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# GAMOW-TELLER TRANSITIONS : PROGRESS AND PROBLEMS

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**CENTRE DE RECHERCHES NUCLEAIRES**

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# GAMOW-TELLER TRANSITIONS, PROGRESS AND PROBLEMS

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Since the seminal paper by G.Gamow and E.Teller[1], the determination of the so-called GT-matrix elements from β-decay and charge exchange reactions has led to a series of discoveries concerning the structure of the nucleus and the properties of spin-isospin transitions in nuclei. The (p,n) and (n,p) reactions allow to survey experimentally the dominant portion of the transition strength but are limited to nuclei accesible with available targets. The weak-interaction decays bring invaluable complements on well-resolved transitions and allow to investigate nuclei far from stability. More precisely, our knowledge of the region near the drip lines is, in most cases, limited to the results given by the prominent GT transitions.

Recently there has been a renewed interest in this field for different reasons :

New experimental results are available. The intermediate energy (n,p) charge-exchange reaction at forward angle has now been measured for several nuclei and complement the (p,n) cross section measurements. Weak decay results have been obtained for very proton (or neutron) rich nuclei and more accurate measurements of GT-matrix elements are now available in many cases of interest .

New theoretical descriptions of the GT strength , using RPA, large-basis shell-model spaces and in some cases Monte-Carlo path evaluation techniques, can now be compared to the experiment for many "light" nuclei ($A < 60$). In this mass range, the model space can include the spin-orbit partners of all single particle levels. These calculations have improved the comparison with existing data, allowed to predict new decay modes far from stability and modified the analysis of the reduction of the GT strength in nuclear medium.

The importance of weak interaction rates in stellar matter evolution has led to many studies in order to understand the present data and improve the parametrization of the GT strengths in cases of interest for the evolution of massive stars. In addition, the scrutiny of the neutrino signal accompanying central events in the sun requires a precise knowledge of the neutrino detector efficiency and thereby precise beta decay results.

In this talk, recent results will be presented in order to illustrate this development and emphasis will be laid on the comparison experiment versus calculation. It is indeed a point where substantial progresses have been made and also problems can be surmised. We will restrict ourselves to allowed GT transitions. A recent compilation [2)] for 10 < A < 100 indicates that the corresponding log ft distribution for 2227 such transitions is close to the gaussian curve with center at 5.56 and a width (fwhm) equal to 2.03.

## GT Strength and Sum Rules

The existence of a strong, model independent, sum rule for the total GT strength issued from a given initial state is of particular interest. Such a relation should allow to characterize nuclear ground states without the complexity of microscopic models for final state spectrum. Before discussing the application of the GT sum rule, it is useful to restate the relevant formalism and to distinguish different aspects in the experimental tests of the GT strength.

Weak decay experiments give access to the GT nuclear matrix element $\langle\sigma\tau\rangle$ through the beta decay rate :

$$ft = K\left[g_V^2\langle\tau\rangle^2 + g_A^2\langle\sigma\tau\rangle^2\right]^{-1}$$

where $K = 1.23\ 10^{-94}\ \mathrm{erg}^2\ \mathrm{cm}^6\ \mathrm{s}$.
and $g_V$, $g_A$ are the vector and axial-vector coupling constants.

The transition strength for the GT process,

$$B(GT) = (g_A / g_V)^2\langle\sigma\tau\rangle^2$$

and the evaluation of $K/(g_V)^2$ from available data on $0^+ \to 0^+$ superallowed decays[3)], allows to formulate

$$ft = \frac{K/(g_V)^2}{B(F)+B(GT)} = \frac{6147 \pm 7}{\langle M_F\rangle^2 + (1.262 \pm 0.04)^2\langle M_{GT}\rangle^2}$$

A recent reanalysis of the experimental[4)] data leads to :

$$K/(g_V)^2 = 6127 \pm 9$$

For the summed strength for a given initial state with N, Z, we now have the GT sum rule[5,6)]

$$S^- - S^+ = \sum_f \langle f|\sigma\tau^-|i\rangle^2 - \sum_f \langle f|\sigma\tau^+|i\rangle^2 = 3(N-Z) \qquad [1]$$

where i and f label the initial and final states and the summation is over all the possible final states.

This exact relation states that the difference between $S^-$ and $S^+$ is independent of the structure of the parent state, whereas each quantity is strongly dependent of this structure. What are the implications of the sum rule with the experimental results ?

3 categories of experiments can be distinguished :

**1)** In a number of cases, the experimental quantities $S^-_{ex}$ and $S^+_{ex}$ corresponding to the same parent state are accessible and have ben measured.

**2)** $S^+$ is expected to be very low in many cases due to Pauli blocking, and the lower limit obtained for $S^-$ from [1]: $S^- \geq 3(N-Z)$ leads to $S^- \approx 3(N-Z)$. In such cases, $S^-_{ex}$ should be close to the sum rule value.

The approximation $S^+ \approx 0$ is expected to be valid in nuclei with a filled proton shell like $^{18}O$, $^{42}Ca$ and $^{90}Zr$. In these three cases, $S^-_{ex}$ measured is substantially lower than the 3(N-Z) value. [$S^-_{ex} / S^-_{SR}$ being respectively equal to 3.97/6, 3.20/6 and 18/30][7,8,9)]. For $^{90}Zr$, $S^+_{ex}$ has been reported ( $S^+_{ex} \leq 3.6$)[10)]. In the limits of the approximation, a sizable part of the strength is therefore missing if $S^-_{ex}$ is a measure of $S^-$.

**3)** In beta decay experiments, the number of measured transitions is limited by the beta decay window and the measured strength can only be compared with a model dependent calculation.

In the two first categories, we must keep in mind for the discussion of results that $S^-_{ex}$ might differ from $S^-$ for different reasons [overestimation of the background, spread of the strength beyond the investigated excitation range, dilution of the strength in indiscernible components...].

We come back to the 3 different categories for further discussion :

**1)** In a few cases, (n,p) forward cross sections has been measured by the CHARGEX Collaboration at TRIUMF and $S^+_{ex}$ deduced (Fig.1). This set of data illustrates the inadequacy of the single particle estimations for astrophysical applications and allows a comparison of the differences ($S^-$-$S^+$) and ($S^-_{ex}$ - $S^+_{ex}$).

In the case of $^{54}Fe$, the reactions $^{54}Fe(p,n)^{54}Co$ [ref.12] and $^{54}Fe(n,p)^{54}Mn$ [ref.13] yield for example $S^-_{ex} = 7.5 \pm 0.7$ and $S^+_{ex} = 3.1 \pm 0.6$. With these values ,we obtain $S^-_{ex} - S^+_{ex} = 4.4 \pm 0.9$ which compared with the 3(N-Z) = 6 value indicates that 74 % of the sum rule is seen in the experiment. This difference does not reveal a violation of sum rule, but the fact that the experiment is incomplete as $S_{ex}^{+}$ might also be different from $S^+$ for reasons given above for $S^-$ (see ref. 14).

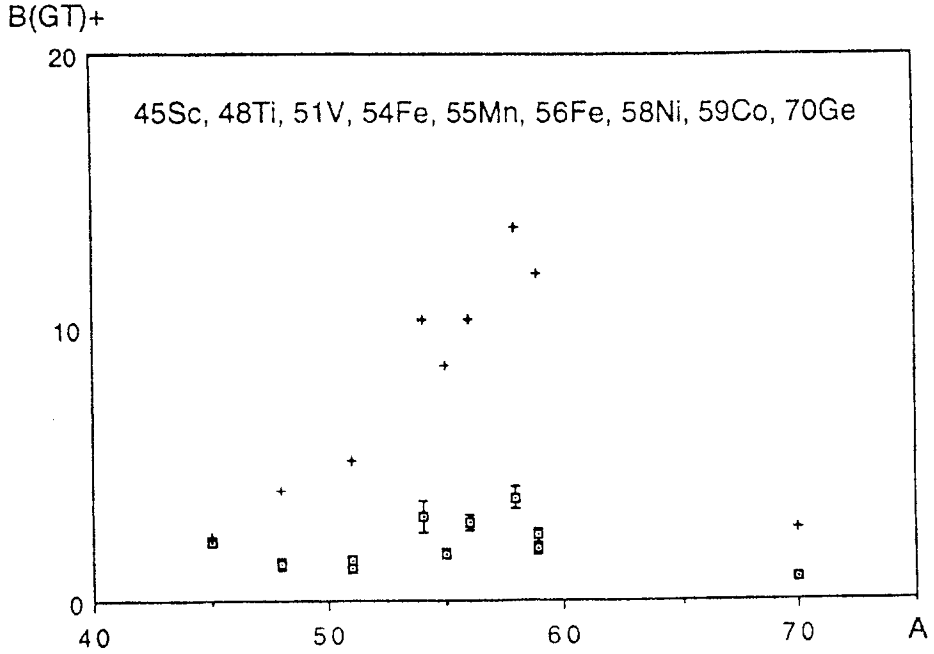


Fig.1 : Comparison of $S_{ex}^{+}$ for $E_X < 8$ MeV extracted from (n.p) data taken at TRIUMF (taken from ref.11) with values given by the single particle model (+).

