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Study of The Giant Gamow–Teller Resonance in Nuclear Beta Decay: The Case of ^{33}Ar

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Abstract

Delayed proton and gamma emissions following the beta decay of ^{33}Ar have been studied. From the calculated intensity of the feeding to the $T = 3/2$ analogue state in ^{33}Cl, the proton intensities have been put on an absolute scale leading to a proton branching ratio of 38.7 ± 1.0%. A proton branch to the first excited state in ^{32}S at 2230.2 keV ($I^\pi = 2^+$) with an intensity of 0.77 ± 0.10% was obtained from gamma singles and proton-gamma coincidence data. The complete spectroscopic information on ^{33}Ar allows the Gamow–Teller (GT) strength function from the gound state and up to 9.25 MeV excitation energy in ^{33}Cl to be deduced. The total strength observed in this interval is 2.90 in absolute units.

1. Introduction

In a recent paper [1] we reported on the first detailed investigation of ^{32}Ar, a nucleus with isospin projection $T_z = (N - Z)/2 = -2$. The special motivation for this experiment was that is is essentially only in nuclei with $Z > N$ that the main part of the allowed beta-decay strength, traditionally referred to as superallowed decay, becomes observable as transitions to the analogue state and the Gamow–Teller Giant Resonance (GTGR). In the present paper we report on a complete spectroscopic investigation of the next heavier argon isotope with mass number 33 and with T, $T_z = 3/2, -3/2$.

Although a remarkably precise and detailed study of ^{33}Ar has been carried our by Hardy *et al.* [2], we have two reasons for reverting to this problem. The first is that the development of a very powerful target-ion source system [3] at ISOLDE (CERN) allows us today to investigate this isotope with mass-separated samples. The second is that for the evaluation of the quenching factor it is essential to include all intensity in the decay and not only the part that is resolved, and to use coincidence information to correct for weak branches from high-lying states, which, owing to their small statistical weight factor, can carry appreciable strength. The data collected for ^{33}Ar give a detailed mapping of the Gamow–Teller (GT) strength up to 9.25 MeV excitation energy in ^{33}Cl. The results are in striking agreement with a large shell-model calculation by Müller *et al.* [4] except for an over-all scale factor changing the axial vector strength to 58 ± 6% relative to the free-nucleon value. Although this is in agreement with other estimates of the axial-vector interaction in nuclei, in particular with the value of 0.58 ± 0.04 obtained [5] from a comprehensive analysis of beta decay to (principally) low-lying final states in sd-shell nuclei, we underline that the reduction factor found here can only be a tentative conclusion based on a model that does not necessarily give the optimal description of the giant resonance states.

2. Experimental techniques and results

2.1. *Production of ^{33}Ar*

The present study of ^{33}Ar was performed at the ISOLDE facility at CERN, where the radioactivity was produced in spallation reactions in a CaO target [3] bombarded with a 600 MeV proton beam of 2.4 μA from the CERN Synchrocyclotron. The target material, which had an effective thickness of calcium of 6.5 g/cm^2, was kept at a temperature of 1900°C. The production yield of ^{33}Ar from the ^{40}Ca(p, 3p5n) reaction was about 2×10^4 atoms per second. The target was connected to a FEBIAD ion source via a cooled line, which assured the chemical selectivity since only the noble gas argon could pass through it while neighbouring, less volatile, elements were retained by condensation. The pure Ar^+ beam from the ion source was accelerated to an energy of 60 keV and subsequently mass separated in the ISOLDE electromagnetic isotope separator [6]. The ion beam was finally directed to the measuring station via an external beam line. In order to minimize the background from contaminants of the heavy elements in the ISOLDE isotope separator, the experiments were performed at the beginning of a running period after a few months of cooling of the separator. No α contamination was observed in the charged-particle spectrum.

