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Search for the weak non-analog Fermi branch in the ^{42}Sc ground state beta decay*

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We have searched for the β-decay branch from the ^{42}Sc ground state to the 1.837 MeV level in ^{42}Ca. Since both states are $J^{\pi} = 0^+$, $T = 1$, this decay is an example of a non-analog Fermi decay which could occur by reason of some mixing of the analog ground states into the lowest excited 0^+ state in both ^{42}Sc and ^{42}Ca. As a signal for this branch, we looked for a subsequent cascade γ ray with a Ge(Li) detector-rabbit arrangement. We found a branching ratio of $(2.2 \pm 1.7) \times 10^{-5}$ relative to the superallowed ground state to ground state decay. Interpreted as an upper limit, this corresponds to a branching ratio $< 3.9 \times 10^{-5}$ at the 84% confidence level. This result is at the lower bound of what present theory can predict with a Coulomb force mixing calculation.

[RADIOACTIVITY ^{42}Sc(g.s.); measured upper limit on β-decay branching ratio to the 1.837 MeV level in ^{42}Ca relative to the ground state.]

I. INTRODUCTION

The ^{42}Sc(g.s.) $\rightarrow$ ^{42}Ca(g.s.) β decay has been of interest for some time in connection with the determination of the Fermi coupling constant for nuclear β decay. This superallowed $0^+ \rightarrow 0^+$ Fermi decay within a $T = 1$ multiplet is one of a series of examples in light nuclei which exhibit a relatively constant ft value after corrections for radiative and nuclear structure effects are made.[1] Among the latter corrections is that due to the mixing of the ground states with non-analog excited 0^+ states. In particular, the Coulomb force can mix eigenfunctions of the nuclear isospin conserving Hamiltonian, leading to physical states having nonanalog impurities. To the extent that this mixing differs for the $T_z = 0$ ^{42}Sc levels and the $T_z = 1$ ^{42}Ca levels, a reduction of the Fermi decay strength will occur. This reduced strength reappears as a β decay feeding to the excited 0^+ levels.

Both ^{42}Sc and ^{42}Ca have a first excited 0^+ level at about 1.85 MeV. In first approximation, a two-level mixing calculation should be appropriate. Following Towner[2] we write for the ground and excited state nuclear wave functions,

$$\psi_0 = A\,|2\text{p}\rangle + B\,|4\text{p-}2\text{h}\rangle ,$$

$$\psi_1 = B\,|2\text{p}\rangle - A\,|4\text{p-}2\text{h}\rangle ,$$

where p = particle and h = hole relative to the ^{40}Ca core. According to Gerace and Green,[3] $A = 0.890$ and $B = 0.465$. Charge dependent forces will mix these states of good isospin in differing amounts in ^{42}Sc and ^{42}Ca:

$$^{42}\text{Sc(g.s.)} = \psi_0 \xrightarrow{\text{Coul. force}} \psi_i(T_z = 0)$$

$$= b_0\psi_0 + b_1\psi_1 ,$$

$$^{42}\text{Ca(g.s.)} = \psi_0 \xrightarrow{\text{Coul. force}} \psi_{f0}(T_z = 1)$$

$$= a_0\psi_0 + a_1\psi_1 ,$$

$$^{42}\text{Ca(1.837 MeV} = \psi_1 \xrightarrow{\text{Coul. force}} \psi_{f1}(T_z = 1)$$

$$= a_1\psi_0 - a_0\psi_1 ,$$

where the a's and b's are functions of T_z. Here we are only concerned with the states of interest in the ^{42}Sc(g.s.) decay as shown in Fig. 1.

The Fermi matrix elements for the ground state to ground state and ground state to 1.837 MeV state decay are given, respectively, by

$$M_0 = \langle \psi_{f0}(T_z = 1)\,|\,\tau_+\,|\,\psi_i(T_z = 0)\rangle ,$$

$$M_1 = \langle \psi_{f1}(T_z = 1)\,|\,\tau_+\,|\,\psi_i(T_z = 0)\rangle ,$$

where τ_+ is the isospin projection raising operator.