2) We discuss now the case where only one quantity ($S^-$ or $S^+$) has been measured.
Different attempts were made in order to substituate to relation [1] a GT rule for the individual $S^+$ and $S^-$ strengths. The aim was twofold :

- compare the predicted value to one class of experiments,
- bring to light the details of the nuclear structure and of ground-state correlations. These effects, which are crucial for the value of each term, cancel out in the difference.

The rules derived by Macfarlane$^{15)}$ for separate total (n,p) and (p,n) GT strength were obtained with one simplifying assumption (in even nuclei, protons and neutrons separately have total angular momentum zero) and are explicitly related to the occupation numbers (nb of particles in the initial orbit and number of holes in the final orbit). Its application was unsuccessful, in particular G. Mairle et al.$^{16)}$ using occupation numbers carefully deduced from transfert experiments were able to demonstrate that the resulting strengths were larger by factors 2 to 4 than those measured. An interesting outcome was the comparison of this rule with shell-model estimates of $S^{\pm}$ made by Hino et al.$^{17)}$ for even-even nuclei and calculated in the full $(sd)^n$ space. The sum rule operator $S^{\pm}$ is expressed as a sum of two terms, one including the occupation number probability and an additional proton-neutron correlation term.

Results, are presented (Fig.2) for even-even sd nuclei in three conditions for the ground state description : LC, lowest configuration limit; ON, occupation number approximation (corresponding to the Macfarlane approximation) and F, the full result where the proton-neutron correlation term is not neglected). It can be seen from Fig. 2 :

- the considerable amount of reduction due to n-p correlation effects which affects $S^+$ and $S^-$ in the same manner so as to cancel in the sum-rule,
- the resulting inadequacy of the $\left| J_p = 0^+ \times J_n = 0^+ \right\rangle$ approximation,
- the very high sensitivity of $S^+$ to these n-p correlations.

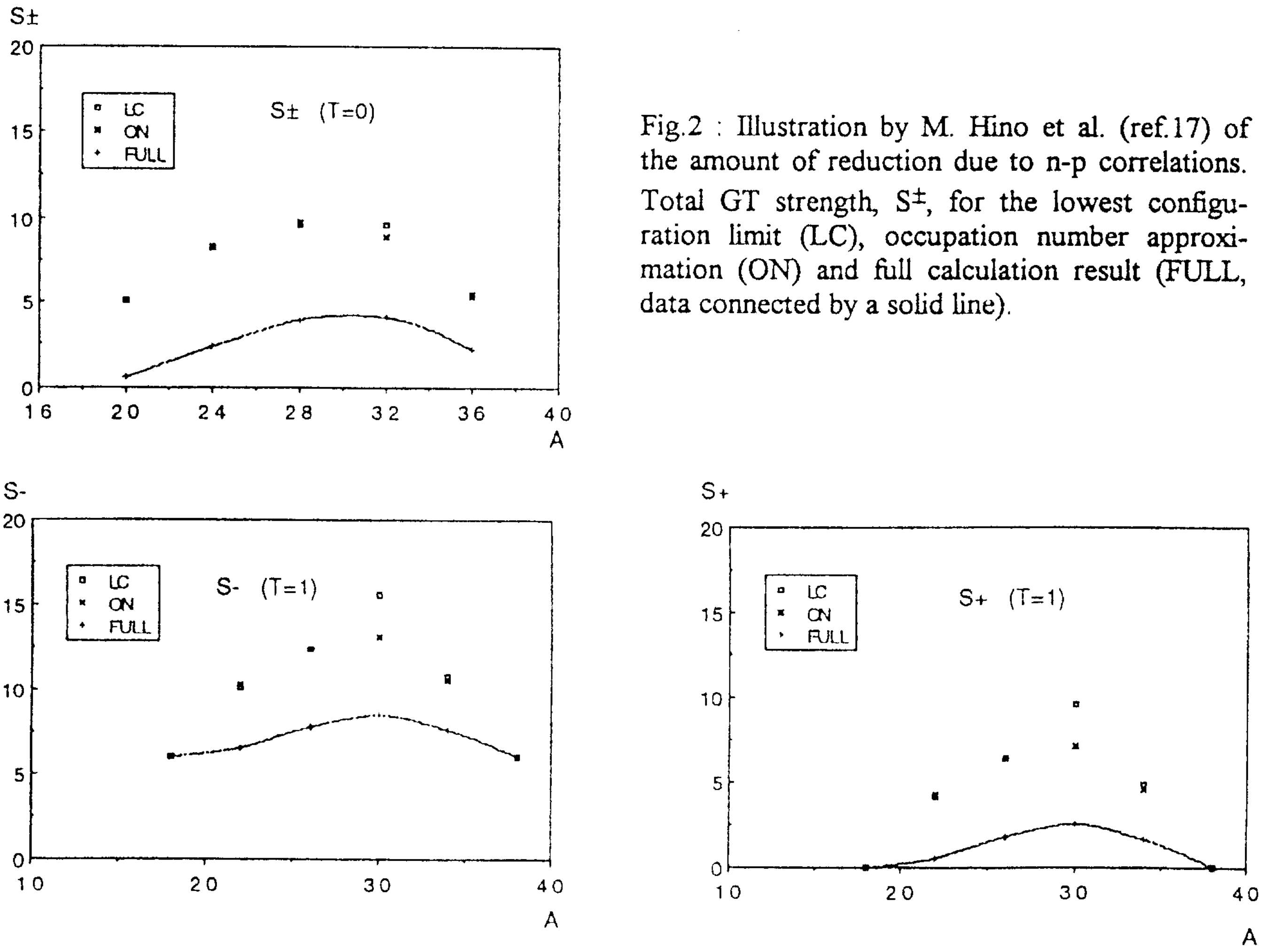


Fig.2 : Illustration by M. Hino et al. (ref.17) of the amount of reduction due to n-p correlations. Total GT strength, $S^{\pm}$, for the lowest configuration limit (LC), occupation number approximation (ON) and full calculation result (FULL, data connected by a solid line).

Furthermore, we can see that these values are clearly model-dependent (with closed shells assumed for $^{18}O$, $^{38}Ar$). If experimental values, available for some of these nuclei, are compared to the full calculation, they present reduction factors between 0.5 and 0.7 ($^{32}S$, $^{18}O$, $^{26}Mg$)[18,7,19].

In parallel with these calculations, it is of interest to note the simple parametrization proposed recently by S.E.Koonin and K.Langanke[11)] for the total B(GT$^+$) strength in fp shell nuclei with N(fp) > 8. The role of occupation numbers and proton-neutron correlation effects lead to parametrize $S^+$ as :

$$S^+ = a\,Z_{val}\,(20\text{-}N_{val}) \qquad \text{with } a = (4.29 \pm 0.15) \times 10^{-2}$$

the global agreement inside the fp shell seems insensitive to subshell structure.

3) The interest of weak decay results is therefore apparent; comparing predicted and observed B(GT) values for individual transitions, they allow to trace further the validity of the models. No information on the missing strength will be obtained but the evaluation of the quenching is important and reveals either specific structure effects or a general effect which can modify the "free nucleon" operator value.

