The axial-vector strength in the proton-rich argon isotopes

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Abstract

The proton-rich isotopes ^{32}Ar - ^{35}Ar represent the first sequence for which the super-allowed Gamow-Teller strength is known out to $Z-N = 4$. The results are compared with two sets of predictions from large shell-model calculations, which give systematically different quenching factors, on the average 0.54 and 0.89. Possible reasons for this are discussed. A comparison is also made with the Gamow-Teller strength of proton-rich isotopes of neighbouring elements.

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1. Introduction

The measured axial-vector (or, Gamow-Teller) strength in nuclei is smaller than that calculated from models, in which the nucleons are assumed to be point particles with the free-nucleon value g_A of the coupling constant. This reduction arises largely from pionic contributions and is thus one example of subnucleonic effects in nuclear physics. Very approximately one may say that part of the effect arises from virtual hole-delta pairs and another part from second-order core polarization brought about by the tensor force, itself due primarily to one-pion exchange. We refer to a recent volume [1] and a book [2] for a discussion of these phenomena and for references to the extensive theoretical literature. The present paper makes use of accurate data for ^{32}Ar and ^{33}Ar obtained recently [3, 4]. We refer to these publications for details of our experiments and concentrate in the present article on the conclusions that can be drawn from the Gamow-Teller strengths in the argon series, pointing out that a discrepancy, previously noted for ^{34}Ar , is part of a systematic behaviour extending to ^{33}Ar and ^{32}Ar . The results on the argon isotopes are also put into a broader perspective by comparing them to the Gamow-Teller strength from proton-rich isotopes of the elements S, Cl, K and Ca.

Part of the results of the present paper has already been presented elsewhere [5].

As a first step we attempt to relate the strength, via nuclear-model calculations, to an overall reduction factor $(g'_A/g_A)^2$, which may be thought of as accounting empirically for changes in the coupling and for corrections to the matrix element of $\sigma\tau$. The most accurate determinations of $(g'_A/g_A)^2$ have come from the analysis of beta transition rates [1]. This approach was pioneered by Wilkinson [6, 7], who used data from fast beta transitions together with wave functions based on complete diagonalization within the p and lower sd shell to calculate a reduction factor of 0.80 ± 0.06 . Several analyses covering the whole sd shell have since been performed, most recently by Brown and Wildenthal [8–11] who, using a new set of wave functions [9], carried out a comprehensive analysis of beta decays to (mainly) low-lying final states and found an average value $(g'_A/g_A)^2 = 0.58 \pm 0.04$. The difference between the results for the p shell and for the sd shell seems to indicate that the reduction factor decreases with increasing mass. The first results for proton-rich nuclei in the fp shell, obtained by Sekine et.al. [12], indicate that the factor there also is about 0.6.

Experiments to determine the reduction factor in beta decay are made difficult by the existence of a collective spin-isospin mode, the Gamow-Teller giant resonance (GTGR). In the decay of nuclei with $N > Z$ this resonance is in general not energetically accessible, and the rates of the allowed beta transitions reflect mainly the screening of the interaction due to the GTGR. It is for this reason that the analysis in the following is limited to cases with $Z > N$.

It was found some years ago (see [13]) that the GTGR can be excited through (p,n) reactions at high energy on neutron-rich targets, and that there is a close, but maybe not one-to-one [14, 15], connection between these cross-sections and the re-

duced transition probability, B_{GT} , measured in beta decay. The large energy window in this reaction permits a comparison of the measured strength directly with the sum-rule limit¹

$$\Sigma B^-_{GT} - \Sigma B^+_{GT} = 3(N - Z),$$

where for cases with a large neutron excess, the Pauli principle ensures that the β^+ strength is negligible. In the (p,n) experiments [13] one observes in the resonance and lower-lying GT states a total of 50–65 % of the sum-rule strength, in good agreement with the analyses of beta decays in the sd shell. The uncertainty comes mainly from possible strength hidden in the high-energy tail of the resonance [13].