2.2. *The half-life of ^{33}Ar*

The daughters after beta decay and beta-delayed proton emission from ^{33}Ar are ^{33}Cl ($T_{1/2}$ = 2.51 s) and ^{32}S (stable). Neither of these nuclides are precursors for beta-delayed proton emission, so a clean one-component decay curve can be obtained if the measurement is based on the protons only. The present experiment used a collection time of 200 ms, followed by a 2.2 s counting period, and the measuring cycle was repeated until a decay curve containing 36 500 events had been collected. At the beginning of each measuring cycle a ramp generator was started and each proton event triggered the ramp generator to create a pulse with an amplitude proportional to the time elapsed from the start of the cycle. These pulses were analysed in an analog-to-digital converter (ADC) and stored in the memory of a computer. The clock used for the timing as well as the linearity of the ramp generator and the ADC were carefully controlled. The half-life was determined from a χ^2 fit to the decay curve and the result

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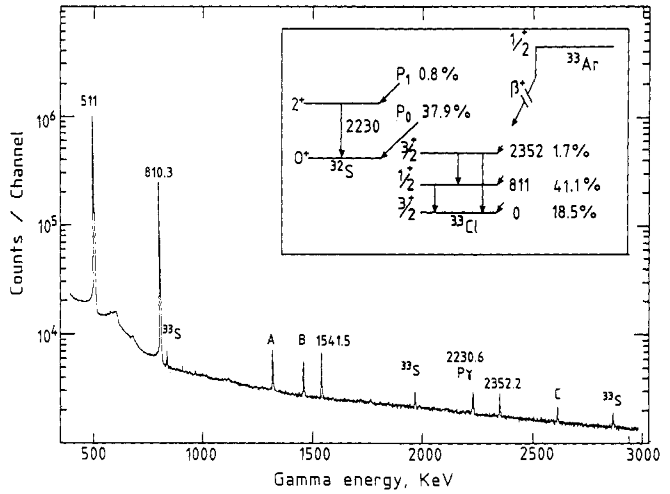

Fig. 1. Gamma-ray spectrum from the β^+ decay of ^{33}Ar and (inset) schematic level diagram. The three gamma rays at 810.3, 1541.5 and 2352.2 keV originate in the feeding of two excited states at 810.7 and 2351.8 keV in ^{33}Cl. The line at 2230.6 keV is due to a 0.8% proton branch to the first excited 2^+ state in ^{32}S. The spectrum was measured in-beam, and the known transitions in ^{33}S from the ^{33}Cl decay are also seen in the spectrum. The peak marked with an A has an energy of 1321.5 keV and is the sum peak of the 810.3 keV gamma ray and 511 keV annihilation radiation. Two background lines, one (B) from ^{40}K and another (C) from ^{208}Bi, are also observed.

$T_{1/2} = 174.1 \pm 1.1$ ms with $\chi^2 = 40.4$ for 33 degrees of freedom, is in perfect agreement with the value 173 ± 2 ms given by Hardy *et al.* [2].

2.3. *Gamma spectrum from* ^{33}Ar.

A gamma energy spectrum from ^{33}Ar was measured with a 34% Ge(Li) detector. The detector efficiency and its energy dependence was determined with a calibrated set of gamma-ray standards (^{60}Co and ^{56}Co). The gamma spectrum was measured by placing the Ge(Li) detector right behind the collecting position and the measurement was thus performed with the mass 33 activity in saturation. The spectrum obtained in a 4 h measuring period is shown in Fig. 1. The strong line at 810.3 keV is from the ^{33}Ar feeding to the first excited state in ^{33}Cl at this energy. A weak beta branch to the $3/2^+$ state at 2351.8 keV (see Ref. [6] and Ref. [7] page 364) is observed here for the first time, but the state has been seen previously [9] in (p, γ) resonance reactions. The reaction study did not observe any resonances with spin and parity $1/2^+$, $3/2^+$ between this level and the level at 3972 keV, which is our lowest proton emitting state (subsection 2.4). It is therefore unlikely that there is any unobserved beta feeding to levels in this 1600 keV interval. From the intensities of the 2352.2 and 1541.5 keV lines a relative feeding to the $3/2^+$ state of 4.0% is obtained. Since one can deduce an absolute proton branching ratio of 38.7% and an absolute ground-state feeding of 18.5% (see Section 3) we are left with a beta feeding to particle-bound excited states of 42.8% of which 1.7% goes to the 2352 keV level and the rest to the level at 811 keV. We note that the 2352 keV level in ^{33}Cl lies 75 keV above the proton separation energy according to the 1983 mass table [10].

