THE DECAY OF A $T_Z = -2$ NUCLEUS: ARGON-32

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ABSTRACT

Beta-delayed protons have been observed from ^{32}Ar ($t_{1/2} \sim 75$ msec), the most neutron-deficient nucleus whose radioactive decay has ever been recorded. From the proton spectrum, the $T = 2$ state in ^{32}Cl has been identified to have a mass excess of -8295.6 ± 5.2 keV. As the fourth accurately known member of an isobaric quintet, it provides the most accurate test yet available among narrow $T = 2$ states for a cubic term in the isobaric multiplet mass equation: the coefficient of such a possible term is determined to be 0.5 ± 2.5 keV.

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In the absence of charge-dependent forces in nuclei, the members of an isobaric multiplet of states would have the same mass and identical wave functions. Patently they do not; but the extent to which they do not can provide a specific view of isospin symmetry-breaking forces. This measure of significance has stimulated the accurate determination of masses among $T = 3/2$ multiplets for many years.

If it is assumed that two-body forces are responsible for charge-dependence in nuclei then, to first order, the masses of members of any multiplet would be described by the so-called isobaric multiplet mass equation (IMME):

$$M(A, T, T_Z) = a(A, T) + b(A, T)T_Z + c(A, T)T_Z^2, \quad (1)$$

where the coefficients are related to diagonal reduced matrix elements of the charge-dependent part of the total Hamiltonian.

In second order, however, the IMME will include additional terms, $dT_Z^3 + eT_Z^4$, where d and e now are functions of off-diagonal matrix elements. Evidently it is only by mass measurements among multiplets with $T \geq 3/2$ that these higher order terms -- signature of charge-dependent mixing or more complex phenomena -- can be determined experimentally. Of the 20 cases of known $T = 3/2$ multiplets, only one -- the ground state $A = 9$ quartet¹⁾ -- has a non-zero result (namely $d = 5.8 \pm 1.5$ keV).

Tests of the IMME for $T = 2$ quintets have only recently become possible at all. The sole case where all five masses are known^{2,3)} is for $A = 8$, and although a non-zero d (and/or e) coefficient is indicated, its significance is somewhat clouded by the fact that two of the states involved are unbound to isospin-allowed particle emission: the resulting difference in radial wave functions can also give rise to higher order terms. The only other case where more than three members of a quintet are known⁴⁾ is for $A = 20$, but the uncertainty of the resultant d coefficient is ± 20 keV and hence it does not yet provide a demanding test.

We wish to report observing the beta-delayed proton decay of ^{32}Ar . With $T_Z = -2$, this is the most neutron-deficient nucleus whose decay has ever been observed. Its beta decay populates the 0^+ , $T = 2$ analogue state in ^{32}Cl , from which protons are subsequently emitted (though this decay channel is isospin forbidden). The measured energy of the proton group yields a precise mass for the state in ^{32}Cl , which then becomes the fourth member of the $T = 2$ multiplet to be known. Since all members are bound to isospin-allowed particle decay, this constitutes the first exacting test of the IMME for such a $T = 2$ multiplet.

Argon isotopes were produced in spallation reactions by bombarding a 38 g/cm^2 vanadium target (in the form of VC powder) with $1 \mu\text{A}$ of 600 MeV protons from the CERN Synchro-cyclotron. The temperature of the target was held at about 2100°C ,

so that most of the elements produced by the bombardment diffused out of the target -- some (such as argon) very rapidly. They then had to diffuse through a cooled (to 30°C) copper tube before reaching a plasma ion source; this tube had the effect of passing argon nuclides but retaining all neighbouring elements (through condensation or chemical reactions). The beam extracted from the ion source was separated into its constituent atomic masses by the ISOLDE electromagnetic isotope separator. For a selected mass, the beam could then be intercepted by a 40 $\mu\text{g}/\text{cm}^2$ carbon foil, behind which a 700 μm silicon surface-barrier counter detected subsequent particle emission from the collected activity. The collection could be continuous or, for a determination of the decay half-life, it could be interrupted by a periodic electrical deflection of the ion beam. In the latter case, sequential energy spectra were recorded following each collection.

The response of the system was calibrated by observing beta-delayed protons from the well-known⁵⁾ decay of ^{33}Ar . This served two purposes. First, the transmission of the separator was optimized for the relatively strong (~ 15 atoms/sec) ^{33}Ar beam so that the instrument settings could be confidently extrapolated for the much weaker (~ 0.2 atoms/sec) beam of ^{32}Ar . Second, the energy calibration of the detector was established from the proton spectrum of ^{33}Ar ; the laboratory energy of the two peaks appearing in Fig. 1b were taken to be 2109 ± 13 keV and 3169.2 ± 3.1 keV from the energies of levels in ^{33}Cl to which they correspond^{5,6)}. The calibration spectrum was recorded both before and after the collection of ^{32}Ar , and the linearity of the system's energy response was confirmed through the use of a mercury pulser.

The beta-delayed proton spectrum observed for ^{32}Ar is shown in Fig. 1a. Only one peak is evident, with a laboratory energy of 3350.5 ± 5.0 keV. The time decay of the peak yields a half-life for ^{32}Ar of 75 ± 30 msec.