2. Experimental results on the isotopes ³²⁻³⁵Ar

We have studied the super-allowed decays of ³²Ar [3] and ³³Ar [4], in which a large part of the GTGR is populated; the nuclear-model calculations can therefore be tested here in great detail, possibly leading to a more unambiguous identification of the causes for the quenching (see ref. [11]). The decays of ³²Ar (99 ms) and ³³Ar (174 ms) populate excited levels up to 10 MeV in the daughter isotopes, so that detailed measurements are needed, including proton spectra, gamma spectra, p γ and β p coincidences. The element argon is an especially favourable case owing to the development at CERN's ISOLDE facility of a fast target-ion-source system [19]. It was, in fact, with a forerunner for this system that ³²Ar was discovered [20] as the first isotope with a proton excess of $Z - N = 4$. The details of the experiments are reported elsewhere [3, 4], but it may be useful to repeat that the measurement of a strength-function differs in some respects from normal spectroscopic studies. First of all, the strong energy dependence of the beta transition probability makes it difficult to detect the weak branches to highly excited levels, and second, the entire proton intensity should be included, not only the part contained in resolved peaks. The results after conversion to a strength function are shown in Fig. 1 and in Table I, which also contains data for ³⁴Ar and ³⁵Ar [21, 22, 23] and for ³⁷Ar [24]. In the last case only the ground state to ground state transition is observable, it thus illustrates the small GT strength in the configuration states as compared with the super-allowed decays.

¹ This sum rule has been given in slightly different forms by Ikeda [16], Sorensen [17], and Gaarde et al. [18]. It can be derived from the commutation relationships of the σ and τ operators under the assumption that the nuclear wave function is characterized fully by space, spin and isospin coordinates. Hence, it is obeyed also in the large shell-model calculations that form the reference basis of the present work.

Figure 1: The upper part of the figure shows the experimental GT strength functions [3, 4] compared with the calculations of Müller et al. [25] (middle) and of Brown and Wildenthal [8, 10] (below). The arrows indicate the energy cut-off used in the analysis.

Table I Total observed and calculated ΣB_{GT}^+
in the allowed EC, β^+ decays of the argon isotopes

Isotope, T_z	Experiment		Theory			
	Energy cut-off (MeV)	ΣB_{GT}^+	Refs. [8, 10] ^{a)}		Refs. [25, 26]	
			ΣB_{GT}^+	$(g_A'/g_A)^2$	ΣB_{GT}^+	$(g_A'/g_A)^2$
$^{37}\text{Ar}, +1/2$	b)	0.0309	0.0723	(0.43)	0.029	(1.07)
$^{35}\text{Ar}, -1/2$	~ 4.0	0.308	0.464	0.66	0.548	0.56
$^{34}\text{Ar}, -1$	~ 4.0	1.73	1.82	0.95	3.30	0.52
$^{33}\text{Ar}, -3/2$	9.25	2.90	2.43	1.19	5.04	0.58
$^{32}\text{Ar}, -2$	8.75	3.8	5.09	0.75	7.80	0.49

a) 'Free-nucleon value'.

b) Only one transition observed. We include this case to illustrate the extremely small amount of GT strength in the configuration states as compared with the superallowed decays.

3. Comparison to shell-model predictions

The experimental results for the argon isotopes were compared with multi-configuration shell-model predictions [8, 9]. These are based on a complete diagonalization within the space of the sd shell and completely define the wave functions once the basic set of interaction matrix elements has been specified. Our earlier analysis of the ^{32}Ar and ^{33}Ar experiments [3, 4] was based on predictions [25, 26] obtained with the Chung-Wildenthal interaction [27]. The appearance of a new, presumably better, set of parameters and of calculations of Gamow-Teller strengths [8, 10] offer an interesting possibility for using the argon data to compare the performance of the two sets, Fig.1 and Table I. The main observation is that the large shell-model calculations have a marvellous predictive power. Fig. 1 shows that, apart from an over-all scale factor, both calculations correctly predict strong transitions to states at 1 and 4 MeV in the ^{32}Ar decay and essentially no strength to low energies in the ^{33}Ar decay. The gross structure of the feeding to higher-lying levels is also well reproduced. Note that the structure in the ^{32}Ar spectrum is governed by the spin-orbit splitting between the proton $d_{5/2}$ and $d_{3/2}$ hole states [3].

