LA-UR -86-3588

CONF-8610??-- 1

Received by OSTI

NOV 0 7 1986

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--86-3588

DE87 001970

TITLE: ON THE QUENCHING OF GAMOW-TELLER STRENGTH

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SUBMITTED TO: The Canadian Journal of Physics

Los Alamos

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On the Quenching of Gamow-Teller Strength

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(Index Classification: 24.10)

Abstract

The (p,n) reaction at intermediate energies has been used to measure differential cross sections in light nuclei, to final states characterized with a $\Delta J^{\pi} = 1^{+}$ transfer (GT states). Experimental ft values for allowed beta-decay transitions in these nuclei are used to normalize the strength of the GT transitions in units of B(GT). This experimental GT strength is compared with predicted shell model strength. For p-shell nuclei the calculated excitation energies of the GT strength using Cohen and Kurath wave-functions are in general agreement with the empirical GT distribution. Up to an excitation energy of about 20 MeV, the total experimental and calculated GT strengths are used to obtain the quenching factor, $Q_F = \Sigma B(GT)_{exp}/\Sigma B(GT)_{th}$. It is found that Q_F decreases as the shell gets filled-up. The lowest value seems to occur for single-hole nuclei. This decrease may be explained by configurations mixing not specifically included in the calculations.

1. *Introduction*

The (p,n) reaction at intermediate energies has been extensively used to study spin-isospin excitations in nuclei. It has been reported(1-3) that at zero degree the (p,n) spectra are dominated by isovector transitions characterized by the transfer of zero orbital angular momentum ($\Delta L = 0$). Empirical proportionality factors are used to relate these zero degree cross sections to the Fermi (F) and Gamow-Teller (GT) strengths for the corresponding transitions(4). These GT transitions are used to estimate the total GT strength, total in the sense of covering the excitation energy range containing all states with GT strength on the basis of conventional shell model calculations(5).

The GT states, its strength distribution in nuclei and the empirically evaluated total strength compared to theoretical predictions, has lately received much attention. As it has been reported(3,6) it seems that up to about 20 MeV excitation energy the quenching factor $Q_F = \Sigma B(GT)_{exp}/\Sigma B(GT)_{th}$ is $Q_F = 0.65 \pm 0.05$. This quenching has been interpreted as a mixing of the GT nuclear excitations with non-nucleonic degrees of freedom(7) while Arima(8) has stressed the importance of configuration mixing in these transitions.

This paper presents a more detailed study of GT transitions in light nuclei. In this region final states populated by these transitions are well separated and wavefunctions such as those of Cohen and Kurath (CK) for p-shell nuclei[9] may be used to obtain transition densities needed for the comparison between experiment and theory.

2. *Results and Analyses*

Many of the (p,n) transitions studied in p-shell nuclei are in mirror nuclei. For these nuclei the ground state mirror transition ($T_Z = 1/2$) is rather simple and may proceed either through Fermi or GT transitions. The observed β-decay strength is an incoherent sum of these two components. The Fermi matrix element is unity because it transforms a $T = 1/2$ state to its mirrored state. Thus, the total transition probability may be decomposed to obtain the GT matrix element from the ft value derived from the beta-decay energy and half-life. A summary and analysis, together with comparisons with shell-model calculations of the ground state mirror transitions, is presented in Ref. 10. The deduced GT empirical strength is usually about 50% of the shell-model value. Brown and Wildenthal[11] have reported on experimental and theoretical GT beta-decay observables for sd-shell nuclei. Their conclusion is that in the middle of the sd-shell the effective matrix elements are quenched by an overall factor of 0.76 ± 0.03 relative to the "free-nucleon" values based on the neutron beta decay. This corresponds to a quenching of $(0.76)^2 = 0.58$ of the GT strength.