## Developments in the Theoretical Estimates of the GT Strength

The systematic study of B(GT), made by Brown and Wildenthal[20,21] for A=17-39 nuclei had revealed the quenching of effective matrix element by a factor of 0.76 ± 0.03 relative to the free-nucleon value. This important result appears now to correspond to a more general situation. In the sd shell, a few cases have been reported where the experimental strength is close to the calculated one ($^{29}$S, $^{37,39}$Ca, $^{33}$Ar). Nevertheless none gives a clear evidence for an absence of quenching whereas the standard reduction is supported by a broad range of data.

A recent comprehensive analysis of the GT beta decay rates for $A \leq 18$ has been made by W.T. Chou et al.[22] and 83 decay matrix elements have been calculated using an interaction appropriate to the 0p-shell. The strong 0p-shell decays are well reproduced with a quenching of the "free-nucleon" operator by a factor :

$$q = 1 - 0.19\,(A/16)^{0.35}$$

In Fig.3, the normalized values of M(GT), R(GT)

$$R(GT) = M(GT) / \left|g_A / g_V\right| \left[(2J_i + 1)3(N_i - Z_i)\right]^{1/2}$$

are compared with the "effective" value of R(GT) for 16 0p-shell decays. Except the transition from $^{12}$Be $0^+$ g.s. to the $^{12}$B $1^+_1$ which is weaker than predicted (with possible contribution of intruders in the parent state which require an extension of the model space), the good fit on the diagonal is evident.

In the fp shell, previous shell-model calculations, with a limited number of particles in the upper orbits ($n \leq 2$), indicated a good agreement for transitions to low excited states with a renormalization factor of the same order as in the sd shell. In Fig.4 we have reported the experiment versus prediction comparison for 50 values of B(GT) corresponding to transitions in the fp-shell[23].

The configuration space : $f^n + f^{n-1} r^1 + f^{n-2} r^2$ is limited to 2 particles in orbits higher than $f_{7/2}$ and the effective coupling constant has the value 0.76 $g_A$.

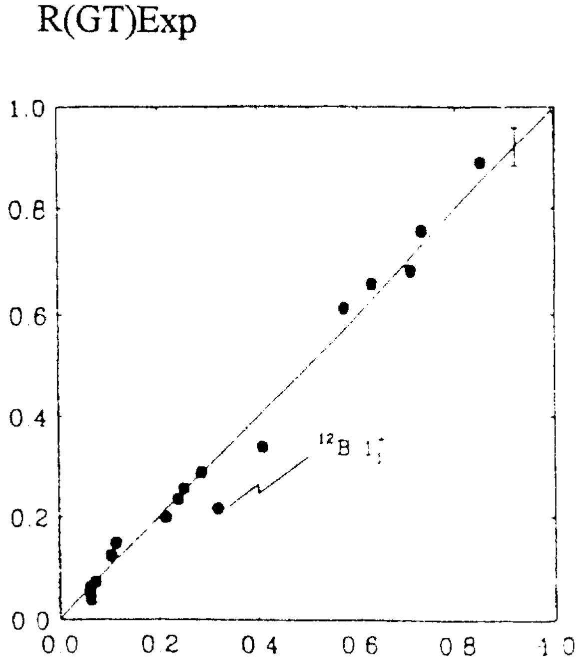


Fig.3 : Comparison of the experimental and "effective" values of R(GT) for 16 0p-shell decays made by W.T. Chou et al. (ref.22). The error bar corresponds to a theoretical uncertainty, assumed independent of R(GT) and discussed by the authors. The most deviate point in this comparison is found in $^{12}$Be decay and could be related to intruder ($\geq 2\ \hbar\omega$) admixtures, not taken into account in the model space.

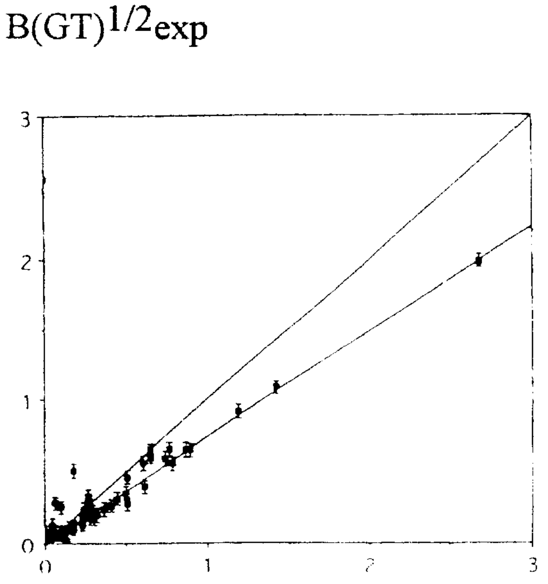


Fig.4 : Comparison of the experimental and "effective" values of B(GT) for 50 fp-shell decays in the A=41-55 range. The theoretical values are calculated by H. Miyatake et al.[23)] with particle excitations from the $f_{7/2}$ orbit to upper fp shell limited to $N_{jump}=2$. These calculated results are reported here with a renormalization factor of 0.76, identical to the one used in Ref.20-21 for the sd shell. The most deviate point is found for $^{42}$Ti to $^{42}$Sc, $1^+_2$ decay ($B(GT)^{1/2}_{exp}$ = 0.509) for which $N_{jump}$ = 1 gives a much better agreement and illustrates the model dependence of the calculation.

The comparison between experimental and calculated values of the GT strength in a large energy range including the Gamow Teller Giant Resonance, appeals to results from (p,n) reactions at intermediate energy or detailed decay studies of proton-rich nuclei. Recent results from charge transfert reactions and decay far from stability can be compared with new large scale calculations (shell model and RPA or QRPA) and it is of interest to illustrate the situation with the case of $^{54}$Fe for which total strength has been measured[13,24] and many theoretical evaluations are available[25-27].

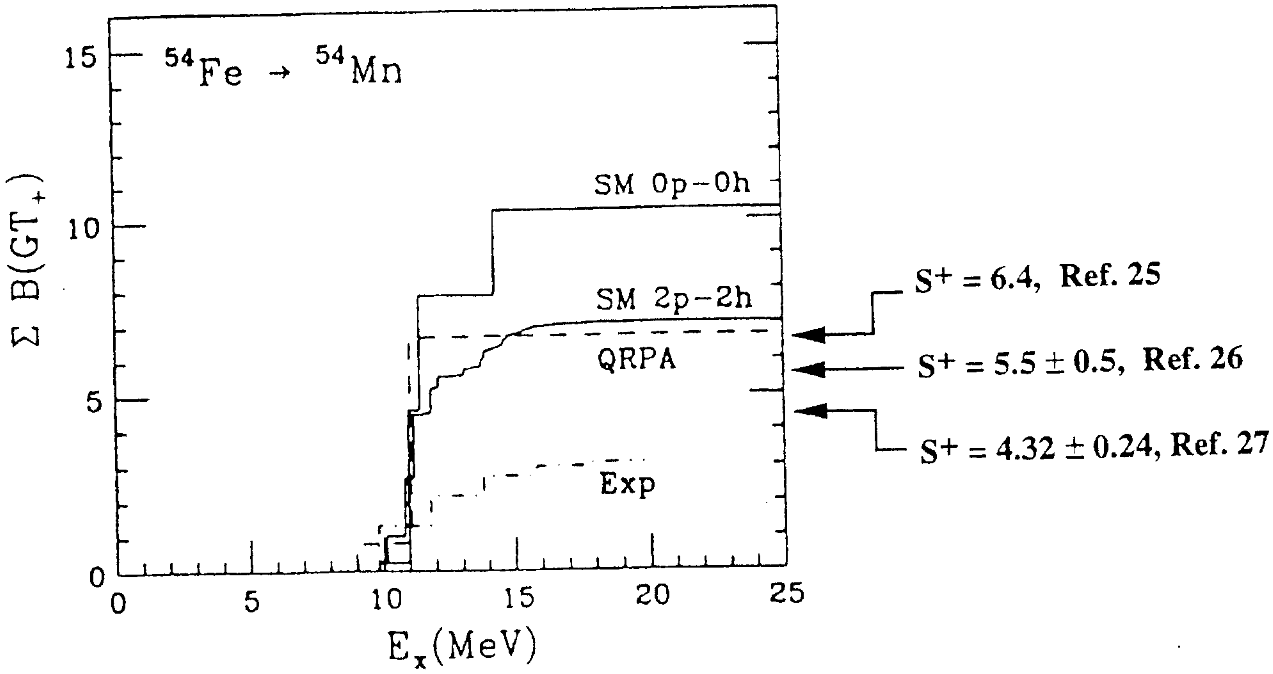


Fig.5 : Running sum of B(GT$^+$) for $^{54}$Fe taken from Auerbach et al. (ref.25). Are also indicated values of the total strength at E$_x$=25 MeV, S$^+$, obtained in three different approaches :
1) By extrapolation of 2p-2h shell model calculation (see text). Auerbach et al., ref.25.
2) By a large scale shell model calculation involving up to 5 jumps from $f_{7/2}$ shell to the other orbits. Caurier et al., ref.26
3) Resulting from a Monte Carlo shell model calculation. Alhassid et al., ref.27.

