forward angle dominated by transitions corresponding to excitation of collective states carrying a significant part of total sumrule strength. The zero degree spectra give information on the Gamow-Teller strength distribution. The analysis shows that only 30-50% of the strength is observed, and the coupling to the Δ-resonance could be responsible for part of the missing strength.

1. Introduction

The neutron time-of-flight facility[1] at the Indiana University Cyclotron has made possible the study of the (p,n) reaction up to an energy of 200 MeV. It was early discovered[2,3,4,5] that at these energies the neutron spectra at forward angles are dominated by isospin-spin excitations. This is in contrast to the findings at energies below 50 MeV where the spin independent excitations are important[6]. At 200 MeV the ratio between cross sections for spin flip and non-spin flip transitions (with comparable strength) is typically 10. The (p,n) reaction (at 200 MeV) is therefore an excellent tool for the study of isospin-spin correlations in nuclei, e.g. the Gamow-Teller strength distribution.

The zero degree spectra for heavy nuclei show that a significant part of the Gamow-Teller strength is concentrated in a collective state. Such a concentration of strength was proposed by K. Ikeda, S. Fujii and J.I. Fujita[7] as early as 1963.

In a shell model picture of e.g. ^{208}Pb the Gamow-Teller operator $\sigma_\mu t_-$ has non-zero matrix elements with all the 44 excess neutrons (and the 12 $h_{11/2}$ neutrons in the next lower shell). The collective state then corresponds to a transition where all these nucleons coherently change direction of isospin and spin. In a field description the giant GT state corresponds to a vibration in a $\vec{\sigma}\cdot\vec{\tau}$ field produced by $\vec{\sigma}_i\vec{\sigma}_j\vec{\tau}_i\vec{\tau}_j$ interactions. In such a field description[5] one finds that around 80% of the (renormalized) strength coming from the transformation of the 44+12 neutrons is concentrated in the coherent state, indeed a collective state.

The $\vec{\sigma}_i\vec{\sigma}_j\vec{\tau}_i\vec{\tau}_j$ interaction is repulsive (at small momentum transfer) and the coherent state is shifted up in energy. The correlations remove GT strength from the low energy region, and the GT transitions as studied in β-decay are therefore very hindered for heavy nuclei.

Another interesting subject connected with the Gamow-Teller strength function is the possible renormalization of the axial vector coupling constant[8]. The coupling to the Δ-resonance could remove a significant part of the strength from the nuclear energy region[9,10].

The strength distribution is also important for the nucleosynthesis[11] and for evaluating efficiencies in neutrino detectors.

2. Experimental procedure

Beam energies of 120,160 and 200 MeV have been used in the systematic studies with targets ranging from ^{6}Li to ^{208}Pb.

The data are obtained with the beam swinger facility with 2 detector stations with flight paths 70-100 m and 24° between the stations. Time compensated large volume neutron detectors are used[12]. The dimensions are 15 x 15 x 100 cm³. The detectors are tilted at the appropriate angle to obtain sub-nanosecond resolution. At e.g. 200 MeV the tilt angle is around 10°, the 15 x 15 cm² end is (almost) facing the target, resulting in a geometric solid angle of $\sim 10^{-5}$ sr at a distance of 70 m. The intrinsic efficiency is around 0.5 resulting in an efficiency x solid angle of 5×10^{-6} sr per detector. 2 or 3 detectors are usually running in parallel at each angle. The typical overall time resolution is 700-900 psec which results in energy resolutions ranging from 350 keV at 120 MeV and 100 m flight path to around 1 MeV for 200 MeV and 70 m flight path.

Self-supporting targets are used with thicknesses from 30 to 150 mg/cm². The beam currents used are between 50 and 300 nA (on target) and are often limited by computer deadtime. Typical running time to obtain a spectrum varies from 10 min. to 1 hour. The rather small solid angle is compensated by the thick targets that can be used and the large cross sections encountered in these reactions.