In general and because of energetics, beta decay excites only a rather small fraction of the total strength expected from the GT sum rule. Thus, and as has been pointed out[5], the model dependence of the comparison between measurements and calculations can be considerably reduced when the comparison is made for a larger fraction of the sum strength. This may be done using (p,n) reaction data at intermediate energies which are extremely suited to obtain the GT strength up to about 20 MeV excitation energies. The (p,n) data presented here were taken using the Indiana University Cyclotron time-of-flight facility. In all cases, unless otherwise noted, the measured zero degree (p,n) cross section in mb/sr, were expressed in units of B(GT) by using the procedures indicated in Refs. 2-6. In mirror nuclei, the zero degree (p,n) cross sections for the gs → gs transition was decomposed as an incoherent sum of $\sigma_{GT}(0°)$ and $\sigma_F(0°)$ using the empirical relation[12]

$$R^2 = \left(\frac{E_p}{55.4}\right)^2 = \frac{\sigma_{GT}(0°)/B(GT)}{\sigma_F(0°)/B(F)} \quad .$$

The deduced $\sigma_{GT}(0°)$ value extrapolated to zero momentum transfer, is used to obtain the proportionality constant to its B(GT) value (obtained from β-decay). For GT transitions to excited states, Q-dependent corrections are calculated to deduce the corresponding B(GT) values.

In the next sections results for p-shell nuclei and some sd-shell nuclei are presented.

2.1 *p-shell nuclei*

A = 6,7. The $^{6,7}Li(p,n)^{6,7}Be$ reaction has been measured at E_p = 80, 120, 160, and 200 MeV (J. Rapaport et al., manuscript in preparation.) The B(GT) values deduced from the (p,n) data are shown in Fig. 1 and are compared with calculated B(GT) values using CKWF, set (6-16) 2B [9]. The $^{6}Li(p,n)^{6}Be(gs)$ transition carries all the observed GT strength which is about 80% of the value predicted by the CKWF. The $^{7}Be(gs,3/2^-)$ and $^{7}Be(0.43\ MeV,1/2^-)$ states carry almost all of the GT strength. Transitions at $E_X \sim 7$, 9.9 and 16.3 MeV carry a small fraction of the total GT strength. The total observed strength is about 80% of the predicted strength using CKWF.

A = 9. The $^{9}Be(p,n)^{9}B$ reaction has been studied at E_p = 135 MeV by Pugh[13]. In Fig. 2 are shown the empirical and calculated B(GT) values. An empirical $\Sigma B(GT) \sim 2.2$ has been estimated (F. Petrovich, private communication) which is about 70% of the predicted CKWF value.

A = 11. The $^{11}B(p,n)^{11}C$ reaction has been studied at 26 MeV[14] and at 160 Mev (T. N. Taddeucci et al., manuscript in preparation). The spin transfer probabilities have also been measured at 160 MeV. The comparison of B(GT) values are presented in Fig. 2. A total GT strength of 3.0 is estimated from the data which is about 83% of the CKWF value.

A = 12,13,14. The study of the $^{12,13,14}C(p,n)$ reactions have been recently reported (J. Rapaport et al., manuscript in preparation). The comparison of B(GT) values are presented in Fig. 3. The $^{12}C(p,n)^{12}N(gs)$ transition carries all the GT strength which agrees very well with the CKWF predicted value.

The GT strength in the $^{13}C(p,n)^{13}N$ reaction is distributed in several states and a sum strength $\Sigma B(GT) = 1.8$ has been estimated. This value is only 46% of the CKWF predicted value. For ^{14}C the observed total GT strength is about 60% of the CKWF total strength of 6.0.

A = 15. The $^{15}N(\vec{p},\vec{n})^{15}O$ reaction has been studied at 160 MeV and reported in Ref. 15.

In the assumption that ^{15}N is a simple p-hole shell nuclei, the GT strength should be concentrated in just two states: the $p1/2 \rightarrow p1/2$ gs mirror transition and a $p1/2 \rightarrow p3/2$ transition with GT strength of 1/3 and 8/3 respectively. The experimental values show that the p3/2 strength is highly fragmented and the estimated total GT strength is $\Sigma B(GT) = 1.56$ compared to a predicted value of 3.0.

The calculated quenching factors Q_F for these nuclei are presented in Fig. 4. In the top of the figure values for A = 1 and A = 3 (Ref. 10) are presented, while the middle section has values for p-shell nuclei. An obvious decrease in Q_F is noticed as A increases in a given shell.