Letting $|M_0|^2 = 2(1 - \delta_c)$, where δ_c is the fractional reduction from the pure isospin symmetric case, one finds that

$$|M_1|^2 = 2\delta_c$$

and

$$\delta_c = (a_1 - b_1)^2 .$$

Within the framework of first-order perturbation theory and assuming that only the Coulomb force is responsible for the charge dependent mixing, Towner obtains[2]

$$\delta_c = \left(\frac{ABE^- - C_{12}}{\Delta E(A^2 - B^2)}\right)^2 ,$$

where ΔE = excitation energy of the excited 0^+ state $\cong$ 1.85 MeV, E^- = difference between the excitation energies of the excited 0^+ state in ^{42}Sc and ^{42}Ca = 38 keV, $C_{12} = \langle 2p\,|\,e^2/r\,|\,4\text{p-}2\text{h}\rangle_{J=0}$ (off-diagonal Coulomb matrix element) $\approx$ 38 keV,[4] and A, B are

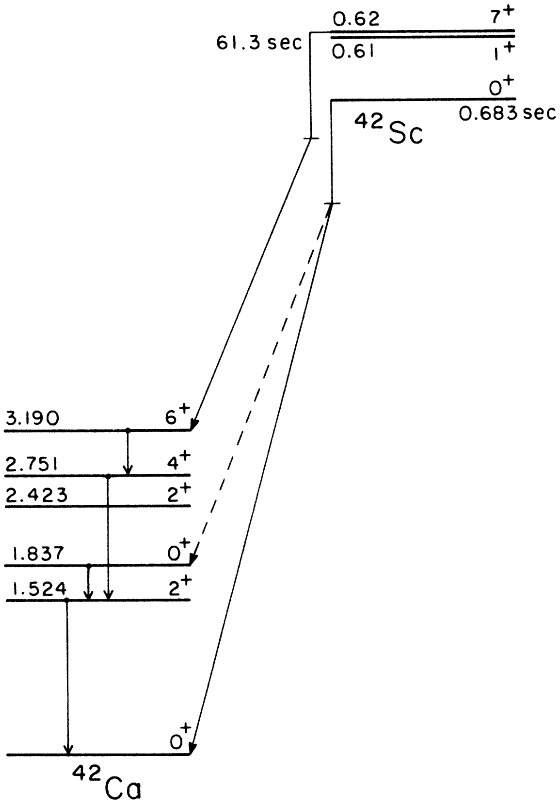

FIG. 1. Decay scheme of ^{42}Sc.

the amplitudes of the two-particle and four-particle–two-hole components of the ground state nuclear wave function. Using the Gerace and Green amplitudes given above ($A = 0.890$, $B = 0.465$), one obtains

$$\delta_c = 4.35 \times 10^{-4}.$$

For the branching ratio R of the decay to the excited state relative to the ground state, one obtains

$$R = \frac{f_1}{f_0}\delta_c \quad (\text{for } \delta_c \ll 1),$$

where f_0 and f_1 are the statistical rate functions for the two decays. For the case considered here $f_1/f_0 = 0.15$, so that

$$R = 6.5 \times 10^{-5}.$$

A measurement of this β-decay branching ratio has been attempted previously.[5-8] References 5, 6, and 7 obtained upper limits; the most stringent was $R < 1.2 \times 10^{-4}$ (50% confidence level). Reference 8, in an experiment which proceeded concurrently with the work reported here, obtained $R = (6.3 \pm 2.6) \times 10^{-5}$. This latter number agrees well with the above theoretical estimate. In view of the difficulty of this experiment, however, it is important to have independent measurements. This is especially true here because Ref. 8 had to contend with an unresolved impurity γ ray of the same energy as the one sought. Our experiment is free of this problem.