Other weak lines at 840.4, 1967.3 and 2867.7 keV are from the decay of ^{33}Cl, the β^+-decay daughter of ^{33}Ar. The line at 2230.6 keV is due to the feeding of the first excited 2^+ state in ^{32}S, the daughter after delayed proton emission from the highly excited states in ^{33}Cl. The proton branch calculated from the singles gamma data is $0.7 \pm 0.2\%$ which is in perfect agreement with the result obtained from the proton-gamma coincidence data (subsection 2.5). The main findings from the gamma spectroscopy of ^{33}Ar are summarized in Table I and the partial decay scheme for the low-energy transitions is shown as an inset in Fig. 1.

Table I. *γ-ray transitions observed in the* ^{33}Ar *decay*

Nuclide	E_γ (keV)	I_γ (%)†
^{33}Cl	810.3(5)	42.1(8)
	1541.5(5)	1.0(2)
	2352.2(9)	0.7(2)
^{32}S	2230.6(9)	0.7(2)‡
^{33}S	840.4(9)	0.55(6)
	1967.3(9)	0.42(4)
	2867.7(9)	0.55(5)

† Intensities per ^{33}Ar decay.
‡ The pγ experiment gave a feeding of 0.77(10)%.

2.4. *Energy spectrum of delayed protons from* ^{33}Ar

The Q_{EC} value of ^{33}Ar is 11620 ± 30 keV [10] and the proton separation energy in ^{33}Cl is 2276.5 ± 0.5 keV [9]. The gamma spectrum showed feeding to only two bound excited states in ^{33}Cl, and it turns out that about 40% of the beta decay populates states above the proton separation energy. The main information about the GT strength is therefore contained in the delayed proton spectrum. It is unlikely that there could be appreciable undetected gamma decay in competition with proton emission as the measured proton widths for the $1/2^+$, $3/2^+$ states are 1–40 keV [8] while total gamma widths are typically of the order of 0.1 eV. Even for the isospin-forbidden decay of the 115 eV wide analogue state [11] this would mean a 0.1% correction only, negligible in comparison with our experimental errors.

The delayed proton spectrum from ^{33}Ar was measured with a 500 μm thick, 300 mm^2 silicon surface barrier detector with a resolution corresponding to a FWHM of 25 keV at 5 MeV. The energy calibration was based on two internal points at low energies, the $3/2^+$ level in ^{33}Cl at 3971.9 ± 1.2 keV (see Ref. [7] page 363) and the energy of the isobaric analogue resonance in ^{33}Cl observed [12] in the ^{32}S (p, p′) reaction, which correspond to delayed proton energies in the laboratory frame of 1643.4 ± 1.2 keV and 3167.2 ± 1.0 keV, respectively. At high energy, the 5804.96 keV alpha line from a ^{244}Cm calibrated source was used. The alpha energy was corrected for the estimated difference of 14 keV between the energy losses for protons and alphas in the gold window of the surface barrier detector, giving a calibration point of 5791 ± 10 keV. The final calibration curve was obtained from a parabolic fit to the three calibration energies given above.

In order to avoid the effects resulting from prompt summing of protons and the preceeding β^+ particle in the detector, a second annular detector was placed close to the collection point, facing the proton detector. The data were then recorded with the requirement that there was a coincidence between a proton in one detector and a β^+ in the other. Such a β^+ coincident spectrum is shown in the upper part of Fig. 2. The main peaks in the spectrum are numbered and the corresponding energies and intensities are given in Table II. In order to correct this spectrum for the response function of the Si detector to the protons, an unfolding of the spectrum