2.2 Some sd - shell nuclei. We discuss briefly three sd shell nuclei for which data have been reported.

A = 19. The $^{19}F(p,n)^{19}Ne$ reaction has been studied at 120 and 160 MeV[16]. As was the case for $^{6,7}Li(p,n)^{6,7}Be$ reactions, the beginning of p-shell nuclei, a large part of the GT strength is concentrated in the mirror transition. Excited states carry only 15% of the total strength. For mirror nuclei the sum rule for GT transitions (2) indicates:

$$S_{\beta-} - S_{\beta+} = 3(N-Z) = 3$$

where $S_{\beta-}$ is the total (p,n) GT strength while $S_{\beta+}$ represents the total (n,p) GT strength. Thus, in this case, the expected total (p,n) GT strength is

$$S_{\beta-} = 3 + S_{\beta+} \quad .$$

A value $\Sigma B(GT)_{exp} = 1.95$ is reported for the total observed strength which is 65% of the minimum expected value, assuming $S_{\beta+} = 0$.

A = 26. Experimental results for the $^{26}Mg(p,n)^{26}Al$ reaction, GT strengths and shell model calculations have been reported by Bloom et al.[17] There is good agreement between the observed and calculated excitation energies of GT states and it is estimated that 52% of the calculated strength is experimentally observed.

A = 39. Results for the $^{39}K(p,n)^{39}Ca$ reaction studied at 120 and 160 MeV are reported in Ref. 16.

Assuming that the target gs wavefunction may be represented as a 1d3/2 proton-hole, only two states should carry the GT strength: the gs d3/2 → d3/2 mirror transition and the d3/2 → d5/2 transition. The situation is similar to the A = 15 case. The d5/2 strength is highly fragmented, and many transitions carry this strength. The total GT strength estimated from the data up to about 10 MeV excitation energy is only $\Sigma B(GT) = 1.1$ or 37% of the sum rule predicted value.

3. *Conclusions*

The ratio of measured $\Sigma B(GT)$ over calculated total shell-model GT strengths are presented in Fig. 4. The trend observed in 1p shell-nuclei seems to be reproduced in the cases shown for sd-shell nuclei. The value of Q_F decreases as A increases in a given shell reaching a rather low value $Q_F \sim 0.4$ for single-hole shell nuclei. For the adjacent single-particle shell nuclei the value of Q_F increases drastically to $Q_F \sim 0.6$.

Medium mass 1f7/2 nuclei also follows a similar tendency. In ^{48}Ca, a value

$$Q_F = 0.71 \pm {}^{0.08}_{0.15}$$

was estimated(18), while in ^{51}V only 63% of the predicted strength is observed. In another N = 28 isotone nucleus, near the end of the 1f7/2 shell, ^{54}Fe, just 52% of the shell-model estimated strength has been observed(19). By measuring the $^{54}Fe(n,p)^{54}Mg$ reaction, Häusser (O. Häusser, manuscript in preparation) has been able to estimate a similar Q_F value.

A possible explanation of this shell closure effect, is that there is an overall quenching due to non-nucleonic degrees of freedom that reduce the GT strength to about 80-85% (A = 6,7,9,11,48, for example); however, when configurations mixing becomes important (A = 13,15,39,54, for example), they contribute a sizable amount to the calculated quenching of the GT strength. It should be interesting to perform calculations to estimate the GT strength in nuclei near the end of the shell, using a large shell model space including several $\hbar\omega$ and with many particle-many hole configurations. The predicted strength below 20 MeV excitation energy could then be compared with the present results. It is well known[20] that using a larger shell model space, some of the low lying GT strength gets pushed up in excitation energy, possibly escaping experimental observation. Thus, larger Q_F values for the GT strength below 20 MeV are expected.

Acknowledgments

The help provided by D. Kurath in evaluating excitation values and strengths for GT transitions in p-shell nuclei is greatly appreciated. This work was supported in part by a grant from the National Science Foundation.

