Search for Branching in the β Decay of ^{42}Sc†

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Experimental limits have been set on the intensity of a branching in the β^+ decay of the the ^{42}Sc ground state to the 1838-keV 0^+ state in ^{42}Ca, providing an upper limit on the departure from isospin purity in the $A=42$ system. The limits are branching ratio $< 4.6 \times 10^{-4}$ with 95% confidence; branching ratio $< 1.2 \times 10^{-4}$ with 50% confidence.

Beta decays which proceed between states of the same spin and parity have proved to be sensitive measures of departures from isospin symmetry. Two classes of such decays have been usefully studied. In the one type, the initial and final states of the decay are members of a $T=1$ isospin multiplet with spin and parity 0^+. For these only the Fermi transition contributes, and in the absence of isospin mixing the ft values should be the same for all. That they are, to a precision of roughly 1 part in 300, has been shown by Freeman.[1] In the other type, the initial and final states have different isospins. For this case Fermi transitions are forbidden in the absence of isospin mixing, and measurement of the contribution of the Fermi transition to the decay directly measures the degree of that mixing. The information from this type of decay is summarized by Bloom.[2]

In the decay of the 0^+, $T=1$, ^{42}Sc ground state the possibility exists that a decay closely akin to the second type can occur in competition with a decay of the first type. The known decay proceeds to the 0^+, $T=1$ ground state of ^{42}Ca (see Fig. 1). However, the 1838-keV state in ^{42}Ca is also 0^+, $T=1$, and decay to it is energetically permitted. The branch is forbidden if isospin is a good quantum number; not, as in the type-II decays, because of selection rules, but because the Fermi matrix element between states that are not isospin analogs must vanish. Thus a branch to this state directly measures a departure from isospin conservation, but of the sort termed "dynamic distortion" by McDonald.[3]

Actually, the branch does not measure the total distortion effects in either nucleus, but rather the difference between the effects in Sc and Ca. More specifically, if $\varphi_n(T, T_z)$ represent the states of the mass-42 system for the isospin-conserving Hamiltonian, then the eigenstates $\Psi_k(T, T_z)$ of the full Hamiltonian will be expressable as

$$\Psi_k(T, T_z) = \sum_n a_{kn}(T_z)\varphi_n(T, T_z).$$

The matrix element for the branching decay will be

$$M = \langle \Psi_1(1, 1) | T_+ | \Psi_0(1, 0)\rangle,$$

which, since $a_{11}(1)$ and $a_{00}(0)$ are essentially unity, becomes approximately

$$M = \sqrt{2}\,[a_{10}(1) + a_{01}(0)]. \tag{1}$$

In terms of the energy matrix elements of the isospin-nonconserving interaction c, the a_{kn} are approximately

$$a_{10}(T_z) = -a_{01}(T_z) = \langle \varphi_1(T_z) | c | \varphi_0(T_z)\rangle / \Delta E,$$

where ΔE is the state separation. Since the matrix element for ground state $\rightarrow$ ground state is essentially unperturbed, the matrix-element ra-

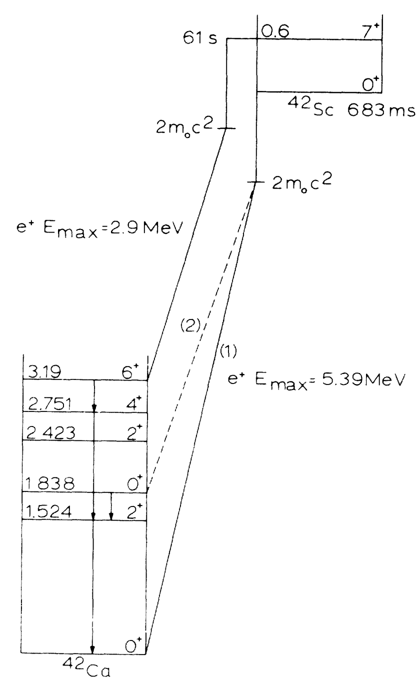

FIG. 1. Decay scheme of ^{42}Sc from its ground and first excited states. The excited-state decay leads to the 440–1223–1524-keV γ-ray cascades. The ground state decays via the superallowed Fermi decay (1) or the as yet unobserved allowed Fermi decay (2).