3. Experimental results

Figure 1 shows neutron time-of-flight spectra for a number of targets. The spectra are zero degree spectra for E_p= 200 MeV[5]. The resolution is around 1 MeV. The large peaks in the spectra are interpreted as the giant Gamow-Teller resonances. The angular distributions show an ℓ=0 angular momentum transfer and the (bombarding) energy dependence shows a ΔS=1 transfer. The final states are therefore 1^+-states. For the ^{112}Sn and ^{90}Zr spectra the 0^+ IAS's are shown with arrows, and it is seen that the cross sections are indeed very much smaller for these non-spin flip transi-

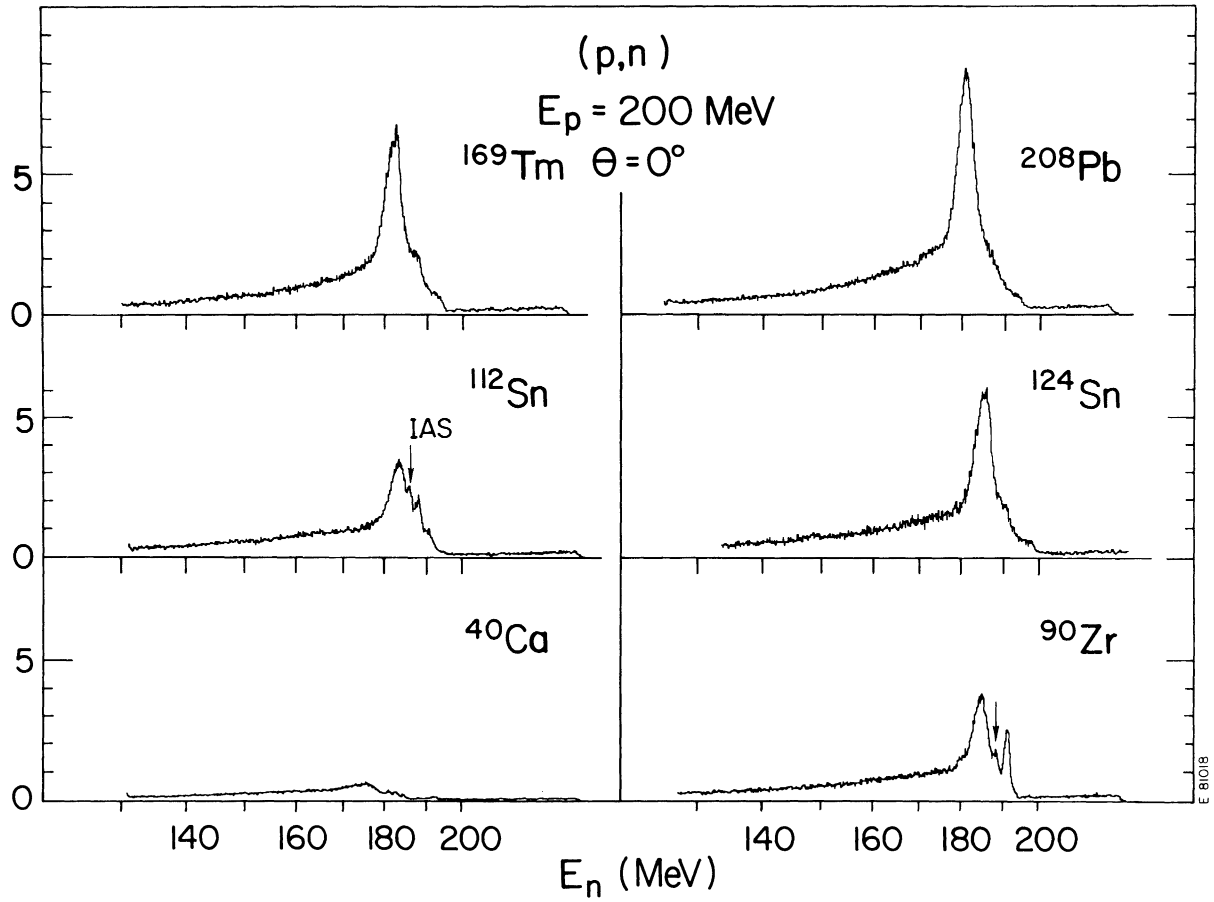

Fig. 1. Neutron t.o.f. spectra at 200 MeV. The spectra are normalized to show relative cross sections[5]).

tions. For ^{208}Pb, ^{169}Tm and ^{124}Sn the analogue states are not resolved from the GT states, but cross section systematics give an 8% contribution for the 0^+ cross section to the total cross section in the peak.