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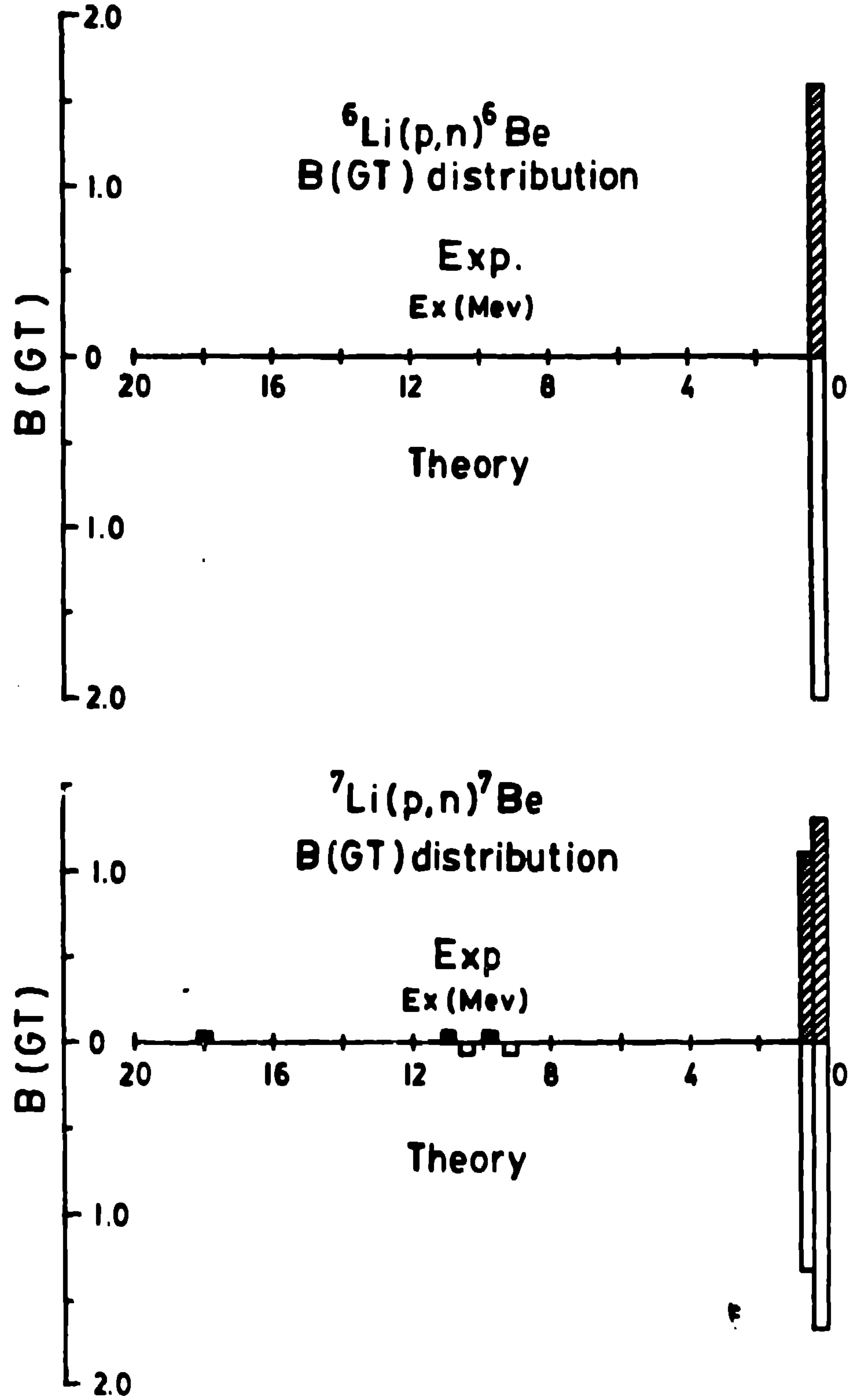
Figure Captions

Fig. 1. Comparison between observed and calculated GT transitions for the $^{6,7}Li(p,n)^{6,7}Be$ reactions. The shell model B(GT) values are obtained using Cohen and Kurath wavefunctions, set (6-16) 2B (Ref. 9). The use of Kumar interaction(21) changes slightly the strength distribution, but not the total sum.

Fig. 2. Same as in Fig. 1 except for the $^{9}Be(p,n)^{9}B$ and $^{11}B(p,n)^{11}C$ reactions.