Argon-32, with $J^\pi = 0^+$ and $T = 2$, is expected to undergo ordinary allowed (Gamow-Teller) beta decay to 1^+ ($T = 1$) states in ^{32}Cl , although it is evident from the mirror $^{32}\text{Si} \xrightarrow{\beta} ^{32}\text{P}$ decay that the transition to the 1^+ ground state must be strongly ℓ -forbidden. In addition, a strong superallowed (pure Fermi) transition is anticipated to populate the 0^+ ($T = 2$) analogue state in ^{32}Cl . This state is predicted to be at an excitation energy of approximately 5035 keV by application of the quadratic IMME [Eq. (1)]. If it subsequently decays by proton emission to the ground state of ^{31}S , it should give rise to a proton peak at a laboratory energy of about 3350 keV, in close agreement with our experimental results. Such a decay channel is also consistent with the isospin-forbidden proton decay of the lowest $T = 2$ state in ^{32}S , which should have analogue similarities to the situation in ^{32}Cl ; it proceeds entirely⁷⁾ to the ground state of ^{31}P . (The alpha-decay branches also seen for the ^{32}S state are energetically forbidden for ^{32}Cl .)

The identification of the observed proton peak with the decay of the lowest 0^+ , $T = 2$ state in ^{32}Cl is further confirmed by the following argument. Transition strengths of $0^+ \rightarrow 0^+$ superallowed beta transitions between $T = 1$ states have been studied extensively in the past [for example, see Hardy and Towner⁸⁾]. The decay of ^{32}Ar exhibits the first case ever observed of such a $0^+ \rightarrow 0^+$ transition between $T = 2$ states. Assuming that the effects of charge-dependent mixing are approximately the same for both, the $T = 2$ transition will be twice as fast as an equivalent $T = 1$ decay; thus its log ft value should be 3.18. This, when combined with the measured ^{32}Ar half-life, indicates a branching ratio of $17 \pm 1\%$ for the superallowed transition. Consequently, even if most of the remaining intensity were concentrated in a single allowed transition to a proton unstable state -- a very unlikely possibility -- it still could not account by itself for the observed proton peak, since the superallowed branch must in that case produce a second observable peak. No second peak appears in Fig. 1a.

The proposed decay scheme appears in Fig. 2. When combined with the mass excess of ^{31}S from the 1977 Mass Evaluation⁹⁾, the energy of the observed proton peak yields a mass excess for the 0^+ , $T = 2$ state in ^{32}Cl . This value appears in Table 1, and is actually more precise than that for the ground state⁹⁾ of ^{32}Cl . It corresponds to an excitation energy of 5033 ± 10 keV in ^{32}Cl .

The masses of the other known members of the $A = 32$ quintet (namely the 0^+ , $T = 2$ states in ^{32}Si , ^{32}P , and ^{32}S) are also given in the table. The four masses were used, within the context of a cubic mass equation, to derive the coefficients of the IMME, and also to calculate the mass excess of ^{32}Ar , the fifth member of the quintet. The coefficient of the T_Z^3 term ($d = 0.5 \pm 2.5$ keV) is consistent with zero and thus gives no indication that charge-dependent mixing plays a significant role in this quintet.

The results previously obtained for the $A = 8$ quintet³⁾ provide an interesting comparison. In that case, all five masses are known and it is possible to derive a value for the d coefficient *independently* of any assumptions about the magnitude of e . The result is $d = 4.4 \pm 3.0$ keV, and if this actually does indicate a non-zero value, the present experimental results suggest that it is not a general feature of $T = 2$ multiplets. As the first precise measurements relating to a $T = 2$ multiplet of *narrow* states, the $A = 32$ experiment exhibits no greater effects from charge dependence than had been evident previously for $T = 3/2$ states. Presumably a non-zero d coefficient for mass 8 must indeed be attributable³⁾ to the fact that two of the members of that multiplet are unbound to allowed particle decay.

Finally, it may be noted that the effects of charge-dependent mixing can also be investigated through beta transitions between members of a multiplet⁹⁾. The superallowed beta-decay branch observed from ^{32}Ar is of this type. If a more intense source of ^{32}Ar were to become available, it would then be possible to measure the absolute transition rate of that branch and compare for the first time superallowed $0^+ \rightarrow 0^+$ decay between $T = 2$ states with the equivalent, and well-understood, decays between $T = 1$ states.

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Table 1

Properties of the A = 32 isobaric quintet

Nucleus	T_Z	Mass excess (keV)	E_x (keV)	Reference
^{32}Si	+2	-24092.0 ± 7.0	0.0	9
^{32}P	+1	-19231.6 ± 1.2	5073.1 ± 0.9	9, 10, 11
^{32}S	0	-13965.1 ± 4.0	12050.0 ± 4.0	9, 12
^{32}Cl	-1	-8295.6 ± 5.2	5033.0 ± 10.0	this work
^{32}Ar	-2	-2232.2 ± 33.1	0.0	IMME prediction
$M(T_Z) = a + bT_Z + cT_Z^2 + dT_Z^3$: $a = -13965.1 \pm 4.0 \text{ keV}$ $b = -5468.5 \pm 3.1 \text{ keV}$ $c = +201.5 \pm 4.8 \text{ keV}$ $d = +0.5 \pm 2.5 \text{ keV}$				

Figure captions

Fig. 1 : Energy spectra of delayed protons observed following the decays of ^{32}Ar and ^{33}Ar . The detector efficiency was $\sim 20\%$ of 4π sr, which results in the appearance of "sum" peaks corresponding to the simultaneous detection of a proton with its preceding positron. Such a peak is clearly visible about 200 keV above the large ^{33}Ar proton group.

Fig. 2 : Proposed decay scheme for ^{32}Ar .

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Fig. 1

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Fig. 2