II. EXPERIMENT

We use the ^{42}Ca(p,n) reaction to produce ^{42}Sc. The negative Q value ($Q = -7.214$ MeV) makes it possible to excite the ^{42}Sc ground state without exciting the 7^+ state at 0.62 MeV which also β decays. A beam energy of 7.9 MeV was employed. This is about 100 keV below the 7^+ threshold but 500 keV above the ^{42}Sc ground state production threshold. The signal for the branch sought was the cascade γ ray of 1.524 MeV as can be seen in Fig. 1. The 0.68 sec half-life of the ^{42}Sc(g.s.) permits the use of a target transport (rabbit) system. However, it was desirable to use a thin self-supporting ^{42}Ca foil in order to reduce the number of fast positrons annihilating near the target. These positrons produce a high-energy annihilation-in-flight tail which is the major source of background in the γ-ray energy region of interest.

Conventional pneumatic rabbits are not suitable for air-sensitive fragile targets. We developed a new rabbit system for this experiment, which should prove to be useful for a variety of β-decay studies. Since it has been described elsewhere,[9] only a brief summary will be given here. Figure 2 shows a schematic drawing of the device. The rabbit consists of a grooved soft iron bar to which a tantalum strip holding the target foil is attached. The bar moves vertically, guided by two stainless steel rods over a distance of about 1 m. The iron bar-target holder assembly weighs about 0.5 kg. The propulsion is provided by the force which a current carrying solenoid exerts on an iron bar partially inside it. Since this force always acts to pull the bar into the solenoid, the current must be pulsed in order to achieve a net acceleration (or deceleration). This magnetic propulsion permits the rabbit to move entirely in vacuum and, by careful adjustment of currents and timing, allows for precision control of acceleration and deceleration.

The target chamber in Fig. 2 is a thin-walled narrow plastic chamber designed to further reduce the number of fast positrons annihilating near the detector. The Ge(Li) detector (not shown) was surrounded by ~1 cm of lead. In front of the lead was a layer of plastic thick enough to stop all the positrons heading towards the Ge(Li) detector. The entire counting area was surrounded by a concrete walled chamber topped with a 10 cm thick layer of lead bricks. The proton beam was chopped

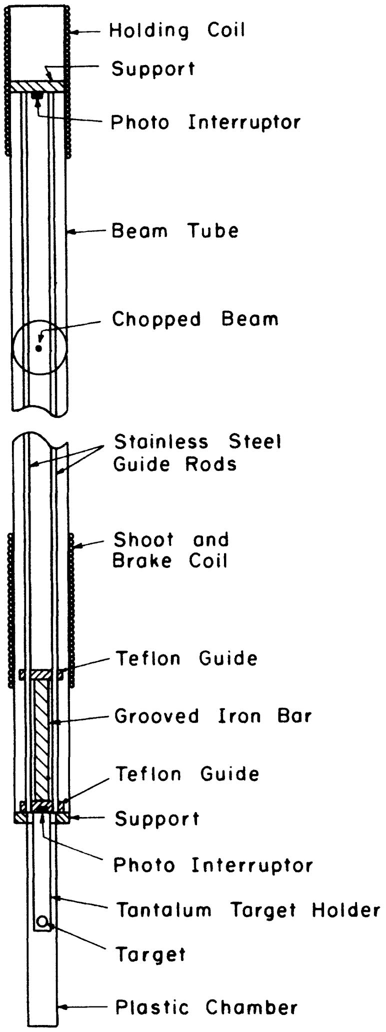

FIG. 2. Schematic mechanical diagram of the rabbit system.

TABLE I Efficiency calibrations.

β Decay	Branching Ratio	$E_{\beta\mathrm{max}}$ (MeV) for dominant decay mode
^{27}Si $\rightarrow$ ^{27}Al(2.211 MeV)	$(1.56 \pm 0.21) \times 10^{-3}$	3.788
^{35}Ar $\rightarrow$ ^{35}Cl(1.219 MeV)	$(1.22 \pm 0.05) \times 10^{-2}$	4.942
^{42}Sc(7^+) $\rightarrow$ ^{42}Ca(3.190 MeV)	1.00	2.836
^{42}Sc(g.s.) $\rightarrow$ ^{42}Ca(g.s.)		5 409

and was only present when the target was at rest in the top bombardment position. Hence virtually no beam related background was present during the counting portion of the cycle.