Figure 5 taken from A.Auerbach et al.[25] presents the running sum of the B(GT$^+$) values for $^{54}$Fe with excitation energy. S$^+$ is the total value obtained at 25 MeV,with three calculations : shell-model 0p-0h and 2p-2h with MSOBEP[28] interaction and quasi particle RPA calculations; experimental results are from ref.13. The corresponding theoretical results for $^{26}$Mg, for which a full calculation is available[25], are also reported to illustrate the sensitivity of these evaluations to the truncation of the model space. In order to report the theoretical situation, we have also indicated, in Fig.5, three values of the total strength S$^+$, calculated in different approaches :

$S^+ = 6.4$ corresponding to the full calculation extrapolation made by Auerbach et al.[21] on the basis of the truncated $^{54}$Fe and full $^{26}$Mg results. A correlation between the total GT strength quenching and the increase of E2 strength[29] from $^{54}$Fe to $^{26}$Mg is used for this extrapolation.

$S^+ = 5.5 \pm 0.5$ corresponding to the extrapolation given by a large scale shell model calculation SMLS, made by Caurier et al.[26] involving transitions with up to 5p-5h in the parent state, the daughter being described by configurations up to 6p-6h. The interaction effect is also evaluated as results are given with two different interactions.

$S^+ = 4.32 \pm 0.24$ which represents the full model space extrapolation obtained by Alhassid et al.[27) with a Monte Carlo shell model calculation, SMMC.

A detailed discussion of these results is given in ref.25,26 but the two main features are clearly apparent in figure 5 :

- the inclusion of many particle-many hole configurations leads to a large reduction of the total strength,
- if the GT operator is renormalized by a factor 0.77 [ $g_A(\text{eff}) = \sqrt{0.6}\, g_A$] the resulting strength comes very close to the experiment. Corresponding values are given below for $^{54}$Fe

| | | |
|---|---|---|
| $S^+_{ex}(^{54}\text{Fe})$ | ref.13 | $S^+ = 3.1 \pm 0.6$ |
| Extrapolated value (Caurier et al, SMLS ref.26) | | $S^+ = 5.5 \pm 0.5$ |
| Calculated $S^+$ strength with universal quenching factor 0.6 | | $S^+ = 3.26 \pm 0.3$ |
| Corresponding $S^-$ prediction ($S^- = S^+ + 3(N-Z)$) | | $S^- = 11.5 \pm 0.5$ |
| Calculated $S^-$ strength with universal quenching factor 0.6 : | | $S^- = 6.8 \pm 0.3$ |
| $S^-_{ex}$ | ref.13 | $S^- = 7.7 \pm 1.2$ |
| | ref.30 | $S^- = 7.8 \pm 1.9$ |

How the standard quenching factor is introduced in these model calculations has also been discussed in a recent analysis (ref.31) of the $^{48}$Ca(p,n)$^{48}$Sc results. In this calculation, made in the full $(pf)^8$ space, the strength is divided in two parts, one related to the model space (here fp) : $S_m$, and another corresponding to the contribution from the rest of the space : $S_r$. Then the sum rule splits in two as :

$$S^- - S^+ = (S^- - S^+)_m + (S^- - S^+)_r$$

$$= 3\langle K|\hat{n}_m - \hat{z}_m|K\rangle + 3\langle K|\hat{n}_r - \hat{z}_r|K\rangle$$

where $n_m + n_r = N$ *and* $z_m + z_r = Z$

and $|K\rangle$ is the target exact eigenstate where the correlations make impractical the theoretical estimate.

Equating separately the m and r terms, Caurier et al. obtain :

$$(S^- - S^+)_m = 3\langle k|n_m - z_m|k\rangle \; [0.70(5)] \qquad [2]$$

where $|k\rangle$ stands for the model target eigenstate, accessible to the calculation. The factor 0.70(5) which measures hole occupancies at the Fermi level in $^{40}$Ca, is given by (d,p) data.

As most of the measured strength, in the resonance region, is related to states described in the model space, relation [2] gives an evaluation of the measured strength. The contribution due to intruders transfer some of the strength in the upper part of the spectrum, and is difficult to discriminate from the background in a region of high level density.

To conclude, the theoretical description of the total strength for fp shell nuclei is fairly successful with the large calculations now available.

The theoretical estimate comes very close to the experimental value when the standard reduction factor is used. This reduction factor is close to the global quenching factor reported from the analysis of beta transitions in sd-shell nuclei. In both cases it appears related to the relative importance of the model states.

We should also note that the choice of the interaction is critical in these calculations and for relevant discussions, see ref.31 to 33.

## Strong GT Transitions Near the Drip-Lines

### *1) Neutron drip-line nuclei :*

In most (p,n) reactions the Giant GT resonance (GTGR), can be seen a few MeV higher than the Isobaric Analog State which is also populated. Due to the Coulomb energy, the $\beta^-$ decay is unable to feed the IAS and can usually only explore the remote tail of the giant resonance. Up to now, the observation in nuclear beta decay of the GTGR was therefore limited to the $\beta^+$ decay of $N < Z$ nuclei. M. Borge et al.[34,35] had reported a number of beta-decay branches of neutron drip-line nuclei ($^6$He, $^8$He, $^9$Li and $^{11}$Li) presenting a similar pattern with strong feedings to levels a few MeV below the parent state (Fig.6).

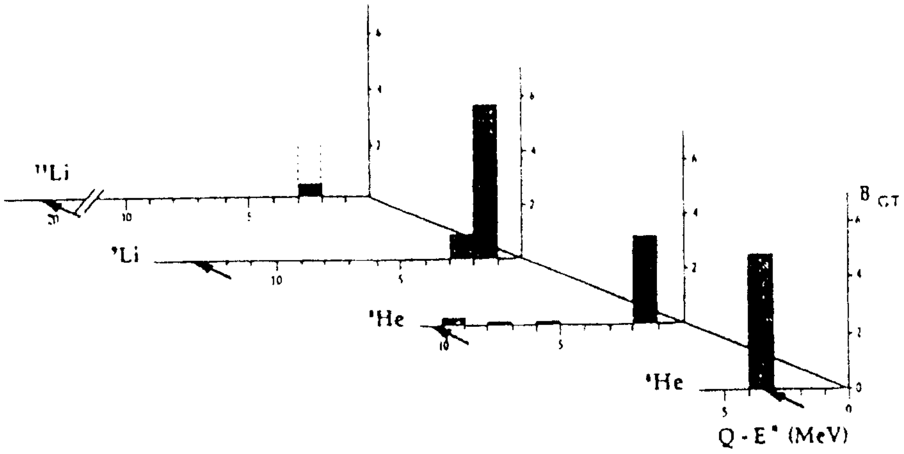


Fig.6 : Experimental distribution of B(GT) values for $^6$He, $^8$He, $^9$Li and $^{11}$Li measured by M. Borge et al.[34]. Energies are measured from the parent state. The strong B(GT) values observed for transitions to final states very close to the parent state, are in most cases, only lower limits. In $^8$He, recent measurements[35] of the β-delayed triton branch to the 9.3 MeV level in $^8$Li indicate a B(GT) value of 5,18, twice the value reported here.