The observed ^{40}Ca(p,n)^{40}Sc 1^+ cross section gives a B(GT)≈0.2 $g^2_A/4\pi$; in these units the free neutron decay has B(GT)=3. The ^{40}Ca g.s. is therefore a closed shell as regards spin correlations with an accuracy of around 0.1 single particle strength units.

The cross sections at 200 MeV to the collective states are very large, around 100 mb/sr for ^{208}Pb and around 50 mb/sr for ^{90}Zr and show an almost linear dependence in (N-Z)[5]).

The energy dependence is demonstrated in Fig.2 where the zero degree spectra for ^{90}Zr(p,n)^{90}Nb at E_p=120 MeV[2]) and 200 MeV[5]) are shown. From the raw spectra it is evident that the ratio between cross sections of spin flip and non-spin flip transitions is increasing with energy.

The ^{90}Zr spectrum is illustrative for the structure of zero degree (p,n) spectra at intermediate energies. If we describe the ^{90}Zr g.s. as $(\nu g_{9/2})^{10}$ the analogue state, the Fermi state, will be $(\pi g_{9/2}\nu g_{9/2}^{-1})_{0+}$ T=5, whereas the Gamow-Teller strength is distributed on 2 configurations $(\pi g_{9/2}\nu g_{9/2}^{-1})$ and $\pi g_{7/2}\nu g_{9/2}^{-1}$. The first has T=4 and the latter T=4 and 5.

$$\sum_k \sigma(k)t_-(k)|g.s.\rangle = \sqrt{110/9}\,|g_{9/2}g_{9/2}^{-1}\rangle_{1+,T=4} + \sqrt{160/9}\{\sqrt{9/10}\,|g_{7/2}g_{9/2}^{-1}\rangle_{1+,T=4} + \sqrt{1/10}\,|g_{7/2}g_{9/2}^{-1}\rangle_{1+,T=5}\}$$

Interactions of form $\sigma_i\sigma_j\tau_i\tau_j$ will mix the two groups of T=4 states in such a way as to place most of the strength on the state with the main configuration $\pi g_{7/2}\nu g_{9/2}^{-1}$. A wave function

$$0.97|\pi g_{7/2}(\nu g_{9/2})^9\rangle + 0.23\;|\pi g_{9/2}(\nu g_{9/2})^9\rangle$$

for the upper state (the "giant" state) and the orthogonal combination for the lower state is consistent with both the energy and strength distribution of 4 : 1 between the 2 states.

The 1^+, T=5 state has a strength of only 0.06 of the total of 30 and is therefore more difficult to observe in the (p,n) reaction. In a recent experiment the IAS of this state (the M1 state) has been observed in ^{90}Zr(p,p') at E_p= 200 MeV[16]) consistent with the previous analysis of the (p,n) data. The distribution of strength on a high lying collective state with a width of around 4 MeV and on a group of states 6-8 MeV lower (somewhat more than $\Delta_{\ell s}$) with 1/4 of strength on the giant seems to be a general result for heavy nuclei. In ^{90}Zr we see that the lower group can be identified with a definite configuration and the width is small.

In Fig.3 a spectrum is shown at θ=4.5° for ^{208}Pb. The angular distribution for the broad