The γ-ray energy spectrum was fed to an on-line PDP-15 computer. γ-ray counts were stored sequentially in three analyzed arrays of 4096 channels each. The counting time per array per cycle was 1.0 sec (0.4 sec. in a second experiment). This time "binning" was necessary in order to extract the 0.68 sec half-life component of the 511 keV peak from very short and long lived background components. Only about 30% of all 511 keV counts were due to ^{42}Sc(g.s.) decay.

In order to obtain a quantitative measure of the branching ratio of interest, several other similar, but well-known decays, were measured for efficiency calibration purposes. These are shown in Table I. We see, first of all, that these known cases cover a range of β-end-point energies so that extrapolation to the ^{42}Sc(g.s.) decay of interest is reasonable. Secondly, the known decays proceed predominantly to one state with only minor side branches as does the ^{42}Sc(g.s.) decay. A separate γ-ray efficiency calibration was performed with a ^{56}Co source to correct for differences in the γ-ray energies signaling the weak branch. In addition, the known decays could be studied with (p,n) reactions and readily available targets at beam energies close to that required to produce ^{42}Sc(g.s.). These calibration targets were substituted for the ^{42}Ca target on the rabbit without disturbing the Ge(Li) detector shielding and geometry.

The ^{42}Sc experiment was performed twice. Although two separate ^{42}Ca foils were used, they were both about 5 mg/cm^2 thick and about 94% enriched. Both experiments employed a 400 nA, 7.9 MeV proton beam for a total running time per experiment of 50 hours. The first experiment was run with a counting time per spectrum of 1 sec for a total useful counting time per cycle of 3 sec (three spectra) and a cycle time of about 10 sec. The second experiment used a 0.4 sec counting time per spectrum for a total useful counting time of 1.2 sec per cycle, which required about 5 sec for a complete cycle of irradiation, transport, and counting. The lead shielding in front of the Ge(Li) detector was decreased for the second experiment as was the distance between detector and target.

In the first experiment, a 1.2 cm thick lead shield surrounded the Ge(Li) detector which was positioned about 5 cm from the target, while in the second the lead facing the target was reduced to 0.5 cm and the distance of the Ge(Li) detector to the target was about 3 cm. For both cases, the β's were stopped in a 1 cm thick plastic disk inserted between the detector and target. Separate efficiency and calibration runs were performed for the two experiments.

Although the γ-ray energy scale was calibrated with standard sources, the precise location of the

1.524 MeV γ-ray line was established by preceding the ^{42}Sc(g.s.) decay run by a ^{42}Sc (7^+) β-decay run which produces a 1.524 MeV γ-ray in 100% of the decays. The ^{42}Sc 7^+ level was produced by raising the beam energy to 9 MeV. At least three hours elapsed between the ^{42}Sc 7^+ and ground state decay experiments, enough time for the 61 sec half-life 7^+ state to decay completely away.

Figure 3 shows the γ-ray spectrum accumulated in the first of the three analyzed sequential spectra (0.4 sec/cycle counting time). There is a ^{44}Ca contaminant of only about 1% in the target but the ^{44}Ca(p,n) ^{44}Sc Q value of -4.429 MeV permits the long-lived ^{44}Sc to be produced copiously relative to ^{42}Sc(g.s.) production. The low-energy tails on the dominant γ rays in Fig. 3 are a result of using a long integration time constant (4 μsec) at fairly high count rates. They constitute a very small fraction of the peak counts (the log scale distorts the effect). Most of the background above the 511 keV peak is due to annihilation in flight radiation. It decreases noticeably from the first to the last of the three sequential spectra of interest and is, as expected, correlated with the ^{42}Sc decay. All of the dominant contaminant peaks have been identified as indicated in the figure. None of the identified impurities could contribute a γ ray in the immediate vicinity of the 1524 keV peak. The identification of some of the weaker background peaks involved some ambiguity; however, none of the possibilities could produce a peak very close to the 1524 keV peak. In several long background runs, there was no evidence of any contaminant peaks that were close enough to be misidentified as the 1524 keV peak.