These enhanced transitions exhaust a sizeable part of the GT sum rule. On the basis of log*ft* values (which can be as low as 2.84) these transitions appear as "superallowed" but distinct from the usual superallowed decays (here, $\Delta T=0$ being strictly forbidden). The existence of such "super-allowed" decays was tentatively attributed to neutron halos[34].

A very simple model[36] had been used previously by Gaarde[37] to evaluate the energy systematics of the GT resonances. According to this model, the difference between the GTGR and the IAS is determined as a function of (N-Z)/A and for large values [(N-Z)/A > 0.3], the decrease of the GT resonance energy is large enough to come below the IAS energy.

Sagawa et al.[38] performing HF plus RPA calculations, have located the position of the GTGR relative to that of the ground state of the mother nuclei as a function of the neutron excess. A part of their results, reported in Fig.7, shows that the position of the GTGR decreases with increasing neutron number to come in some cases lower than the ground state of the mother nucleus ($^{8}$He, $^{22}$C, $^{28}$O). In these cases, one expects to observe a large fraction of the total GT strength. The lowering of the GTGR relative to the IAS is interpreted as a consequence of the decrease of protons one-particle orbitals with increasing neutron number. This effect is clearly revealed by the HF potentials calculated by I. Hamamoto et al.[39].

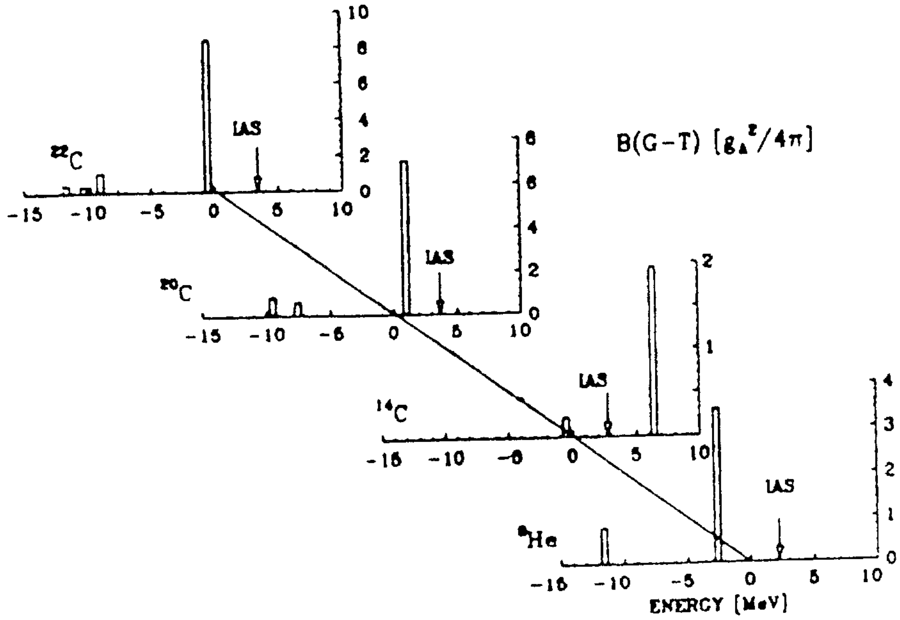


Fig.7 : Theoretical distribution of B(GT) values for $^{8}$He, $^{14}$C, $^{20}$C and $^{22}$C calculated by H. Sagawa et al.[38]. Energies are given with the same reference as in Fig.6. The results of the (HF + TDA) calculations give the relative positions of the IAS (arrow) and GTGR.

The simple model with separable interactions used by Gaarde[37)] allowed also Sagawa et al.[38)] to investigate the relative position of GTGR, IAS and parent states for (N-Z)/A values up to 0.5. To conclude, the beta decay to the GT giant resonant state appears to be possible for very neutron-rich light nuclei and this assumption has been confirmed in a few cases.

It was important to know if such properties could be interpreted in a shell-model context. A study of the extremely neutron-rich $^{28}O$ by Poves et al.[40)] has been performed in a valence space allowing proton and neutron excitation in the sdfp shells. In this description, $^{28}O$ ground state is found with a leading term with a $(fp)^2$ (J=0, T=1) intruder configuration. In the beta decay, the main branch is then predicted to populate a state at high energy with a proton neutron pair $(fp)^2$ (J=1, T=0) with log*ft* = 3, corresponding to the "super-allowed" regime.

The GT decay of very neutron rich nuclei reveal therefore interesting features with the possible study of the GTGR. The very low beta energy involved in these transitions and the presence of different open channels make very difficult the observation of these properties. "Superallowed" transitions correspond to branches in the $10^{-3}$ range (or lower). Progresses in production yields and detection techniques are then necessary for further steps.

## 2) *Proton drip-line nuclei :*

If we turn to the proton-rich nuclei, we know that the GT resonance population in the beta decay may be observed for some light N<Z nuclei. When Z increases, we meet a situation comparable to the one observed for very neutron-rich, but in the opposite direction : due to the Coulomb interactions, energies of one-particle orbitals is lower for neutrons than for protons. I. Hamamoto and H. Sagawa[39)] have used HF + RPA calculations as well as estimations with the Bohr crude model[36)] to select cases around the N=Z line where the beta decay to the GT giant resonance state is possible. From this study, "super-allowed" beta decays are energetically attainable for N=Z nuclei with A ≥ 64, and in particular for $^{100}Sn$.

The GT beta decay of $^{100}Sn$ to low-lying levels of $^{100}In$ in terms of shell model picture is expected to be concentrated in the $\left|\pi g_{9/2}^{10}, 0^+\right\rangle \rightarrow \left|\pi g_{9/2}^{9} \nu g_{7/2}, 1^+\right\rangle$ transition. New studies include the shell model calculations of Brown and Rykaczewski[41)] made in different model spaces and the HF + TDA estimations by Hamamoto and Sagawa[39)]. A very good agreement between these predictions allows to attribute only a few percent of the GT strength outside the 1st $1^+$ ($^{100}In$ ) at $E_X \cong 1.8$ MeV.

The measurement of the strength and of the spreading width of this transition will give a clear signature of the shell closure at N=Z=50. The actual magnitude of isospin mixing (T=1 admixed into the T=0 ground state) has also to be determined. It could amount to 4 % (mixing probability) in the case of $^{100}Sn$ ground state[39)].

## GT Transitions far from Stability

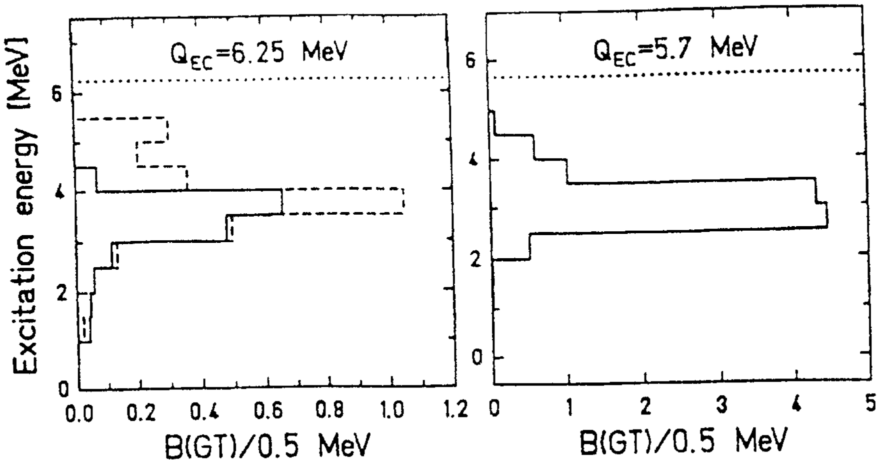
### *1) Experimental GT studies near $^{100}Sn$ :*