Table II. *β-delayed protons from ^{33}Ar*

Peak no.†	E_p (keV)‡	I_p (‰)
1′	1317(3)	1.89(8)
2	1643(1)	3.4(1)
3′	1697(6)	0.46(6)
4	1782(3)	4.3(1)
5	2099(3)	23.5(2)
6	2233(6)	0.10(3)
7	2370(6)	0.19(3)
8	2480(3)	3.3(1)
9	2741(6)	0.45(5)
10′	2883(6)	0.64(6)
11	2936(12)	1.21(8)
12	3070(12)	0.7(2)
13	3167(1)	307(1)
14	3330(20)	7.5(4)
15	3460(30)	4.1(4)
16	3560(6)	1.0(1)
17	3690(6)	0.13(4)
18	3840(3)	8.0(2)
19	3907(6)	0.19(4)
20	4201(12)	0.17(3)
21	4301(12)	0.08(2)
22	4489(10)	0.18(5)
23	4823(10)	0.23(3)
24	5006(6)	3.3(1)
25	5068(7)	1.1(1)
26	5185(7)	0.54(4)
27	5278(9)	0.18(3)
28	5579(11)	2.2(1)
29	5678(11)	1.7(1)
30	5797(12)	0.12(2)
31	6047(17)	0.21(4)
32	6255(18)	0.05(2)
33	6403(15)	0.16(2)
34	6545(15)	0.04(2)
35	6619(15)	0.036(16)

† The coincidence data show that the peaks marked with a prime mainly feed the first excited state in ^{32}S at 2230 keV.
‡ The energies given are in the laboratory frame. For the transitions going to the ground state of ^{33}Cl the excitation energy can be obtained by the formula: $E_{exc} = 2276.5 + 1.03152 \times E_p$

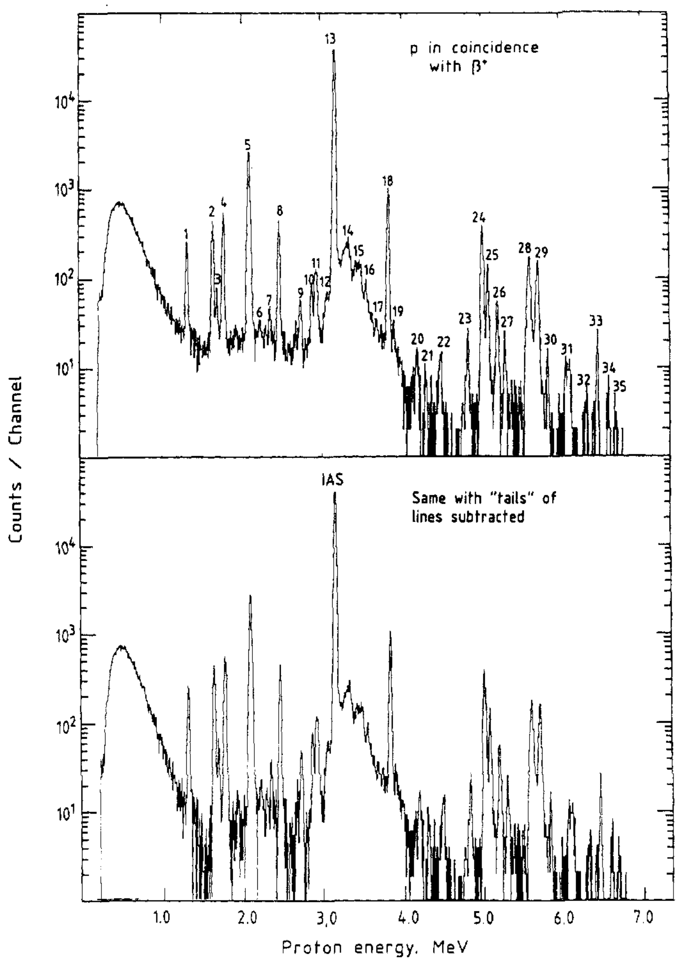

Fig. 2. Spectrum of β^+ delayed protons from ^{33}Ar measured with a 500 μm, 300 mm² Si surface barrier detector (FWHM 25 keV at 5 MeV) operated in coincidence with an annular Si detector placed upstream from the collection point. This coincidence requirement eliminates, in the recorded spectra, both the β^+p summing and the background from long-lived α-activities. The energies and intensities for the peaks marked with numbers are given in Table II. The lower part of the figure shows the same spectrum unfolded with the response function for protons of the Si detector (see text).

was done. The response function used in the unfolding procedure consisted of a Gaussian full-energy peak and a constant tail down to zero energy. A consistent unfolding demanded that the area of the tail was chosen as 3.1% of the full energy peak intensity. The resulting unfolded spectrum is shown in the lower part of Fig. 2., from which it is clear that this correction has little influence on the final beta strength function.