Figure 4 shows sections of the γ-ray spectra for the two experiments in the 1524 keV energy region. The arrow points to the expected center channel of the 1524 keV γ ray. The bars indicate the statistical fluctuations expected in the plotted points. The spectra shown in Fig. 4 are summed spectra. The number of counts in the 1524 keV peak was obtained by summing the five center channels of the peak (as suggested from examination of well defined peaks) and subtracting background. Background was determined from a linear fit through the background points neighboring the 1524 keV peak region.

III. RESULTS AND CONCLUSIONS

The branching ratios obtained from the two experiments are

$$R_{\text{exptl}} = \frac{^{42}\text{Sc(g.s.)}\beta_{\to}{}^{42}\text{Ca(1.837 MeV)}}{^{42}\text{Sc(g.s.)}\beta_{\to}{}^{42}\text{Ca(g.s.)}} = (3.9 \pm 2.7) \times 10^{-5}$$

and $R_{\text{expt2}} = (1.2 \pm 2.1) \times 10^{-5}$. Combining these results (using $1/\sigma^2$ weighting), we obtain

$$R = (2.2 \pm 1.7) \times 10^{-5}\,.$$

The errors in the above numbers are predominantly statistical errors. The technique for correcting for 511 keV detection efficiency took into account effects due to β-end-point energy differences between the known and the ^{42}Sc decays. The uncertainty in the branching ratios of the known calibration decays contributed a small amount

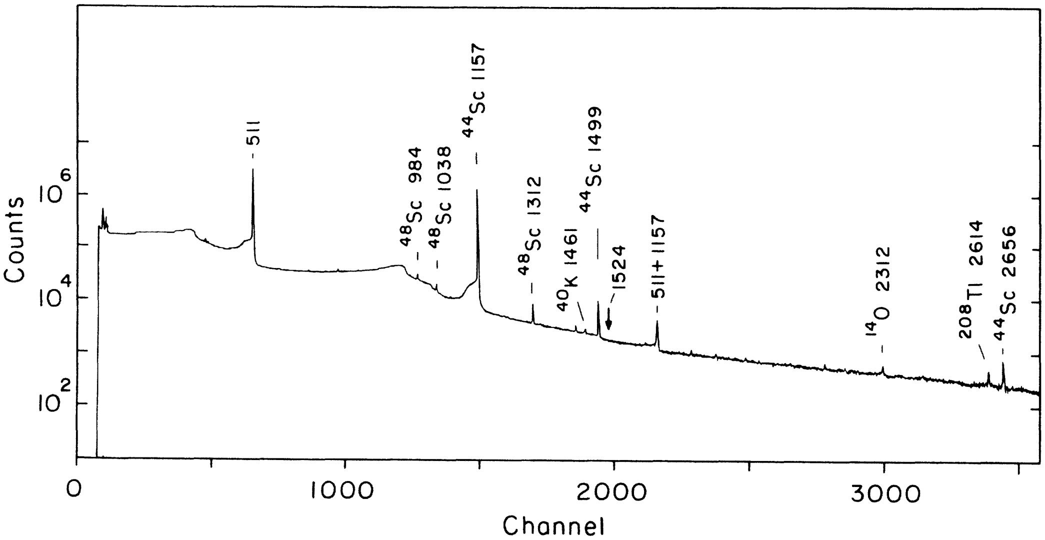

FIG. 3. Complete γ-ray spectrum stored in the first of three sequential arrays. Energies are given in keV (above the γ peaks), and their origin is indicated. This spectrum is for the 0.4 sec time bin from 0.5 to 0.9 sec after the end of irradiation.

