Decay of a $T_z = -2$ Nucleus: Argon-32

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β-delayed protons have been observed from ^{32}Ar ($t_{\frac{1}{2}} \sim 75$ 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 an accurate test for a cubic term in the isobaric-multiplet mass equation as applied to narrow $T = 2$ states: The coefficient of such a possible term is determined to be 0.5 ± 2.5 keV.

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 $T = \frac{3}{2}$ multiplets for many years.

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

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

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 $T \geq \frac{3}{2}$ that these higher-order terms—signature of charge-dependent mixing or more complex phenomena—can be determined experimentally. Of the twenty cases of known $T = \frac{3}{2}$ multiplets, only one—the ground-state $A = 9$ quartet[1]—has a nonzero 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 nonzero 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. Of the other two cases where more than three members of a quintet are known[4,5] only the measurements for $A = 36$ have sufficient accuracy to provide a demanding test. In that case $d = -1.6 \pm 1.8$ keV.

We wish to report observation of the β-delayed proton decay of ^{32}Ar. With $T_Z = -2$, this is the most neutron-deficient nucleus whose decay has ever been observed. Its β decay populates the 0^+, $T = 2$ analog 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 an 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 μA of 600-MeV protons from the CERN synchrocyclotron. 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 neighboring 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-μg/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

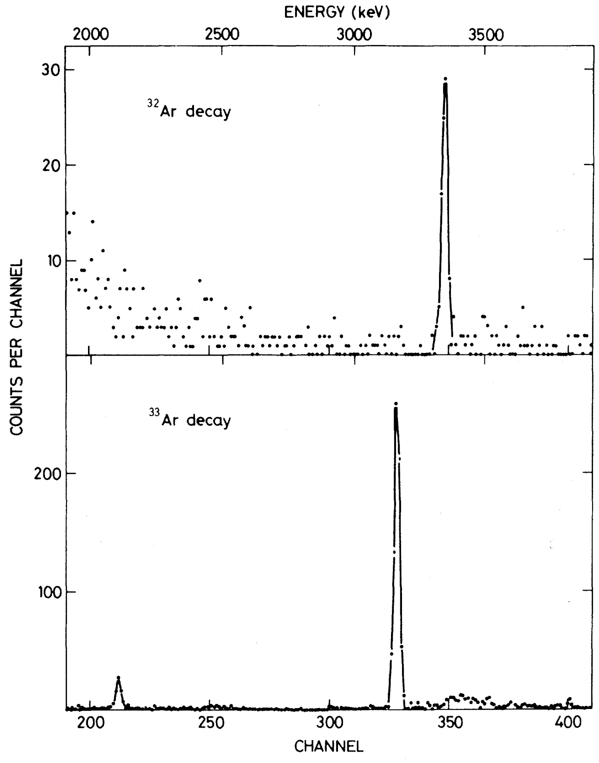

FIG. 1. Energy spectra of delayed protons observed following the decays of ^{32}Ar and ^{33}Ar. The detector efficiency was ~ 20% of 4π sr, which results in the appearance of "sum" peaks corresponding to the simultaneous detection of a proton with its preceding positron. Such a peak is clearly visible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

beam. In the latter case, sequential energy spectra were recorded following each collection.

The response of the system was calibrated by observing β-delayed protons from the well-known[6] 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 energies of the two peaks appearing in Fig. 1(b) were taken to be 2109 ± 13 and 3169.2 ± 3.1 keV from the energies of levels in ^{33}Cl to which they correspond.[6,7] 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 β-delayed proton spectrum observed for ^{32}Ar is shown in Fig. 1(a). 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^{+70}_{-30} msec.

Argon-32, with $J^{\pi} = 0^+$ and $T = 2$, is expected to undergo ordinary allowed (Gamow-Teller) β decay to 1^+ ($T = 1$) states in ^{32}Cl, although it is evident from the mirror $^{32}\mathrm{Si} \xrightarrow{\beta} {}^{32}\mathrm{P}$ 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^+ ($T = 2$) analog 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 analog similarities to the situation in ^{32}Cl; it proceeds entirely[8] to the ground state of ^{31}P. (The α-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 β transitions between $T = 1$ states have been studied extensively in the past [for example, see Hardy and Towner[9]]. The decay of ^{32}Ar exhibits the first case ever observed of such a $0^+ \rightarrow 0^+$ transition between $T = 2$ states. Under the assumption 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 $17^{+16}_{-7}\%$ 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. 1(a).

The proposed decay scheme is shown in Fig. 2. When combined with the mass excess of ^{31}S from *The 1977 Atomic Mass Evaluation*,[10] the energy of the observed proton peak yields a mass excess for the 0^+, $T = 2$ state in ^{32}Cl. This value is given in Table I, and is actually more precise than