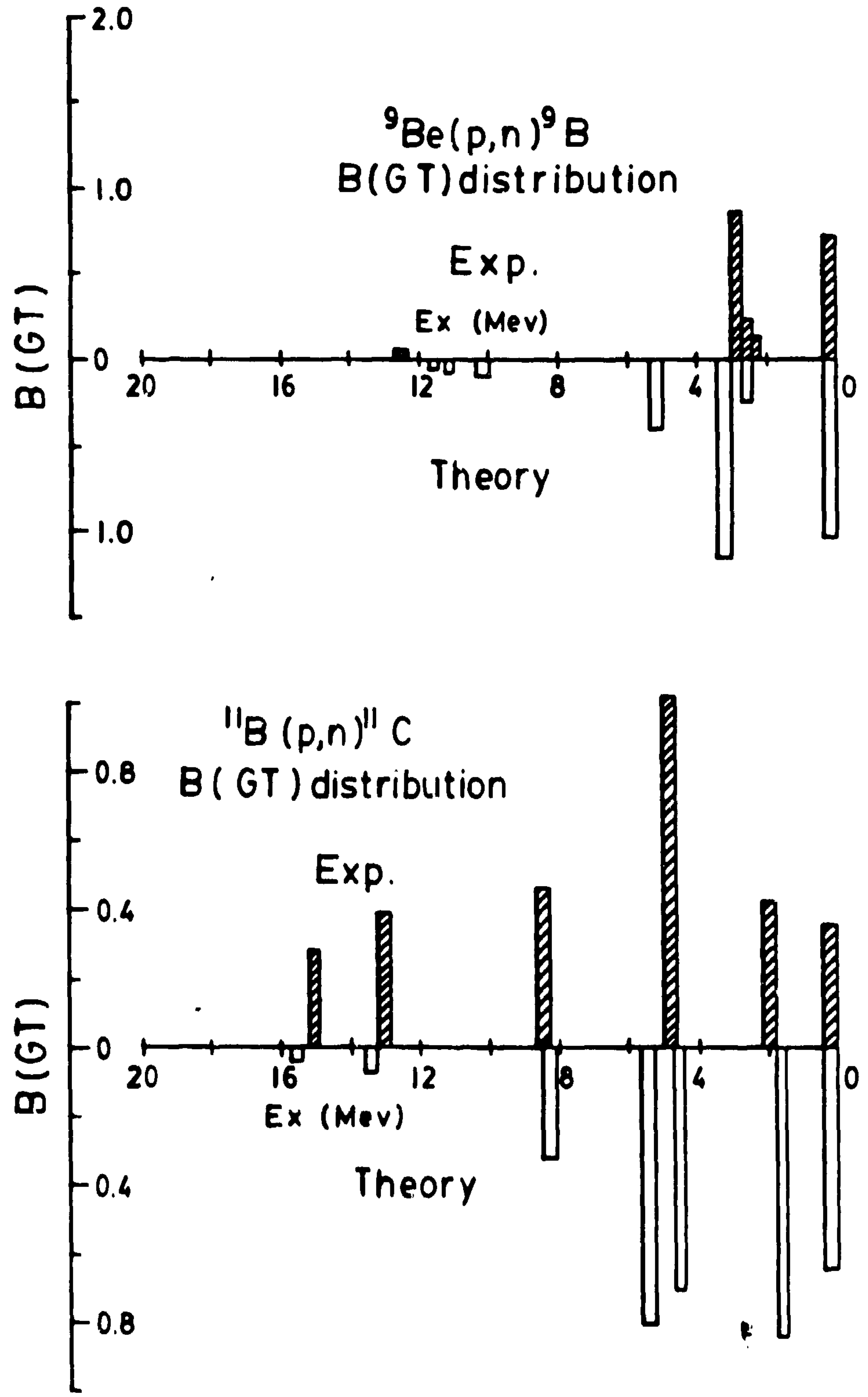
Fig. 3. Same as in Fig. 1 except for the $^{12,13,14}C(p,n)^{12,13,14}N$ reactions.

Fig. 4. Quenching factor Q_F, obtained dividing the total observed GT strength by the total calculated GT strength. Note that the total calculated strength is concentrated below 20 MeV excitation energy, as it is the observed GT strength.