The ^{33}Ar spectrum shows a broad unresolved structure just above the isobaric analogue state (IAS), also noted by Hardy *et al.* [2]. One can exclude that this is due to some remaining contribution from β^+p summing by comparing with our ^{32}Ar experiment [1], which used the same geometry (Fig. 3). The strongest component, the broad line No. 14 with energy 3330 ± 20 keV, is probably identical with a $1/2^+$ resonance with total width 40 keV observed in ^{32}S(p, p′) by Ikossi *et al.* [11], with an energy that in our units corresponds to 3346 keV. It was suggested by Hardy *et al.* [2] that all or part of the beta intensity to the 3.4 MeV complex peak could be caused by isospin mixing with the $T = 3/2$ state. This could in the worst case reduce our intensity scale for the Gamow–Teller strengths by some 10% (relative). It would, however, require Coulomb mixing matrix elements around 30 keV, comparable to the largest observed in simple states, whereas we are here dealing with states of a predominantly complex structure.

2.5. *Proton-gamma coincidence measurements*

The proton-gamma coincidence experiment was performed with the same detectors as those used in the two singles experiments and with a total counting period of 5 h (Fig. 4). The singles gamma spectrum (subsection 2.3) had shown that there is a 0.7 ± 0.2% proton feeding to the first excited 2^+ state in ^{32}S. This assignment is confirmed by the observation of the same line (2230.6 keV) in coincidence with protons (inset in Fig. 4) and with the same intensity (0.77 ± 0.10%). The protons feeding this state originate in the upper part of the ^{33}Cl excitation spectrum, which means that even a small branch may influence the GT strength significantly. It is therefore of special importance to measure the energy distribution of the protons feeding the excited state.

Figure 4 shows the delayed protons in coincidence with the 2230.6 keV gamma line. The peak at 1318 keV which is observed with a coincidence frequency of 0.23 ± 0.05% must be identified with the first peak in the singles spectrum, in which it is seen with an intensity of 0.19%. We use the latter value to normalize the coincidence data. Gamma-

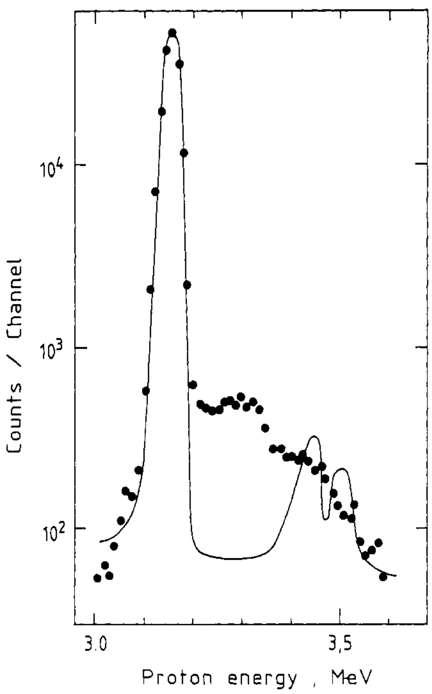

Fig. 3. Detail of the ^{33}Ar delayed proton spectrum in the energy region close to the peak at 3167 keV from the feeding of the $T = 3/2$ analogue state. The dots represent the ^{33}Ar data, while the normalized curve is the measured shape of the 3353.5 keV peak (the IAS) in the ^{32}Ar spectrum [1]. The proton spectra were measured with the same set-up and the comparison shows that the structure above the IAS in ^{33}Ar is real and not a leftover from incomplete suppression of β^+ p summing.