TABLE I. 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	10
^{32}P	+1	-19231.6 ± 1.2	5073.1 ± 0.9	10, 11, 12
^{32}S	0	-13965.1 ± 4.0	12050.0 ± 4.0	10, 13
^{32}Cl	−1	-8295.6 ± 5.2	5033.0 ± 10.0	This work
^{32}Ar	−2	-2232.2 ± 33.1	0.0	IMME prediction

that for the ground state[10] 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. This gives

$$M(T_Z)=a+bT_Z+cT_Z^2+dT_Z^3,$$

with $a=-13\,965.1\pm 4.0$, $b=-5468.5\pm 3.1$, $c=201.5\pm 4.8$, and $d=0.5\pm 2.5$ keV. 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 $A=8$ qunitet[3] provide an interesting comparison. In that case, all five masses are known and it is possible to derive a value for the d coefficiently *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 nonzero value, the present experimental results combined with those[5] for $A=36$ suggest that it is not a general feature of $T=2$ multiplets. Evidently, $T=2$ multiplets of *narrow* states exhibit no greater effects from charge dependence than has been evident previously for $T=\frac{3}{2}$ states. Presumably a nonzero d coefficient for mass 8 must indeed be attributable[3] 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 β transitions between members of a multiplet[5]. The superallowed β-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 $0^+\to 0^+$ decay between $T=2$ states with the equivalent, and well-understood, decays between $T=1$ states.

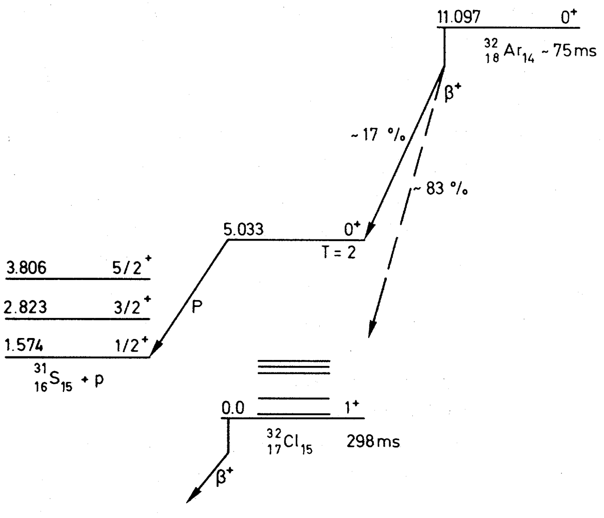

FIG. 2. Proposed decay scheme for ^{32}Ar.

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Upper Limit on Parity-Nonconserving Optical Rotation in Atomic Bismuth

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We have searched for optical rotation near the 8757-Å magnetic-dipole absorption line in atomic bismuth vapor. The experiment is sensitive to parity nonconservation in the weak neutral-current interaction between electrons and nucleons in atoms. We find $R \equiv \mathrm{Im}(E_1/M_1) = (-0.7 \pm 3.2) \times 10^{-8}$, which is considerably smaller than the value $R = -2.5 \times 10^{-7}$ obtained by central-field calculations for this bismuth line using the Weinberg-Salam theory of neutral currents.

We present here results of an experiment in which we search for parity-nonconserving (PNC) optical rotation in atomic bismuth vapor.[1,2] We set an upper limit to PNC rotation that is significantly below the value calculated[3-6] for bismuth on the basis of the Weinberg-Salam theory[7,8] of neutral currents.

We look near a magnetic-dipole absorption line where optical rotation would result from interference between the normal magnetic-dipole amplitude M_1 and an electric-dipole amplitude E_1 added to the transition by PNC forces in the atoms. The rotation angle[9] has the form $\varphi_{\mathrm{PNC}} = -4\pi\lambda^{-1}(n-1)lR$, where $R \equiv \mathrm{Im}(E_1/M_1)$, l is the length of vapor, λ the wavelength, and n the refractive index due to the M_1 transition. The refractive index depends upon λ and has a dispersion shape near the transition which is useful for separating φ_{PNC} from background rotations. For an atomic density giving one absorption length at line center, $\varphi_{\mathrm{PNC}} = R/2$ at a dispersion peak. Increasing the atomic density can produce a rotation much larger than R just outside the absorption line, where in favorable cases such as ours the usable optical depth $(n-1)l$ is not strongly limited by absorption.

Heavy atoms are a good place to look for neutral-current effects, which increase rapidly[10] with the atomic number Z. Bismuth ($Z = 83$) has several allowed magnetic-dipole transitions from its ground state accessible to tunable lasers. We selected the $J=\frac{3}{2} \rightarrow J=\frac{3}{2}$ absorption line at 8757 Å where there is no competing background absorption from Bi_2 molecular bands to limit the usable optical depth outside the atomic line.

In Table I we list values of R for the 8757-Å line calculated by various forms of relativistic central-field approximation. The ±30% agreement is encouraging considering the differing methods, but more complete calculations that include many-particle effects are clearly desirable.

The basic apparatus and the procedure we use for measuring small angles of optical rotation were both described in Ref. 2. We have since made important additions to the apparatus, which include higher-quality Nicol prism polarizers (obtained from the Karl Lambrecht Co. and transmitting less than 10^{-8} when crossed), a more uniformly heated Bi oven, and Permalloy magnetic

TABLE I. Relativistic central-field calculations of $R \equiv \mathrm{Im}(E_1/M_1)$ for the 8757-Å line in Bi, using the Weinberg-Salam theory (Refs. 8 and 9) with a Weinberg angle given by $\sin^2\theta_W = 0.35$.

Ref. no.	Method	$R(10^{-7})$
3	Hartree-Fock	-2.3
4	Hartree-Fock	-3.5
5	Semiempirical	-1.7
6	Multiconfiguration	-2.4