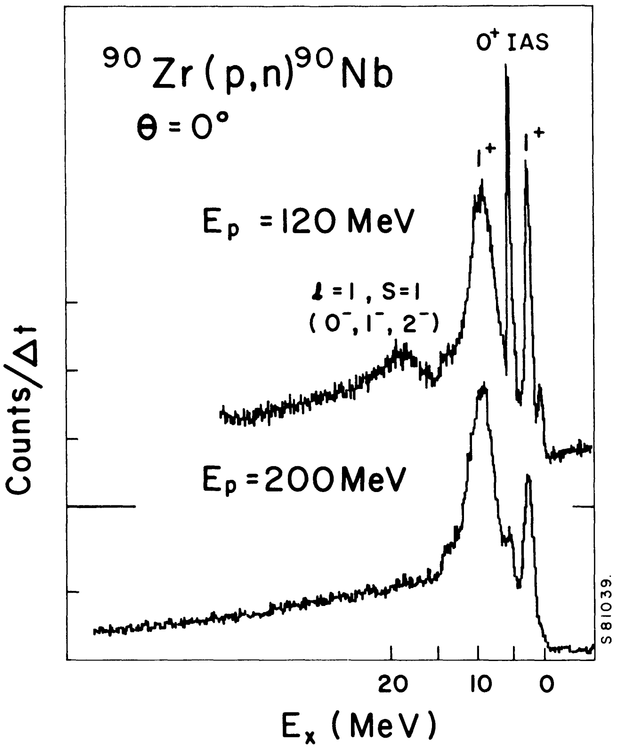

Fig. 2. Neutron t.o.f. spectra for ^{90}Zr at E_p = 120 MeV and 200 MeV. The resolution is around 700 keV and 1 MeV, respectively. The ℓ=1 resonance is only seen at 120 MeV because the angular distribution is narrower (in angle) at 200 MeV[5].

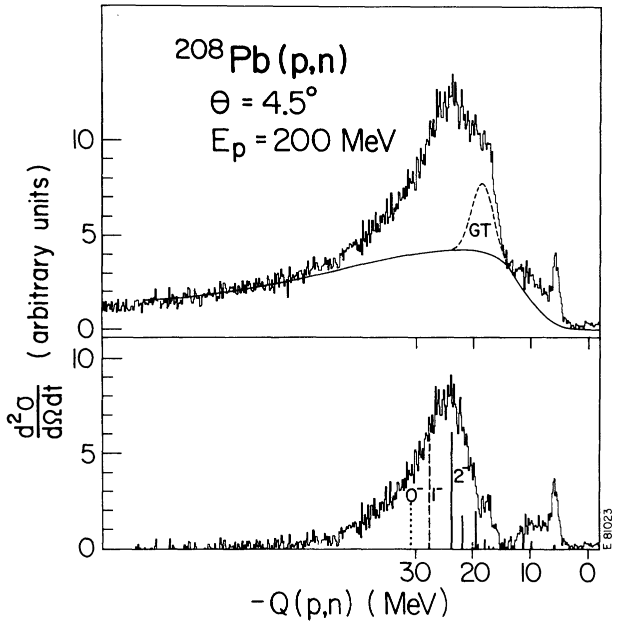

Fig. 3. Neutron t.o.f. spectrum for ^{208}Pb is shown with an assumed continuum. The GT resonance is indicated. In the lower part of the figure the continuum is subtracted. The broad peak has an ℓ=1 angular distribution[5]. Also shown is a RPA strength distribution for spin flip states 0^-, 1^- and 2^-.

resonance in the spectrum shows an ℓ=1 transfer. The energy dependence further shows ΔS=1, and we therefore interpret this peak as the giant spin dipole resonance.

The figure also shows the result for the strength distribution from a RPA calculation[5]. The resonance is following such calculations the envelope of 3 collective states, 0^-, 1^- and 2^- states.

This dipole resonance is as general a feature of the spectra around 5^0 as the GT resonance is at 0^0 (refs.[4,5]).

We shall not here go into any detail with the spin dipole resonance.

We have only showed results for heavy nuclei. Also for lighter nuclei the (p,n) reaction has given new and unexpected information on strength distributions. The reaction is e.g. an excellent tool to exploit SU4 symmetries in nuclei.

4. Reaction mechanism

At the bombarding energies used here the impulse approximation is expected to apply. The effective interaction between the projectile and a neutron in the nucleus is taken from the free nucleon-nucleon (N-N) interaction. Love and Franey[13] have derived the local t-matrix interactions in the different channels from experimental N-N phase shifts. In Fig.4 the result for the energy dependence is shown for momentum transfer