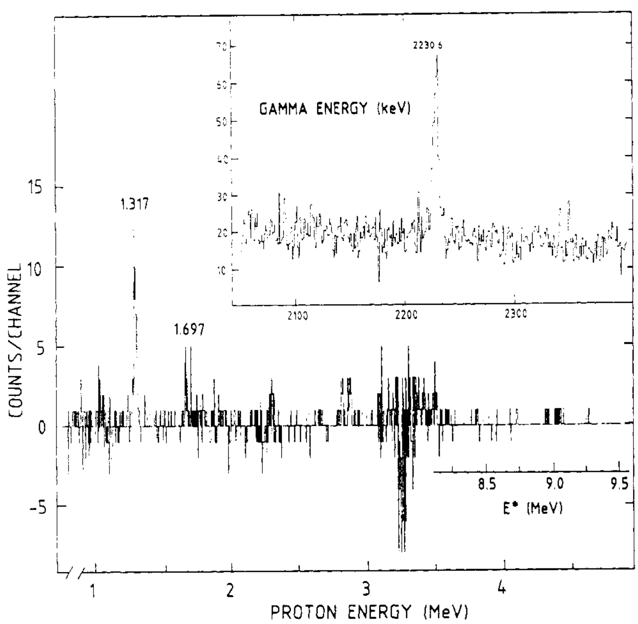

Fig. 4. The inset shows the gamma spectrum in coincidence with delayed protons from ^{33}Ar. The peak at 2230.6 keV is due to a $0.77 \pm 0.10\%$ proton branch to the 2230.2 keV 2^+ state in ^{32}S, while the continuous background is caused by annihilation-in-flight radiation and by positrons penetrating into the detector, hence giving rise to true coincidences. The proton spectrum, shown in the main figure, was generated from a gate on the 2230 keV gamma ray, and from this spectrum was subtracted a background generated from gates on either side of the peak. Note that this correction succesfully eliminates the strong 3.2 MeV peak from the IAS, and hence can be trusted for the (much weaker) remaining part of the spectrum.

coincident protons were observed up to an energy of about 4.5 MeV, which corresponds to beta feedings above 9 MeV excitation energy in ^{33}Cl.

3. Calculation of the GT strength function

The proton branching ratio of ^{33}Ar has been deduced by the same method as in Ref. [1]. The essential point is that the reduced transition probability for the Fermi transition to the isobaric analogue state at 5542.5 keV excitation energy in ^{33}Cl is known accurately, being simply $B(\text{F}) = T(T+1) - T_{z_i}T_{z_f} = 3$. As the beta transition in the present case is $1/2^+ \rightarrow 1/2^+$, it is necessary to correct for the small GT contribution by means of the relation

$$ft = C/\{B(\text{F}) + (g_A/g_V)^2 B(\text{GT})\} \quad (1)$$

with the constant $C = 6160 \pm 4$ [13] and with $(g_A/g_V)^2 = 1.59$ (Ref. [14]). Müller *et al.* [4] calculated $B(\text{GT}) = 0.137$, and for our estimate we made the assumption that the GT quenching was $(g'_A/g_A)^2 = 0.5$. This turns out to be close to our final number for this quantity and we note further that the correction amounts to 3.6% only. A more serious problem would be if the peak No. 13 were double; a contaminant comparable to the strongest peaks in the neighbourhood (Nos. 5 and 18) could increase our scale for the GT strength by several per cent. Isospin mixing, as discussed in subsection 2.4, could give a contribution of similar magnitude and opposite sign. An accurate experimental check on the absolute intensities would clearly be of value. With this reservation, we calculate the ft value to be 1981.4, which gives a feeding to the analogue state of 30.7% and a total proton branching ratio of $38.7 \pm 1.0\%$ where errors arising from the measurement itself have been taken into account.

The feeding to the ground state of ^{33}Cl was estimated by comparison with the $1/2^+ \rightarrow 3/2^+$ mirror decay $^{33}P \rightarrow {}^{33}S$. From the known [7] value of $\log ft = 5.03$ for this transition, together with the known ^{33}Ar half-life of 174.1 ms, we arrive at a ground-state feeding of 18.5% in the $^{33}Ar \rightarrow {}^{33}Cl$ decay in agreement with the value used in Ref. [2]. With the above procedure the proton and gamma data are put on an absolute scale. In order to transform the proton spectrum to a spectrum corresponding directly to the beta feedings to excited states in ^{33}Ar we used the coincidence data to shift the part of the intensity that is due to proton feeding to the ^{32}S 2^+ state to the correct energy.