The two calculations differ considerably, however, for the intensity in the observed part of the GTGR. The quenching factors $(g_A'/g_A)^2$ obtained for ^{32}Ar - ^{35}Ar (Table I) with the Chung-Wildenthal interaction is on the average 0.54; this agrees

with the overall result of 0.58 ± 0.04 obtained with the Brown-Wildenthal interaction [8, 10] for sd shell isotopes, and also with the analysis based on the sum-rule strength for (p,n) reactions [13]. The new calculations give a completely different picture for the argon isotopes, with reduction factors ranging from 0.66 to 1.19 and with an average of 0.89. We believe that this discrepancy arises from differences in the calculated energies for the high-lying collective states. In units of the total sum-rule strength, the predicted shell-model strength amounts to a fraction ranging from 0.65 (^{32}Ar , refs. [25, 26]) down to 0.15 (^{35}Ar , refs. [8, 10]).

In their paper, Brown and Wildenthal [8] note that the most anomalous point is ^{34}Ar , and that the main strength comes from a relatively weak branch to the fourth excited 1^+ state at 3.129 MeV in ^{34}Cl . They suggest that it might be worthwhile to remeasure this intensity. However, the ^{34}Ar decay has been studied carefully [21], and there seems little doubt that the intensity, half-life and Q-value are accurately known. In the meantime, in a low-energy $^{34}\text{S}(p,n)^{34}\text{Cl}$ experiment [28] GT strength has been observed into states at 3.128 and 4.985 MeV, a pattern essentially in agreement with the calculations of ref. [8] although also here surprisingly large intensities were found.

The reason for the different quenching factors predicted by the two calculations clearly lies in the different energies for the collective states in the light argon isotopes as may be seen from the integrated strengths: the GTGR sets in at higher energy in the calculation of refs. [8, 10] than in that of refs. [25, 26]. The displacement is roughly 1.3 MeV for ^{33}Ar and 1.5 MeV for ^{32}Ar .

The reasons for this difference could be twofold. Firstly, as the authors of ref. [28] remark, it may be due to a deficiency of the argon wave functions. Secondly, it might be caused by slight problems with the Brown-Wildenthal effective interaction for nucleons in the upper half of the sd-shell, as has been suggested in ref. [29]. The authors of ref. [29] state a preference for the Chung-Wildenthal effective interaction for those nuclei in accordance with our findings and with the M1 strength distributions derived from inelastic electron scattering experiments in ^{36}Ar [30]. It is very interesting to note, however, that the existing data for other elements seem to indicate (Fig.2) that the problem is specific to the argon isotopes and not one that pertains to the end of the sd shell as a whole.

There is, nevertheless, also a possibility that some of the existing data for proton-rich nuclei could have a systematic bias towards underestimating the strength at high energies for purely experimental reasons. The point is that the measurement of strength functions in some ways differs from normal spectroscopic studies of complex decays. The spectroscopist, concerned with prominent transitions, is often uninterested in the distortion that could come from weak, unobserved branches. For an example of this, we refer to a study of the gamma decay of the fictitious nuclide 145-pandemonium [31].

Figure 2: The observed and calculated [8, 10] GT strengths for the proton-rich isotopes of the elements S, Cl, Ar, K, and Ca. Note that the argon isotopes seem to deviate from the general trend of all other measured cases in the sd shell as given by the hatched area in the graph.

4. Conclusion

In summary, we have pointed out a problem that may be endemic to the argon isotopes, but one that could also be a sign of a more widespread malaise in the determination of quenching factors from beta decay. The theoretical problems posed seem to be first to understand the width and energy of the GTGR, second to understand quantitatively the causes of the quenching. Experimentally, more, accurate data on superallowed decays with $T_Z \leq -3/2$ are needed.

In passing we note that we have recently measured [32] the GT strength function for a nucleus in the beginning of the sd-shell, namely ^{17}Ne , and found almost perfect agreement between the experimental and theoretical strength functions, leading to a quenching factor of $(g'_A/g_A)^2 = 0.82 \pm 0.07$, well within the systematics of quenching factors.

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