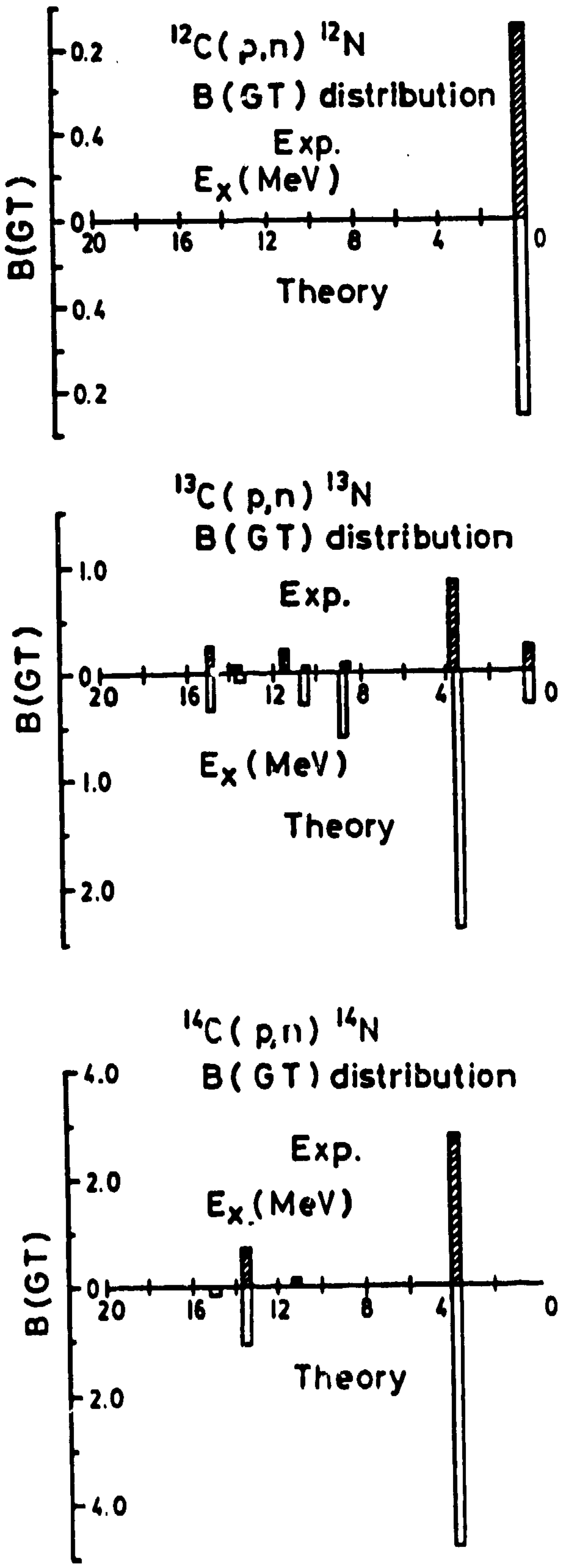
$^6Li(p,n)^6Be$
B(GT) distribution
Exp.
Ex (Mev)
Theory
B(GT)
2.0
1.0
0
20
16
12
8
4
0
$^7Li(p,n)^7Be$
B(GT) distribution
Exp
Ex (Mev)
Theory