In order to convert the experimental beta feedings into a GT strength function one must make the additional assumption that the contributions from forbidden transitions are negligible. This is probably true, but the experimental underpinning for this is lacking. For the light nuclei one observes first forbidden transitions – the only ones that could matter at all – essentially only at the shell junctures. Examples are ^{17}N with $\log ft$ values of 6.8 and 5.9 for the transitions $p_{1/2} \rightarrow s_{1/2}, d_{3/2}$, respectively, and the observed rates are even lower for transitions bridging the sd and fp shells, see, for example, ^{43}K. The conclusion is that for the configuration states, the first forbidden transitions are some 10^2–10^3 times slower than the allowed ones. It would probably not be completely unrealistic to expect a similar ratio to hold also at higher excitation energies, as also the forbidden transitions are expected [15] to exhibit a giant-resonance behaviour. For the light argon isotopes, situated away from the shell junctures, we would assume the role of forbidden transitions to be well below this 0.1–1% estimate and thus to be completely negligible compared to our 10% relative error on the total strength. It is, however, perfectly possible that some of the weaker peaks in Fig. 2 could represent forbidden transitions – the log *ft* value corresponding to peak No. 21 is as high as 6.4. This possibility would definitely have to be considered if one were to use the experimental spectrum for an absolute count of the $1/2^+$ and $3/2^+$ levels.

We limit our analysis to the energy region below 9.25 MeV excitation energy in ^{33}Cl since the data above this energy have too little statistics, both in the coincidence and in the singles experiments. In this window we observe a total strength of 2.90 units, of which 0.90 arise from the coincidence experiment. This contribution is the main source of error on the total strength; we estimate a contribution to the error of 0.2 from counting statistics and a similar contribution from the energy calibration in the top part of the spectrum, leading thus to a combined error of 0.3. Other sources of statistical errors are negligible, and the possible errors from the normalization procedure are not likely to contribute more than a few per cent relative error.

There is excellent agreement between the basic data given by Hardy *et al.* [2] and in the present work as can be seen, for example, by comparing our Fig. 2 with their Fig. 4. The following argument shows that there is also agreement as to the basic intensity scale. The total strength observed in Ref. [2] up to 9.0 MeV excitation energy (their experimental cut-off) was 1.63. In the same region we have 2.3, of which 0.3 arise from the proton-gamma coincidences, not observed in the earlier work. Another contribution of about 0.4 is due to our normalization procedure, which put the intensity to the IAS to 30.7%, whereas Ref. [2] used the value 26.7% derived from a measured p/γ ratio. It is of less importance, but still a contribution in the same direction, when our analysis of the GT strength function used the total observed proton intensity (leaving aside the Fermi part) of 8.1% and not only the 7.2% assigned to individual peaks (Table II).

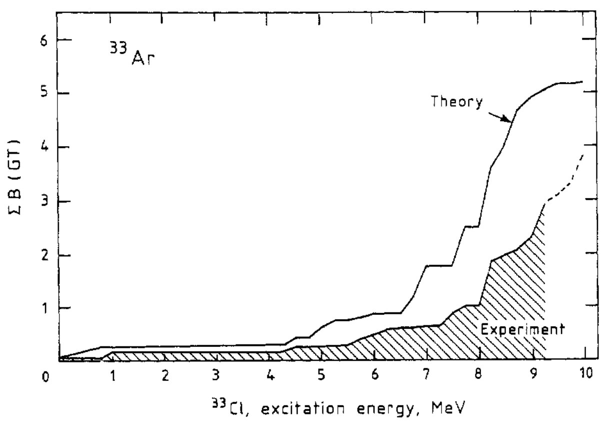

Fig. 5. The integral of the Gamow–Teller strength from ^{33}Ar as a function of the excitation energy in the daughter nucleus ^{33}Cl. The hatched area corresponds to the experimental strength. The data above 9.25 MeV excitation energy are uncertain due to low statistics and the experimental cut-off is therefore put at this energy. The curve shows the strength predicted from a large shell-model calculation by Müller *et al.* [4]. The ratio of the experimental and theoretical strengths gives a renormalization factor of the GT strength of $(g'_A/g_A)^2 = 0.58$. Note that the sum rule strength is $3(Z - N) = 9$ so that roughly 50% of the theoretical strengths falls inside our energy window.