The very simple decay predicted for $^{100}$Sn forms a contrast with the observed GT decay modes for neighbouring nuclei. A comprehensive experimental study of GT decay in the $^{100}$Sn region, made in the recent years by a Collaboration at the on-line mass separators of GSI Darmstadt, ISOLDE CERN and LLN IKS Leuven[42-44], produces important results for understanding the structure of these nuclei (see Proceedings of the Bernkastel-Kues Conference and contributions to this Conference). In addition to the nuclear structure information, this study has specified the reduction of GT strength as compared to model calculations and pointed out the difficulty to extract GT strength in the Q EC/b$^+$ window with the experimental sensitivity limits. The recent results on $^{105}$Sn decay illustrate the problems encountered in the experiment/calculation comparison[43] and one may summarize their results as follows :

The EC/$\beta^+$ decay of $^{105}$Sn ($J^\pi$=5/2$^+$) is associated with a g 9/2 proton from the even-even core, the odd neutron being spectator. The decay is dominated by the transition :

$$\pi g_{9/2}^{10}\, \nu d_{5/2} \rightarrow \pi g_{9/2}^{9},\ \nu d_{5/2},\ \nu g_{7/2}$$

which is expected to populate 3 quasiparticle states, spread over many levels. The resulting B(GT) distribution, obtained from the experiment is reported in Fig.8a and the corresponding shell-model calculation[41] is given in Fig.8b.



a) b)

Fig.8a : Experimental GT distribution for $^{105}$Sn decay measured by Pfützner et al.[43]. The two lines (solid and dashed) reflect experimental uncertainties in the beta balance evaluation of a complex decay scheme.

Fig.8b : Shell model prediction of the $^{105}$Sn decay by Brown and Rykaczewski[42]. Position and width of the calculated distribution are in agreement with the experimental one. Total strength could be reduced by hindrance factors, the importance of which is evaluated with the uncertainties of the experiment.

## GT Transitions far from Stability

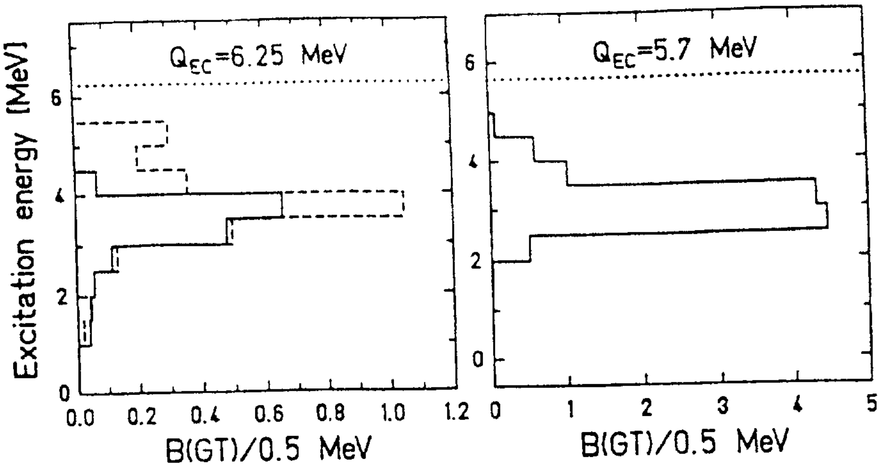
### *1) Experimental GT studies near $^{100}Sn$ :*

The very simple decay predicted for $^{100}$Sn forms a contrast with the observed GT decay modes for neighbouring nuclei. A comprehensive experimental study of GT decay in the $^{100}$Sn region, made in the recent years by a Collaboration at the on-line mass separators of GSI Darmstadt, ISOLDE CERN and LLN IKS Leuven[42-44), produces important results for understanding the structure of these nuclei (see Proceedings of the Bernkastel-Kues Conference and contributions to this Conference). In addition to the nuclear structure information, this study has specified the reduction of GT strength as compared to model calculations and pointed out the difficulty to extract GT strength in the Q EC/b$^+$ window with the experimental sensitivity limits. The recent results on $^{105}$Sn decay illustrate the problems encountered in the experiment/calculation comparison43) and one may summarize their results as follows :

The EC/$\beta^+$ decay of $^{105}$Sn ($J^\pi$=5/2$^+$) is associated with a g 9/2 proton from the even-even core, the odd neutron being spectator. The decay is dominated by the transition :

$$\pi g_{9/2}^{10}\, \nu d_{5/2} \rightarrow \pi g_{9/2}^{9},\ \nu d_{5/2},\ \nu g_{7/2}$$

which is expected to populate 3 quasiparticle states, spread over many levels. The resulting B(GT) distribution, obtained from the experiment is reported in Fig.8a and the corresponding shell-model calculation41) is given in Fig.8b.



a) b)

Fig.8a : Experimental GT distribution for $^{105}$Sn decay measured by Pfützner et al.43). The two lines (solid and dashed) reflect experimental uncertainties in the beta balance evaluation of a complex decay scheme.

Fig.8b : Shell model prediction of the $^{105}$Sn decay by Brown and Rykaczewski42). Position and width of the calculated distribution are in agreement with the experimental one. Total strength could be reduced by hindrance factors, the importance of which is evaluated with the uncertainties of the experiment.

Two features should be noted :

- the reduction of the observed strength as compared to the prediction :
  [ $\Sigma$ $B(GT)_{exp}$ = 1.46 while the sum of the model strength amounts to 11.0],
- the complexity of the spectrum [ 104 $\gamma$ transitions are observed, more than 300 allowed $\beta$ transitions are predicted ].

In these conditions, a complete decay scheme is inaccessible with standard techniques and $\Sigma B(GT)_{exp}$ is only a lower limit, a more realistic value could exceed 3 B(GT) units. Furthermore, the theoretical result has to be corrected for hindrance factors (core polarization, higher order effects) which can bring its value from 11.0 to 4.2. With these corrections, a global agreement with the experiment would be possible.
In the case of $^{105}$Sn, the limits of the high resolution, low efficiency spectroscopy are reached and data will be improved43) using more selective production techniques (new ion sources as laser ion sources) and more sensitive detection techniques (total absorption $\gamma$ spectrometer45)).

### 2) *GT studies for medium mass neutron-rich nuclei :*

With the proton-induced fission of $^{238}$U and ion-guide on-line mass separation technique (IGISOL) a new series of GT transitions has been investigated for very neutron-rich nuclei with $40 \leq Z \leq 44$. Results found in the literature46-49) and reported to this Conference50) concern Zr, Nb, Pd, Ru, Mo, Tc and Ru isotopes. The high neutron excess is responsible for a large $\beta^-$ strength (as predicted by the sum rule) but the (N-Z)/A ratio does not exceed 0.2 and the GTGR is always located above the $Q_\beta$ window. Among the broad data base obtained with this powerful technique, the systematics of the GT strength for the even-even nuclei $^{118-120}$Pd, $^{110-114}$Ru, and $^{104-108}$Mo provides a description of the $1^+$ states in the daughter (Ag, Rh, Tc). For these deformed nuclei, a macroscopic-microscopic model (Dobaczewski et al.51)) can be used to reproduce the distribution of $1^+$ states. The beta decay pattern of the distributions for prolate or oblate deformations being very different, comparison with experimental data leads to the sign of the deformation. In this way, it has been found for very neutron rich Mo isotopes that the $E_{average}(1^+)$ comparison clearly favors the prolate calculation49).

### 3) *GT strength measurements in $^{37,38}$Ca decays :*

The measurement of the distribution and absolute value of GT strength in $^{37}Ca \rightarrow {}^{37}K$ decay has been undertaken in detail by Adelberger et al.52,53) due to its importance on several accounts :

- the determination of the neutrino absorption cross-section in detectors based on the $^{37}Cl(\nu_e,e^-)^{37}Ar$ reaction, $^{37}$Ar being the isospin mirror of $^{37}$K, the $^{37}Cl\ (\nu_e,e^-)^{37}Ar$ cross section is linked to the ft values of $^{37}Ca(\beta^+)^{37}K$ decay,

- the comparison with shell model calculations available for this mass in order to appreciate the validity of the model (description of the distribution) and the need for any renormalization of $g_A$ (absolute strength),
- the unusual possibility to compare the $\beta^+$ decay results to GT strength distributions obtained in (p,n) reaction studies.