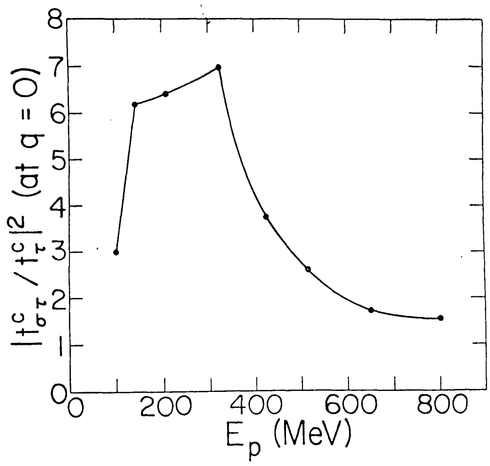

Fig. 4. The ratio between t-matrix elements for the central part of the interactions in the $\sigma\tau$- and τ-channels is plotted versus bombarding energy[13].

q=0 (ref.[13]). The ratio between the square of t-matrix elements for $\Delta S = \Delta T = 1$ and $\Delta S = 0$ $\Delta T = 1$ transfer is plotted versus energy. The calculations[13] show that it is the non-spin flip part that decreases with energy whereas the spin flip part is rather constant up to the π-threshold. The interaction strengths are then used in DW codes such as DWUCK4 and DWBA70 to calculate (p,n) cross sections for single particle transitions.

These calculations show[5] that for a given nucleus the zero degree cross section is proportional to the Gamow-Teller strength for the single particle transition considered. That means that a cross section unit for Gamow-Teller strength can be calculated as a function of A for a given bombarding energy[5]. From the measured zero degree cross section we can therefore extract the (calculated) GT strength for a given transition (Fig. 5).

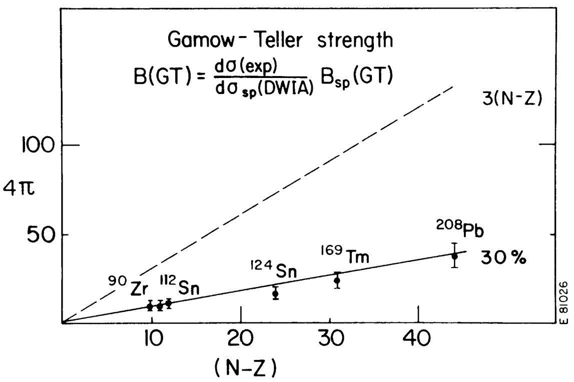

Fig. 5. GT strength systematics. The experimental zero degree cross section[5] for the collective states is divided by a GT cross section unit to obtain (calculated) absolute GT strength. The dashed line is the sumrule limit 3(N-Z) for T>>0. The full drawn curve is 30% x 3(N-Z).

For transitions in (p,n) reactions where the GT strength is known from β-decay this relation between $d\sigma/d\Omega(\theta=0)$ and B(GT) can be tested. For a number of nuclei between ^{6}Li and ^{26}Mg it is shown in ref.3 that such a close relationship between strength and cross section does exist.

In ref.3 a low momentum transfer limit in the impulse approximation is used. The zero degree cross section for a transition with Fermi and/or Gamow-Teller strength can then be written as

$$\frac{d\sigma}{d\Omega}(\theta=0^o) = \left(\frac{\mu}{\pi\hbar^2}\right)^2 \frac{k_f}{k_i}\left(N_\tau J_\tau^2 \cdot B(F) + N_{\sigma\tau} J_{\sigma\tau}^2 B(GT)\right)$$

J_τ and $J_{\sigma\tau}$ are volume integrals of the effective spin independent ($\vec{\tau}\vec{\tau}$) and spin dependent ($\vec{\sigma}\vec{\sigma}\vec{\tau}\vec{\tau}$) central components of the force. N_τ and $N_{\sigma\tau}$ are factors by which the cross sections are reduced due to distortion of the incoming and outgoing waves by the optical potential. These distortion factors can be calculated and inserted in the expression above.

It is important to calibrate the relation between GT strength and cross section also for heavier nuclei. We have now data for ^{42}Ca(p,n) and preliminary data for ^{144}Sm(p,n). There are however very few cases for heavy nuclei of GT transitions between ground states with reasonable fast rates (log ft < 5.0).

A similar approach can be taken for the spin dipole transitions[5]. A cross section unit can be calculated and compared with 1/ft values for e.g. $2^- \to 0^+$ (unique first forbidden) β-decay. Here some good examples are available in the Hg-isotopes.