Fig. 1



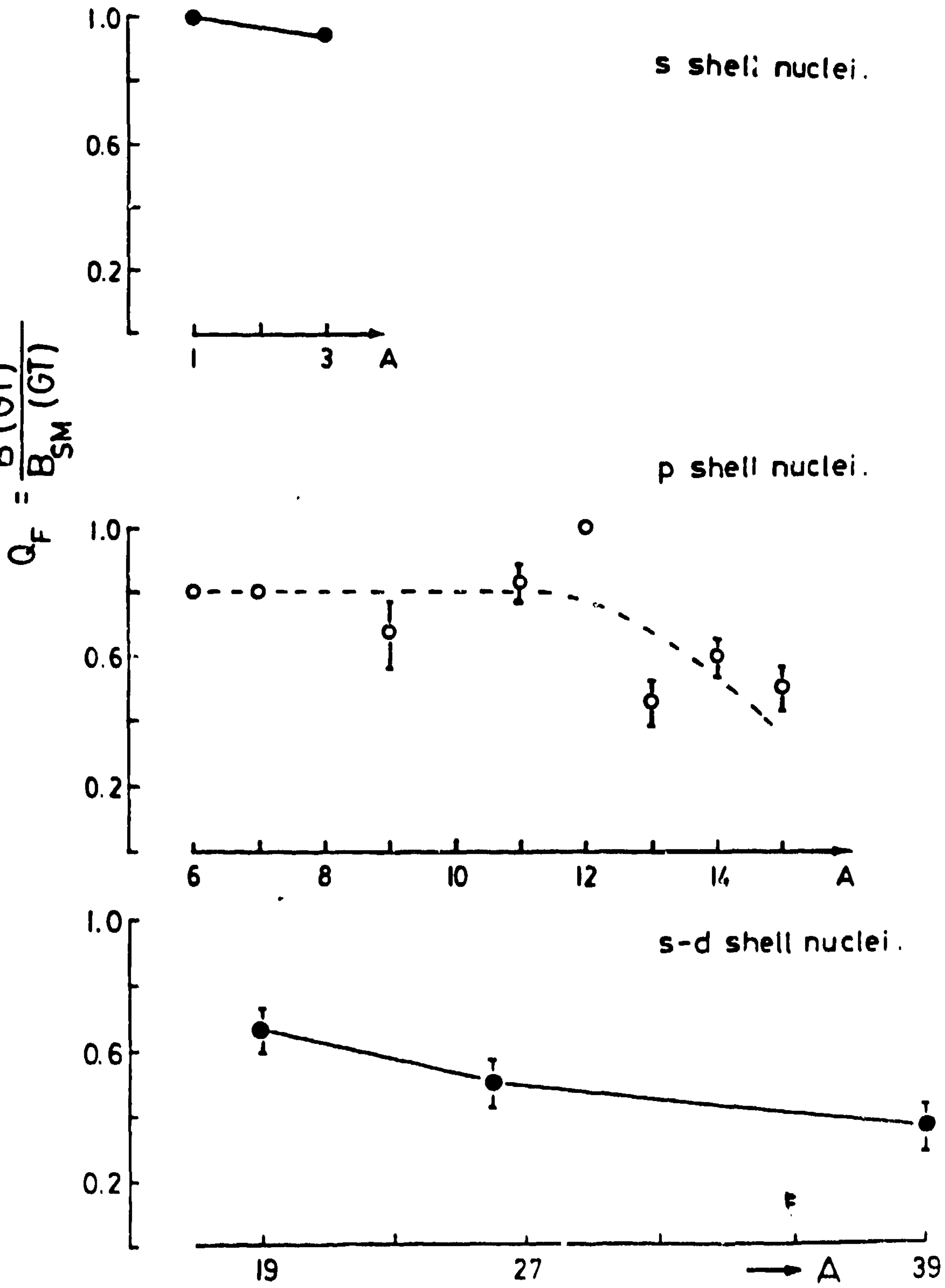
2.0
$^9Be(p,n)^9B$
B(GT)distribution
1.0
Exp.
Ex (Mev)
B(GT)
0
20
16
12
8
4
0
Theory
1.0
$^{11}B(p,n)^{11}C$
B(GT)distribution
0.8
Exp.
0.4
B(GT)
0
20
16
12
8
4
0
Ex (Mev)
Theory
0.4
0.8

Fig. 2



$^{12}C(p,n)\,^{12}N$
B(GT) distribution
Exp.
E_x (MeV)
Theory
B(GT)
0.2
0.4
0
0.4
0.2
20
16
12
8
4
0
$^{13}C(p,n)\,^{13}N$
B(GT) distribution
Exp.
E_x (MeV)
Theory
B(GT)
1.0
0
1.0
2.0
20
16
12
8
4
0
$^{14}C(p,n)\,^{14}N$
B(GT) distribution
Exp.
E_x (MeV)
Theory
B(GT)
4.0
2.0
0
2.0
4.0
20
16
12
8
4
0

Fig. 3



s shell nuclei.
p shell nuclei.
s-d shell nuclei.
$Q_F = \frac{B(GT)}{B_{SM}(GT)}$
1.0
0.6
0.2
1
3
A
6
8
10
12
14
A
19
27
39
A

Fig. 4