A first set of experiments, concentrated on the detection of $\beta^+$ delayed protons52,53) did not reproduce the GT strength profile measured in (p,n) studies54) and motivated new experiments with the hadronic and the weak interaction probes. In particular, the inclusion of $\beta^+$ delayed gammas bring appreciable changes in the $\beta^+$ decay balance and the new results, reported at this conference55), are in fair agreement with those obtained from $^{37}$Cl(p,n)$^{37}$Ar reactions.

The $^{38}$Ca $\rightarrow$ $^{38}$K decay56), was measured in a high sensitivity experiment (at the $10^{-4}$ level) foreseen to measure weak 1st forbidden transitions. The experiment, at the on-line mass separator ISOLDE/Booster needed a chemically selective production of $^{38}$Ca (obtained with CaF$^+$ ions), in order to avoid the $^{38}$K parasitic activity simultaneously produced with much higher yields. With the resulting selectivity and sensitivity, the B(GT) distribution was obtained in a large fraction of the $Q_{\beta}{}^+$ window and revealed to be a crucial test for the analysis of GT strength in this mass region as about 80 % of the total GT strength is located inside the experimental range.

- A test of the model space : five $1^+$ levels in $^{38}$K are found in the experiment below $E_x = 4$ MeV when sd calculations give only three $1^+$ levels below 7 MeV. This result shows the inadequacy of the sd model space for a complete description of B(GT) strength and the presence of intruders. A calculation in the $(d_{3/2},f_{7/2})^6$ model space reveals the first intruder state at 4.3 MeV,

- A test of the equivalence of B(GT) and small momentum transfer measurements. If we compare the B(GT) distribution r from the $^{38}$Ca $\rightarrow$ $^{38}$K decay with the results of the $^{38}$Ar(p,n)$^{38}$K reaction measured recently at 0.2° and 135 MeV by Anderson et al. at Indiana57) (Fig.9) a remarkable agreement is found, confirming the consistency of the two probes for the B(GT) strength determination58),

- Finally, the experiment provides a severe test for the interaction. In the $^{38}$Ca decay where the main strength (> 80 %) is at low energy, within the EC/$\beta^+$ window, B.A. Brown56) found the best agreement for B(GT) distribution by using the Chung-Wildenthal, CW, interaction. The choice of the interaction is essential in the case of the $^{37}$Ca decay where only 20 % of the calculated strength is below 8 MeV and the fraction $B(GT)_{ex}/B(GT)_{th}$ is found considerably different according to the interaction used33).

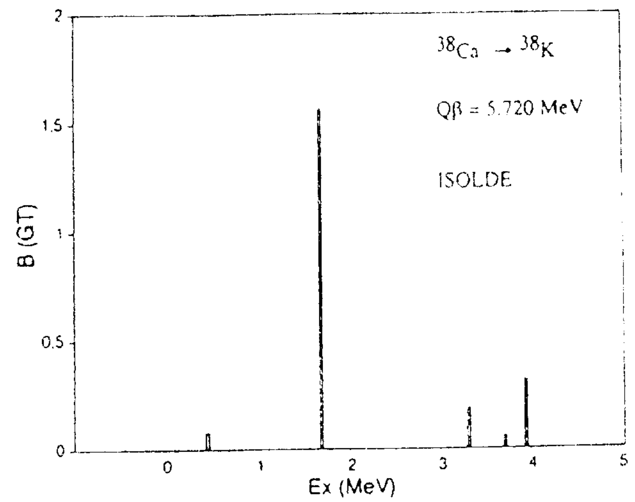


Fig 9a

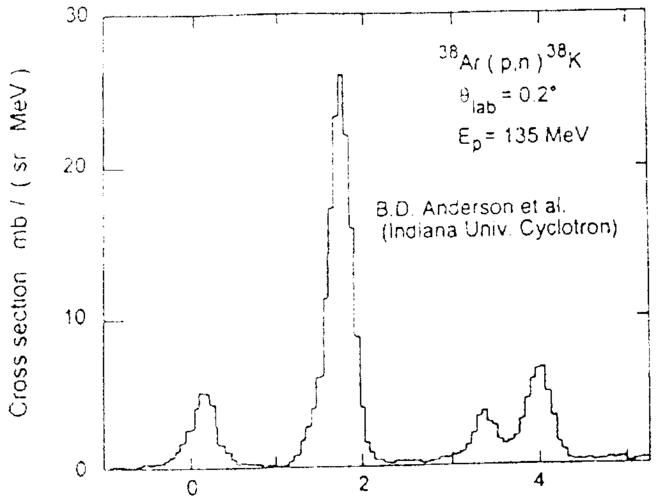


Fig 9b

Fig.9 : Illustration of the two approaches to GT strength determination in the A=38 case. In 9a : Beta decay measurement of B(GT) for $^{38}Ca(\beta^{+})^{38}K$, using gamma spectroscopy, at ISOLDE/Booster. In 9b : Time of flight spectrum measured at 0.2° for $^{38}Ar(p,n)^{38}K$ at indiana Univ. Cyclotron Facility. The reaction is leading at the same final nucleus and the spectrum is displayed with the same excitation energy range. The equivalence of the two probes is clearly illustrated (minor differences resulting from different resolving power and the absence of ground state transition in the B(GT) study). In 9c : The time of flight spectrum up to 20 MeV (excitation energy) reveals that most of the strength is within the beta window.

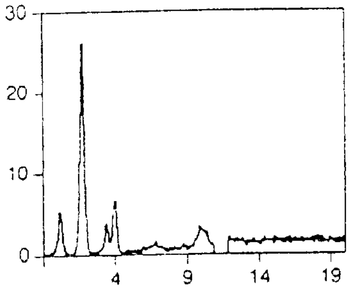


Fig 9c

## GT Strength and Stellar Matter Evolution

We have seen that ft values of the $^{37}Ca$ decay scheme were an important input parameter for the detection of the solar neutrinos with chlorine detectors. All neutrino detectors utilizing inverse β-decay on the proton are calibrated using the accepted values of the nucleon weak couplings. The Sun's energy release depends on the cross-section of the pp process : $p + p \rightarrow D + e^{+} + \nu$, too weak to be measured in the laboratory but evaluated using the value of $g_A$, itself related to the GT matrix element for the neutron. These examples of the implication of weak decay parameters and studies related to to the early stages of stellar matter evolution suggest a broad field of application for the GT studies.

In the late stage of stellar evolution, Bethe et al.59) made the first complete calculations, with a simple model, of the weak processes (beta decay and electron capture) which determine the electron/baryon ratio and are essential for the evaluation of the core collapse of a massive star. It was clear that in the heavy core, electrons could have the necessary energy to reach the GT resonance range which, as a result, corresponds to a major part of the $e^-$ capture rate in a collapsing star. A more detailed treatment of nuclear structure effects was made in the calculations of Fuller, Fowler and Newman60) who used compiled experimental tabulations and for unmeasured GT transitions a shell model calculation with the Chung-Wildenthal matrix elements when available. For the other GT transitions, they used a mean value corresponding to log ft=5.0. Further studies61,62) carried out large-scale shell model calculations for specific nuclei. Very recently, Oda et al.63) published the results of an extensive study in which GT strength distributions are calculated in the full $(sd)^n$ model space for 79 nuclei in the $17<A<39$ range. This work corresponds to a substantial improvement in the evaluation of the weak interaction rates and allows interesting comparisons for wide ranges of isotopes, isotones and isobars. Evaluation of the strength for neutron excess nuclei reproduces the GT giant resonance which was discussed above39,40).

Using the wave functions of the ground state, generated in this study, it was also possible to evaluate $S^{\pm}$, expressed as a sum, $S^{\pm} = S_{ON} + S_{pn}$, (occupation probability term + proton-neutron correlation term) as introduced earlier by Hino17). Results reported in Fig.10 for Mg isotopes are given as $S^{\pm}/S_{ON}$. The total strength, $S^-$, with full correlation increases with neutron number, and the $\beta^+$ strength is strongly suppressed mainly by the proton neutron correlations.