In conclusion: the (p,n) reaction (at intermediate energies) can give quantitative information on strength distributions for isospin-spin transitions, e.g. GT β-decay. In Fig.5 we show the GT strength in the collective state for the nuclei from Fig.1. The strength is calculated from the measured zero degree cross section and a calculated cross section unit. These calculations have not yet been calibrated by β-decay ft-values in this mass region.

5. Sumrules

For charge exchange modes very general sumrules can be derived from commutator relations for operators involving t_+ and t_-. For GT transitions we find[14])

$$S_{\beta-} - S_{\beta+} = \sum_f \sum_\mu |\langle f| \sum_{k=1}^{A} \sigma_\mu(k) t_-(k)|i\rangle|^2$$

$$- \sum_{f'} \sum_\mu |\langle f'| \sum_{k=1}^{A} \sigma_\mu(k) t_+(k)|i\rangle|^2$$

$$= 3(N-Z)$$

The relation states that the difference between β_- and β_+ GT strength from an initial state $|i\rangle$ to all final states is 3(N-Z). The sumrule is model independent since it follows directly from commutators of one body operators t_- and t_+. The only assumption is that σ_μ and $t_\pm$ are one body operators that can only change direction of spin and isospin of nucleons.

A completely analogous sumrule can be derived for the spin dipole strength[5].

The inclusion of the internal degrees of freedom of the nucleon can, however, change the strength distribution significantly. The coupling to the Δ resonance (M = 1236 MeV T = S = 3/2) is very important for the isospin-spin modes[9,10]) and the sum of strength in the nuclear region (E_x<100 MeV) will now be model dependent, dependent on the coupling between the Δ and the nucleon.

In the constituent quark model for the nucleon the reduced matrix element for the N Δ transition is[10])

$$\langle\Delta|||\sigma\tau|||N\rangle = \frac{24\sqrt{2}}{5}$$

With this coupling constant 36% of the strength 3(N-Z) (for nuclei T_0>>1) is shifted to the Δ-region[5]. So even if the Δ-resonance is 300 MeV away it can remove a significant part of the strength.

The effect of the Δ-resonance is then to renormalize all matrix elements involving στ. There will also be an admixture of Δ-particle N-hole configurations into the wave functions of low lying particle-hole states. The amplitude with the coupling constant from the constituent quark model given above will be around 8%: $0.997|ph\rangle - 0.080|\Delta N^{-1}\rangle$.

6. Structure

The spectra in Fig.1 show that a significant part of the strength is collected in a single state. We shall desribe this state as a coherent particle-hole state.

In a field approximation the coherent state is generated by an oscillating average field proportional to $\vec{\sigma}\vec{\tau}$. This is equivalent to expressing the two body interaction in separable form, and we shall here specifically take the particle-hole interaction as $V_{12} = \kappa_N \vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2$. This corresponds to setting all radial matrix elements equal. We shall further assume a volume interaction by having a 1/A dependence of κ_N.

The selfconsistency condition for the oscillating potential leads to a dispersion relation for the energy of the collective state. This relation is equivalent to the RPA equation for a separable force.

$$\sum_i \frac{<(\nu^{-1}\pi)i||1^+,M=0|\sigma_0\tau_{-1})0>^2}{(\varepsilon_\pi-\varepsilon_\nu)_i-\varepsilon} +$$

$$\sum_j \frac{<(\pi^{-1}\nu)_j||1^+,M=0|\sigma_0\tau_{+1}|0>^2}{(\varepsilon_\nu-\varepsilon_\pi)_j+\varepsilon} = -\frac{1}{\kappa}$$

The equation relates to the M=0 states and σ_0 and $\tau_\mp$ are spherical tensor components of the operators $\vec{\sigma}$ and $\vec{\tau}$. ε_π and ε_ν are proton-particle and neutron-hole energies.

For nuclei with a large neutron excess the second sum of terms will be approximately zero because the relevant final states, for the β_+-decay of the ground state, are blocked. The equation then corresponds to the Tamn-Dancoff approximation.