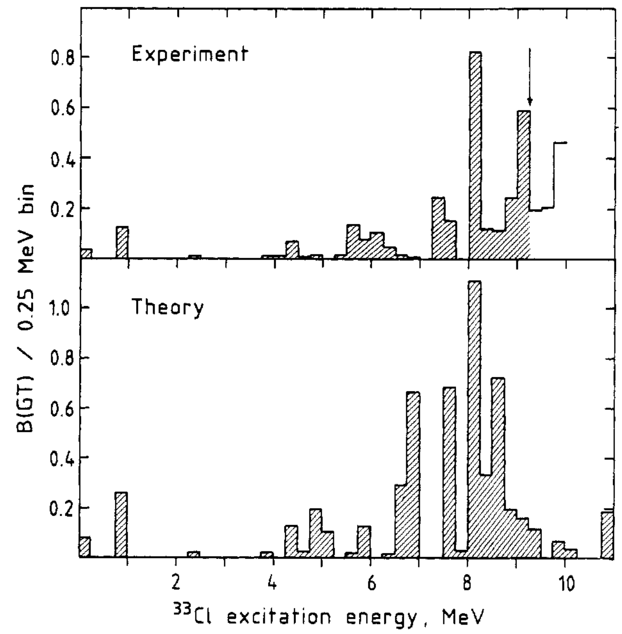

Fig. 6. The experimental and theoretical ^{33}Ar GT strength functions have been binned in intervals of 0.25 MeV. The agreement between our values and the predicted ones from shell-model calculations [4] are discussed in the caption to Fig. 5. We limit the comparison to energies below 9.25 MeV (arrow) since the experimental data have extremely low statistics beyond this point.

4. Conclusion

Figure 5 shows the integral strength function as a function of the ^{33}Cl excitation energy together with the prediction from the calculations of Müller *et al.* [4]. Figure 6 shows the GT strength function on a differential scale with 250 keV bins. One observes a similar energy dependence for the experiment and the theory, but over the whole energy interval the experimental strength is about a factor of 2 smaller than the theoretical prediction. Owing to the experimental uncertainties in the upper part of the spectrum we have put the experimental sensitivity limit at 9.25 MeV. A comparison with theory up to this energy gives for the GT strength the "effective charge"

$$(g'_A/g_A)^2 = 0.58 \pm 0.06$$

where the effective axial-vector coupling constant g'_A is taken to include possible nuclear-structure effects and where g_A is the same parameter for the free nucleon. If the cut-off instead had been chosen as 9.0 MeV, we would have obtained a quenching factor of 0.47 ± 0.05, still in agreement with the value 0.49 ± 0.05 obtained for ^{32}Ar. It turns out [16] that the quenching observed in the nuclides ^{34}Ar and ^{35}Ar also lies within the limits given here, so that for the four Ar isotopes with $T_z < 0$ one has an average quenching of 0.54 ± 0.05. It seems to us, however, that a final word of caution is needed at this point.

The upshot of the present work and of that reported in Ref. [1] is that large shell-model calculations of the type developed by Brown, Wildenthal and others are a very powerful tool for understanding the GT strength function. For example, one notes that the calculations of the beta strength functions [4] correctly predicted that the feeding of the low-lying states in ^{33}Ar would be much weaker than in ^{32}Ar long before the experiments were done, and that these predictions follow directly, with no additional input, from the still earlier [17] specification of the interaction matrix elements which completely define the wave functions involved in the decay.

The effective interaction parameters [17] entering in the exact shell-model calculations, although global, still reflect an adjustment specifically to reproduce nuclear structure at low energies, and in applying this model to (part of) the GTGR we are definitely outside the range of proven validity for the model. The consistent results obtained in the long sequence of neutron-deficient argon isotopes certainly inspires confidence – or, at least, some hope. The fortunate appearance of a new set of calculations [5] based on wha; is described as a better set of interaction parameters, throws light on this problem. Brown and Wildenthal note [5] that the result for ^{34}Ar is inconsistent with the general trend, and the extension to $^{33,32}Ar$ [16] shows that the problem is endemic for all light argons. More theoretical work is clearly needed.

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