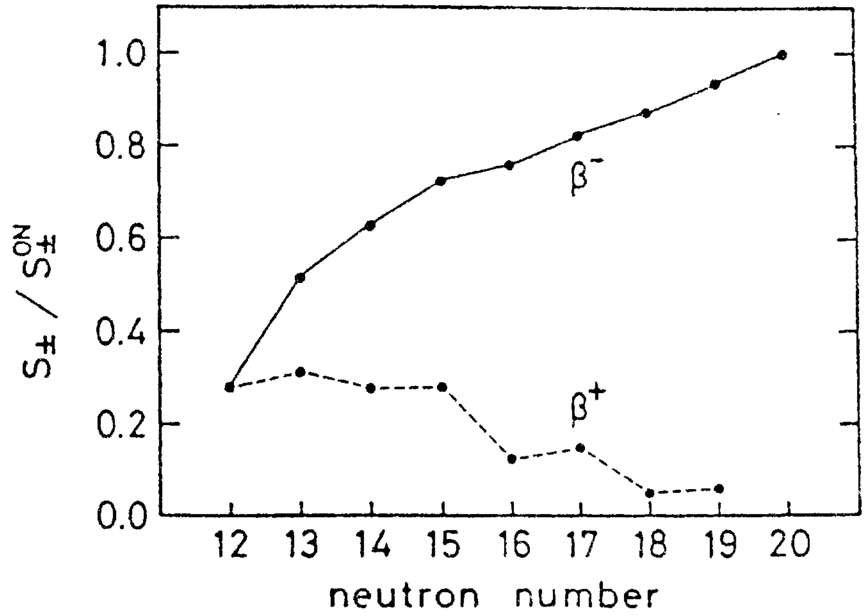


Fig.10 : Calculation by T. Oda et al.63) of the reduction of $S^{\pm}$ due to proton-neutron correlation in the parent state for Mg isotopes.

We note however that these results for $S^{\pm}$ are strongly model dependent and in this particular case (close to N=20) the model choosen (full sd shell) gives poor agreement with experiment64,65).

## Conclusion

The study of GT distribution and strength, either by charge exchange or weak decay, provide excellent tests for nuclear models as these parameters are extremely sensitive to the details of nuclear structure. Recent improvements of these models have reduced, for the most part, differences between experiment and theory, allowing in turn a more reliable estimate of weak decay rates in stellar matter.

A better understanding of the "missing strength" and of the failure of many experiments to detect the strength that is present have also been obtained. Recently, it appeared also that weak decay studies in selected region (proton or neutron rich) of the N-Z plane give access to the GT giant resonance. For these reasons, improvements in experimental techniques (production yields, resolution and sensitivity) are clearly needed.

## References

1) G. Gamow and E. Teller, Phys. Rev. 49 (1936) 895
2) F. Didierjean and G. Walter, Strasbourg CRN, Report 94-01
3) J.C. Hardy et al., Nucl. Phys. A509 (1990) 429
4) D.H. Wilkinson, Nucl. Instr. Meth. A335 (1993) 172
5) K. Ikeda, Prog. Theor. Phys. 31 (1964) 434
K. Ikeda et al., Phys. Lett. 3 (1963) 271
6) C. Gaarde et al., Nucl. Phys. A334 (1980) 248
7) B.D. Anderson et al., Phys. Rev. C27 (1983) 1387
8) C.D. Goodman et al., Phys. Lett. B107 (1981) 406
9) C. Gaarde et al., Nucl. Phys. A369 (1981) 258
10) S. Yen et al., Phys. Lett. B206 (1988) 597
11) S.E. Koonin and K. Langanke, Phys. Lett. B326 (1994) 5
12) B.D. Anderson et al., Phys. Rev. C41 (1990) 1474
13) M.C. Vetterli et al., Phys. Rev. C40 (1989) 559
14) C.D. Goodman et al., Phys. Rev. C42 (1990) 1150
15) M.H. MacFarlane, Phys. Lett. B182 (1986) 265
M.H. MacFarlane, Can. J. Phys. 65 (1987)
16) G. Mairle et al., Nucl. Phys. A490 (1988) 371
17) M. Hino et al., Phys. Rev. C37 (1988) 1328
18) B.D. Anderson et al., Phys. Rev. C36 (1987) 2195
19) R. Madey et al., Phys. Rev. C35 (1987) 2011
20) B.A. Brown and B.H. Wildenthal, Phys. Rev. C28 (1983) 2397
21) B.A. Brown and B.H. Wildenthal, At. Data Nucl. Data Tables 33 (1985) 347

22) W.T. Chou et al., Phys. Rev. C47 (1993) 163
23) H. Myatake et al., Nucl. Phys.A470 (1987) 328
24) J. Rapaport et al., Nucl. Phys. A431 (1984) 301
25) N. Auerbach et al., Nucl. Phys. A556 (1993) 190
26) E. Caurier et al. (1994) to be published
27) Y. Alhassid et al., Phys. Rev. Lett. 72 (1994) 613
G.H. Lang et al., Phys. Rev. C48 (1993) 1518
28) W.A. Richter et al., Nucl. Phys. A523 (1990) 325
29) N. Auerbach et al., Phys. Lett. B304 (1993) 17
30) J. Rapaport et al., Nucl. Phys. A410 (1983) 371
31) E. Caurier et al. (1994) to be published and
E. Caurier et al., Phys. Rev. C50 (1994) 225
32) D.J. Dean et al., Phys. Rev. Lett. 72 (1994) 4066
33) B.A. Brown, Phys. Rev. Lett. 69 (1992) 1034
34) M.J.G. Borge et al., Z. Phys. A340 (1991) 255
35) M.J.G. Borge et al., Nucl. Phys. A560 (1993) 664
36) A. Bohr and B.M. Mottelson, Nuclear Structure, Vol.II (Benjamin, Reading, MA, 1976) Ch.6
37) C. Gaarde, Nucl. Phys. A396 (1983) 1276
38) H. Sagawa et al., Phys. Lett. B303 (1993) 215
39) I. Hamamoto and H. Sagawa, Phys. Rev. C48 (1993) R960
40) A. Poves et al., Z. Phys. A347 (1994) 227
41) B.A. Brown and K. Rykaczewski (to be published) and contribution to this conference
42) K. Rykaczewski, Proc. 6th Int. Conf. on Nuclei far from Stability, Bernkastel-Kues, 1992
ed. R. Neugart and A. Wöhr (IOP Publishing Bristol, Philadelphia, 1993) p.517
43) M. Pfützner et al., GSI 94-23
44) H. Keller et al., Contribution to this Conference
45) L. Batist et al., GSI Scientific Report 1992, GSI 93-01, p.82
46) A. Jokinen et al., Proc. 6th Int. Conf. on Nuclei far from Stability, Bernkastel-Kues, 1992
ed. R. Neugart and A. Wöhr (IOP Publishing Bristol, Philadelphia, 1993) p.563
47) J. Äysto et al., Phys. Rev. Lett. 69 (1992) 1167
48) Z. Janos et al., Nucl. Phys. A552 (1993) 340
49) A. Jokinen et al., JYFL Report 10/1994
50) A. Jokinen, Contribution to this Conference
51) J. Dobaczewski et al., Z. Phys. A329 (1988) 267
52) E.G. Adelberger et al., Phys. Rev. Lett. 67 (1991) 3658
53) A. Garcia et al., Phys. Rev. Lett. 67 (1991) 3654
54) J. Rapaport et al., Phys. Rev. Lett. 47 (1981) 1518
55) W. Trinder et al., Contribution to this Conference

56) P. Baumann et al. (1994), submitted for publication

57) B.D. Anderson, Kent State University, private communication

58) T.N. Taddencci et al., Nucl. Phys. A469 (1987) 125

59) H.A. Bethe, Nucl. Phys. A324 (1979) 487

60) G.M. Fuller et al., Astrophys. J. Suppl. 42 (1980) 447

61) M. Takanare et al., Nucl. Phys. A504 (1989) 167

62) M.B. Aufderheide et al., Phys. Rev. C48 (1993) 1677

63) T. Oda et al., Atomic Data and Nuclear Data Tables 56 (1994) 231

64) G. Klotz et al., Phys. Rev. C47 (1993) 2502

65) A. Poves and J. Retamosa, Nucl. Phys. A571 (1994) 221