tio then becomes

$$\left|\frac{M(0_1^+ \to 0_2^+)}{M(0_1^+ \to 0_1^+)}\right| = \frac{1}{\Delta E}\left[\langle\varphi_1(T_z=1)\,|\,c\,|\,\varphi_0(T_z=1)\rangle - \langle\varphi_1(T_z=0)\,|\,c\,|\,\varphi_0(T_z=0)\rangle\right]. \quad (2)$$

This note describes a search for such a branch. The 1838-keV state in ^{42}Ca, if populated, will decay by cascade γ-ray emission through the 1524-keV first excited state. The essence of the search is to populate the ground state of ^{42}Sc, and attempt to measure the intensity of a 1524-keV γ ray relative to the intensity of annihilation radiation. By subsidiary means, to be described below, the annihilation radiation can be related to the total number of ^{42}Sc decays.

The experiment was done using the 5.5-MeV Van de Graaff accelerator at the University of Arizona. The doubly charged helium beam was used to bombard a thick KI wafer, inducing the reaction ^{39}K$(\alpha, n)^{42}$Sc. The beam was mechanically chopped to bombard the target for intervals of about 1 sec, and for 1 sec the residual γ-ray activity was monitored using a Ge(Li) detector and 1000-channel multichannel analyzer. The beam energy was chosen to avoid populating the first excited state of ^{42}Sc. This level also decays by positron emission to ^{42}Ca, giving rise to the 1524-keV γ ray as part of the cascade including the 440- and 1223-keV γ rays. The beam energy was set at about 8.7 MeV (about 100 keV below the excited-state threshold) by moving downward in energy until the cascade peaks disappeared from the spectrum.

The target was a 99.97% ^{39}K-enriched sample which turned out to have many contaminant materials present. Reactions on these produced γ rays which contaminated the spectrum (Fig. 2).

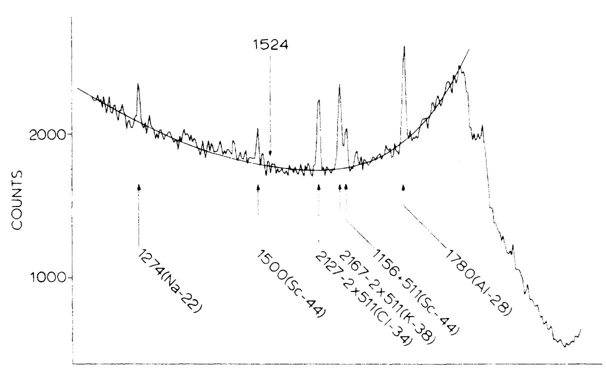

FIG. 2. γ-ray spectrum in the region surrounding 1524 keV for 195 h of data collection. The smooth line is a fifth-order polynomial fitted to the background.

The region near 1524 keV is in the middle of the Compton tail due to the 2127-keV γ ray from ^{34}Cl decay and the 2167-keV γ from ^{38}K decay, materials which appeared due to ^{31}P and ^{35}Cl contaminants present.

The data were recorded in 2-h segments, and the electronics were calibrated between each run. A total of 195 h of data at beam currents of about 65 nA were collected in this fashion, corrected for small gain shifts, and summed.

The summed spectrum was then analyzed to obtain the relative intensities of 511- and 1524-keV peaks. Information on the number of 511-keV quanta due to ^{42}Sc was obtained in two ways. In the first, all of the contaminant peaks were identified, and the number of 511-keV γ rays necessary to account for their presence in the spectrum was calculated. In the second, the 511-keV γ-ray yield was measured as a function of energy. The energy was varied between 6.7 and 8.8 MeV, the total number of 511-keV γ rays being recorded and then plotted as a function of energy. The number of annihilation events due to the formation of ^{42}Sc can be extracted by observing the increase in activity after threshold. Results of this technique agreed to within about 20% of the first calculation, but the latter value was taken to be the more dependable and was used in the subsequent work.