The equation has been solved for ^{208}Pb using experimental values for particle and hole energies, and if we adjust the coupling constant to reproduce the observed energy of the collective GT resonance (19.2 MeV relative to ^{208}Pb g.s.) we find

$$\kappa_{\sigma\tau} = \frac{23}{A}\text{ MeV} .$$

The coupling constant so determined is an effective coupling constant including e.g. the coupling to the Δ-resonance.

The corresponding quantity for the IAS determined using the same particle and hole energies and adjusted to fit the energy of the IAS, (18.8 MeV relative to ^{208}Pb g.s.) is

$$\kappa_\tau = \frac{28}{A}\text{ MeV} .$$

This corresponds to a symmetric energy of V_1 = 4 x 28 MeV = 112 MeV.

The effective coupling constant (in the field approximation) is then smaller for the $\sigma\tau$- than for the τ-mode, and that the energy of the GT resonance is higher than the IA resonance is because the $\sigma\tau$-mode also includes the transitions to spin orbit partners.

The energy systematics for the GT resonances can be discussed in a simple model[5] which contains all the important aspects of the problem. We shall assume that the unperturbed GT strength is clustered in 2 groups of states with energies ε_i and $\varepsilon_i+\Delta_{\ell s}$ and the total strength divided as 3(N-Z)(1-f) and 3(N-Z)·f. In any specific case the value of f can be calculated. For ^{208}Pb f = 0.36 and for ^{90}Zr f = 0.57. The dispersion relation then reads

$$\frac{2(N-Z)(1-f)}{\varepsilon_i-\varepsilon} + \frac{2(N-Z)f}{\varepsilon_i+\Delta_{\ell s}-\varepsilon} = -\frac{1}{23/A}$$

For $\Delta_{\ell s}$ we take 5.6 MeV which applies to ^{90}Zr and ^{200}Pb but also to ^{48}Ca where $\Delta_{\ell s}(\pi f_{5/2}-\pi f_{7/2})\sim 5.7$ MeV.

The solution to the equation is plotted in Fig.6 as a function of N-Z/A. The ordinate is the energy in MeV relative to the unperturbed particle-hole energy ε_i.

The corresponding expression for the energy of the IAS reads

$$\frac{2(N-Z)}{\varepsilon_i-\varepsilon} = -\frac{1}{28/A}$$

and we note that ε_i is the same energy as appears in the equation for the GT energy.

The experimental energies of the GT resonances[4] relative to the IAS energies are plotted in Fig.6 relative to the straight line $\varepsilon-\varepsilon_i$ = 2 x 28 N-Z/A.

We see that this simple model accounts well for the energy systematics of the collective state.

This model places around 80% of the strength (in the nuclear region) in the collective state, and this is then in agreement with the experimental findings that around 1/4 of the strength in the collective state is found at lower excitation energies. The ratio is, however, rather uncertain being dependent on how the continuum is defined in the high energy end of the spectra.

The collective state might also be described by particle-hole interactions of quite different