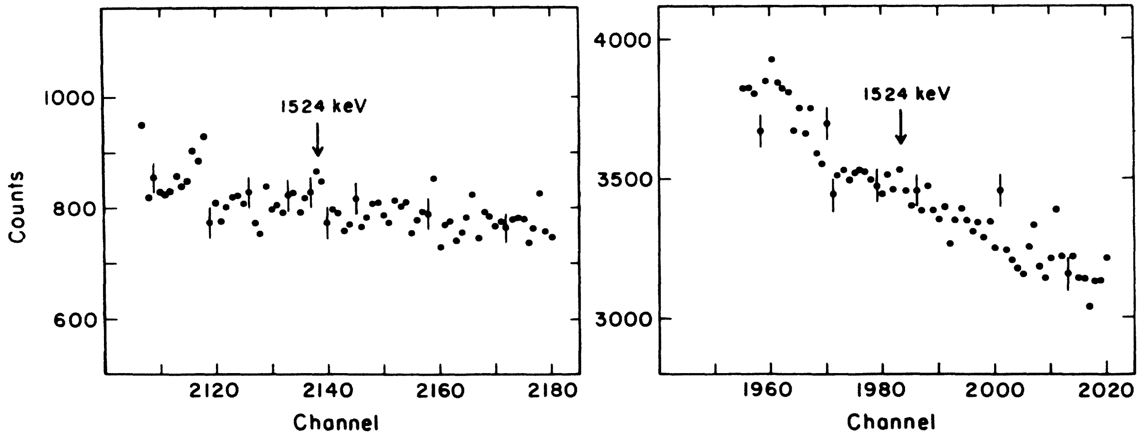

FIG. 4. Summed γ-ray spectra for the 1524 keV energy region. The bars indicate the size of statistical uncertainties. The left spectrum is for the first experiment integrated over two bins (2 sec). The right one is for the faster cycle experiment, integrated over three bins (1.2 sec).

to the above errors. The error involved in subtracting the long-lived component from the 511 keV peak was also relatively small. In view of the barely positive value of the branching ratio measured here, it is perhaps more meaningful to express it as an upper limit:

$$R < 3.9 \times 10^{-5} \text{ (84\% confidence)}.$$

Our upper limit for this branching ratio barely overlaps with the lower limit of the result of Ref. 8 [$R = (6.3 \pm 2.6) \times 10^{-5}$]. It is, of course, consistent with all previously reported upper limits. Our result is low enough that other possible small contributions to 1524 keV γ-ray production are worth considering. One possibility is the decay of the ^{42}Sc 0^+ ground state directly to the 1524 keV 2^+ level in ^{42}Ca. This is a second-forbidden nonunique β decay for which systematic information is available.[10] Empirically, it is found that $\log ft \geq 11.0$ for these decays.[11] For our case, this translates to a maximum direct feeding of 6.7×10^{-9} relative to the ground state to ground state branch or a negligible amount.[12] The branch to the 2423 keV 2^+ level in ^{42}Ca, which cascades through the 1524 keV level in about 50% of its γ decays, is also found to be completely negligible.[12] A contribution to the 1524 keV peak from ^{42}K decay following the second-order $^{42}\mathrm{Ca}(n,p)^{42}\mathrm{K}$ reaction was found to be negligible in a calculation for an experiment similar to ours.[8]

Our branching ratio is significantly below the theoretical result ($R = 6.5 \times 10^{-5}$) mentioned in the Introduction. This theoretical number is, however, quite sensitive to the value of certain parameters deduced from experiment. For instance, if the off-diagonal Coulomb matrix element, C_{12}, is changed from 38 to 30 keV, the theoretical result would agree with our experimental one. Such a change is very likely within the uncertainty of this number. On the other hand, a more detailed shell model calculation involving mixing with higher lying 0^+ states produced an even higher branching ratio for this decay[2] ($R = 2.3 \times 10^{-4}$). Our result can therefore provide a meaningful restriction on future theoretical calculations.

From the experimental branching ratio reported here, we obtain for the Fermi matrix element correction,

$$\delta_c = (0.015 \pm 0.011)\%$$

or

$$\delta_c < 0.026\%.$$

That is a reduction of <0.026% in the Fermi decay strength. This correction is far below that estimated for the lack of perfect wave-function overlap for the two ground states and may therefore be safely ignored. Since the experimental Fermi decay strength correction reported here for ^{42}Sc (as well as that based on previous experiments) is well below original theoretical estimates,[1] it may be worthwhile to reinvestigate other examples of superallowed Fermi β decays theoretically and experimentally (if possible) to see if this correction has been overestimated for them as well.

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