No clear 1524-keV peak was observed in the data. To estimate how many counts could be hidden in the background involved several steps. First, a fifth-order polynomial was fitted to the spectrum in the regions where there were no clear peaks (Fig. 2), the set of differences from this curve constituting a new spectrum. The resulting distribution of values measured the probability that statistics of counting in adjacent channels conspire to form a peak (if the correlation is positive) or valley (if it is negative) in the spectrum.

Because no peak was seen, either in the data or in the correlated spectrum, only a probability could be set that the peak area was less than some value. The distribution in peak-free regions resulting from the correlation procedure measures the likelihood of that value occurring at 1524 keV. To be conservative, the limiting area was deduced from each of the two channels adjacent to the expected 1524-keV peak position, and the larger value was adopted. The results give a confidence level of 95% that the branching ratio R to the excited state is less than 4.6×10^{-4} and a confidence level of 50% that it is less than

1.2×10^{-4}.

A branching-ratio limit of this size does not put very restrictive limits on the matrix elements of an isospin-breaking term in the Hamiltonian. The smaller energy available to the excited-state β decay already inhibits the branch by the ratio of the Fermi functions; so the experimental 50% confidence limit on the branching ratio implies a limit on the matrix element of

$$\left|\frac{M(0_1^+\to0_2^+)}{M(0_1^+\to0_1^+)}\right|=\left\{R\frac{f(0_1^+\to0_1^+)}{f(0_1^+\to0_2^+)}\right\}^{1/2}<0.029. \quad (3)$$

The experiment requires, then, that the difference in the dynamic-distortion matrix elements in the two nuclei is less than about 50 keV [see Eq. (2)].

To see whether this is reasonable, it is necessary to specify the isospin-conserving wave functions φ_k. These states are consistent with two-particle and four-particle, two-hole configurations built on a ^{40}Ca core.[4] Using the wave functions determined in Ref. 4, one can calculate the Coulomb mixing of the two states. Rappleyea and Kunz[5] have carried out an analogous calculation; they have recomputed wave functions in the manner of Ref. 4, including the Coulomb interaction, obtaining the wave functions Ψ_k directly. Their predicted value for the matrix-element ratio is

$$|M(0_1^+\to0_2^+)/M(0_1^+\to0_1^+)|=0.020, \quad (4)$$

which is consistent with the results of this experiment.

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Ground-State Correlation and the Isobaric Analog State

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For an $N\neq Z$ system interacting through a Hamiltonian including the Coulomb interaction, the effect of proton-neutron correlations on the ground state and its isobaric analog is discussed. It is shown that the correlation greatly reduces the isospin impurity in the ground state.

It is well known that for $N\neq Z$ systems isospin is not a good quantum number for the uncorrelated ground-state wave function $|0\rangle$ obtained in the Hartree-Fock (HF) approximation, even when the isospin-symmetry-breaking Coulomb interaction is *not* included in the Hamiltonian. This in fact is a special case of a general property of the variational method utilized in the HF approximation, that $|0\rangle$ is not necessarily an eigenfunction of any operator which commutes with the Hamiltonian. Recently Engelbrecht and Lemmer[1] showed that, in the absence of the Coulomb interaction, the isospin symmetry of $|0\rangle$ is restored if proton-neutron correlations, generated within the framework of the random phase approximation (RPA), are incorporated into it. In this Letter we first explore their notion in more detail, and then introduce the Coulomb interaction into the picture. It is shown that when all the single-particle (sp) Coulomb energies of the protons are degenerate, the correlated ground state $|\tilde{0}\rangle$ is still isospin pure, and the Coulomb displacement energy of its isobaric analog [i.e., the isobaric analog state (IAS)] is equal to the degenerate sp Coulomb energy. This simple picture is disdisturbed, however, when the sp Coulomb energies are nondegenerate. We calculate the shift of the Coulomb displacement energy of the IAS and the isospin impurity in $|\tilde{0}\rangle$ for a simple but very physical nondegenerate case.