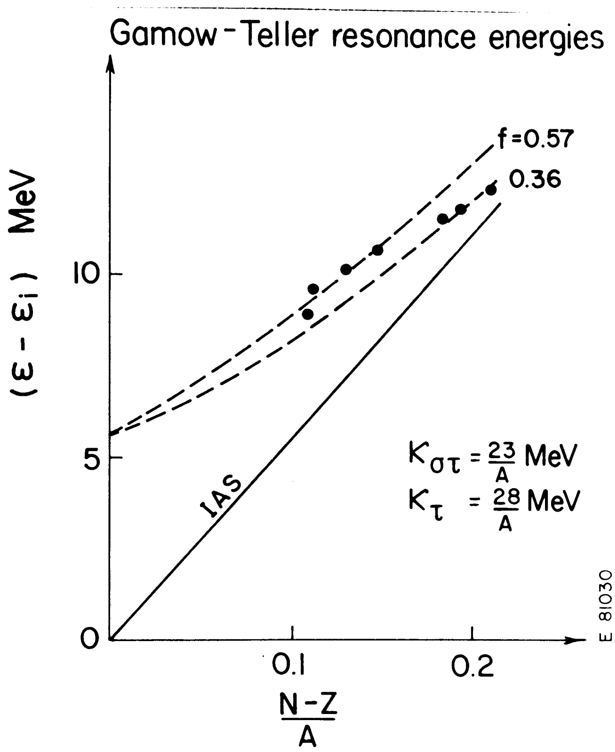

Fig. 6. GT energy systematics. The experimental energies are plotted relative to the IAS as explained in the text. The IAS has (degenerate) unperturbed particle-hole energies $\varepsilon=\varepsilon_i$. The dashed lines correspond to the model for the GT energies where the unperturbed energies lie in 2 groups with $\varepsilon=\varepsilon_i$ and $\varepsilon=\varepsilon_i+\Delta_{\ell s}$ and strength 3(N-Z)(1-f) and 3(N-Z)f, re-respectively.

form. If we assume a particle-hole interaction also inside the nucleus as coming from π- and ρ-exchange[15] then we can approximate the interaction at small momentum transfer (which should be good for $\sigma\tau$ transitions) by a δ-force.

$$V_{12} = g_o' \ \delta(\vec{r}_1-\vec{r}_2)\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2$$

If we adjust g_o' to reproduce the observed GT energy as before we find

$$g_o' = 245 \text{ MeV fm}^3 \ .$$

This quantity should be compared with the volume integral obtained in the field approximation

$$\kappa \cdot \text{volume} = \frac{23}{A} \cdot \frac{4\pi}{3} r_o^{\ 3} A = 168 \text{ MeV fm}^3 \ (r_o = 1.2 \text{ fm})$$

The two models give rather different results for this property.

7. Summary

The (p,n) reaction at intermediate energies is a unique tool for the study of isospin-spin correlations in nuclei. The spectra show that these correlations build up collective states of different multipolarities with a significant part of the sumrule strength. The energy and strength systematics of the collective states can be explained in simple models for one particle-one hole states. The analysis of the cross sections in an impulse approximation establishes cross section units for GT and spin dipole strength. These calculations can be tested for (p,n) transitions where the ft values are known from β-decay. The total GT-strength only exhausts from 30-50% of the sumrule. Coupling to the Δ-resonance could be a possible explanation for the missing strength.

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DISCUSSION

P.G. Hansen: You have in certain cases used β-decay data to "calibrate" the (p,n) cross-sections. Are there any cases, where further measurements of the β-transition probabilities would be useful to you?

C. Gaarde: The calibration of the (p,n) cross section by β-decay is very important for the absolute GT strength. For heavy nuclei we need log ft< 5 transitions to get sufficient accuracy. The only cases we have been able to find are ^{144}Sm, ^{162}Dy and ^{165}Ho. These are g.s. to g.s. transitions. Suggestions for other cases would be welcome.

J. Żylicz: Is there any good way of detecting the small delta/nucleon-hole admixture to the wave function of the lower-energy state?

C. Gaarde: We have not found a good way. An experiment is planned to look for nucleon particle-hole i.e. GT strength in the Δ-energy region.

K. Bleuler: Is it right too that you need in order to interpret your measurements about 8% of Δ-admixtures. If so, that would correspond nicely to our calculation of the binding of nuclear matter through meson-exchange where you automatically obtain an admixture of this order of magnitude.

N.I. Pyatov: The 35% quenching of the GT strength resulting from the virtual excitation of the Δ-hole, agrees rather well with the phenomenological estimate of the local quasi-particle charge for the axial field $1q[\sigma\tau] = 0.8$, which was obtained by the Migdal group from analysis of magnetic moments. But this does not seem to resolve the problem completely, because, as we found in our calculations, the quenching required is different at least for ^{90}Zr and ^{208}Pb (see the paper by Fayans and Pyatov).

O.W.B. Schult: Does one understand the strength that goes into the 13.9 MeV state on the basis of shell-model calculations?

C. Gaarde: The data for ^{14}C(p,n)^{14}N is to be published (C. Goodman et al.). The GT strength distribution was not known, but the general picture is reproduced in shell-model calculations. The ^{14}C(p,n)^{14}N reaction is a good case for the determination of absolute GT strength. The transition to the 3.95 MeV state in ^{14}N has a ft-value known from β-decay and the (p,n) 0° cross section is therefore calibrated in GT strength.