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Decays of ^{39}Ca and ^{41}Sc†

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The decays of ^{39}Ca and ^{41}Sc have been studied because of the related interest in the magnitude of the axial coupling constant in nuclear matter. ^{39}Ca was produced in the ^{39}K$(p,n)^{39}$Ca reaction at $E_p = 10$ MeV and its half-life was measured as 860.4± 3.0 msec resulting in an ft value of 4283± 25 sec. The half-life of ^{41}Sc, formed in the ^{40}Ca$(p,\gamma)^{41}$Sc reaction with 3-MeV protons on thick Ca, is 596.3± 1.7 msec. From the γ-ray energies of 2882.6± 0.3 keV and 3696.9± 0.5 keV measured at the 1.84- and 2.68-MeV resonances the Q value of the ^{40}Ca(p,γ)-^{41}Sc reaction is found to be 1085.7± 1.4 keV. This leads to a ^{41}Sc mass excess of −28 642.2 ± 1.7 keV, to a ^{41}Sc decay energy of 6494.9± 2.0 keV, and to an ft value of 2849± 9 sec. An upper limit of 2×10^{-3} is placed on the β branching of ^{41}Sc to excited states of ^{41}Ca. If the free-space value of g_A is used to extract the Gamow-Teller matrix element $\langle\sigma\rangle_{\rm exp}$ from these data we find $\langle\sigma\rangle_{\rm exp}/\langle\sigma\rangle_{\rm s.p.}$ values of 0.685± 0.009 and 0.761± 0.006 for ^{39}Ca and ^{41}Sc, respectively, where the $\langle\sigma\rangle_{\rm s.p.}$ are the relevant single-particle matrix elements.

INTRODUCTION

The Fermi β decay of complex nuclei is rather well understood. To the extent that isospin symmetry breaking can be ignored, Fermi decay takes place only within an isobaric multiplet with the squared matrix element:

$$\langle 1\rangle^2 = T(T+1) - T_{3i}\,T_{3f}\,.$$

The success of the theory of the conserved-vector current assures us that no renormalization of Fermi β decay is brought about by the strong interactions so that all complex nuclei should vector β decay with the same intrinsic strength: This is borne out to within better than a percent by the classical studies of the $J^\pi = 0^+ \to 0^+$ transitions in nuclei ranging up to ^{54}Co.

However, the situation with regard to Gamow-Teller β decay is different in two respects: The matrix element $<\sigma>$ is wave-function-dependent (except for the decay of the free neutron) and the axial current is not conserved. The latter fact means that, even if $<\sigma>$ were given exactly, we should not be able to calculate Gamow-Teller β decay from it with confidence comparable to that experienced for Fermi decay since the axial coupling constant g_A must to some degree be renormalized, $g_A \to g_{Ae}$, when nucleons are bound into complex nuclei. In any case such renormalization could only be a caricature of a more complicated situation in which many-body effects should be taken explicitly into account.

Two recent studies[1,2] have suggested $g_{Ae}/g_A \approx 0.9$ for A in the range up to 21, but it is not clear whether this represents a "fundamental" renormalization[3] or whether it simply reflects the use of inadequate conventional wave functions (in the sense that very highly-excited core-polarization configurations have not been taken into account[4] or whether these two effects are somehow related.

Whatever the reason for the apparent nuclear renormalization of g_A it is important to have reliable experimental data for the nuclei whose conventional wave functions are the simplest; these are nominally the doubly-closed-shell-plus-or-minus-one-nucleon cases. Data appeared to be reliable either side of the doubly-closed shell at ^{16}O but we felt that the situation near ^{40}Ca should be reinvestigated.

EXPERIMENTAL METHODS AND RESULTS

^{39}Ca

^{39}Ca was produced in the ^{39}K$(p,n)^{39}$Ca reaction by bombarding a potassium target with 10-MeV protons from one of the Brookhaven National Laboratory tandem Van de Graaff accelerators. The target consisted of a 5-mg/cm^2-thick layer of K evaporated onto a 0.012-mm-thick Au backing, and a chopped beam current of 2–3 nA produced a suitable yield of activity. Following the procedures described previously[5] the β rays were detected in an NE102 plastic scintillator located next to the target. The counts were multiscaled at an advance rate of 0.06 sec per channel for a total of 256 channels. Nine runs were made on ^{39}Ca decay using β-

detector biases from 0.8 to 2.4 MeV. Computer fits were made to the data of each run and the final adopted value for the ^{39}Ca half-life is 860.4 ± 3.0 msec. This is to be compared with the compilation value[6] of 877 ± 6 msec and with a somewhat later result[7] of 865^{+7}_{-17} msec. The former number is not compatible with our own, and while the latter is in agreement with our half-life, its errors are asymmetrical and relatively large. We therefore use our own value in what is to follow.

Before extracting an ft value from the half-life we must know the mass relationships and the strength of any competing process. On the latter point it has been established[8] that positron branches to excited states of ^{39}K total less than 0.12%; orbital electron capture is less than 0.1%. We neglect the possible β branches to excited states and apply the small calculated electron-capture (EC) correction. The maximum positron kinetic energy according to the mass tables[9] is 5500 ± 5 keV to which corresponds $f = 4975 \pm 23$, and we obtain $ft = 4283 \pm 25$ sec. (The f values of this paper are computed following a recent definition[10] that takes into account the effects of finite nuclear size; they also include the "outer" radiative correction[11] of order α and screening according to a standard prescription.)

^{41}Sc

The procedures for measuring the half-life of ^{41}Sc were essentially the same as for ^{39}Ca except that the activity was produced in the ^{40}Ca$(p,\gamma)^{41}$Sc reaction by bombarding a thick Ca target with 3-MeV protons from the 3.5-MeV Brookhaven National Laboratory Van de Graaff. A beam current of 4.5 μA irradiated the target for 1.3 sec and after a delay of 0.5 sec the measurement was started using an advance rate of 0.04 sec per channel for 256 channels. Based on the computer fits to the data of five runs at various β-detector biases the adopted half-life of ^{41}Sc is 596.3 ± 1.7 msec. Our value may be compared with previous values of 596 ± 6 msec[12] and 591 ± 5 msec.[13] The three measurements are compatible and for subsequent analysis we combine them to give 595.8 ± 1.6 msec.

We have sought to improve the value for the energy release in the positron decay by determining the Q value of the ^{40}Ca$(p,\gamma)^{41}$Sc reaction for which purpose the energies of the γ rays emitted at the 1.84- and 2.68-MeV resonances were measured. The proton resonant energies have been determined by Youngblood, Aldridge, and Class[12] to accuracies of 1.5–2 keV whereas the errors on their γ-ray energies were 5–8 keV owing to the use of a NaI(Tl) γ-ray detector. We have not attempted to improve on the (p,γ) resonance energy determinations of Youngblood, Aldridge, and Class but felt that greater precision could be obtained for the corresponding γ rays by the use of Ge(Li) detector techniques.

A 20-cm^3 Ge(Li) detector was placed at 90° to a target consisting of 0.5 mg/cm^2 of Ca evaporated onto a 0.12-mm-thick air-cooled Au backing. Beam currents were 3–6 μA and the source-to-detector distance was 3 to 6 cm. Superposed γ-ray calibration sources of ^{88}Y and ^{228}Th were found to be convenient since the two-escape peak of the 2882-keV γ ray from the lower (p,γ) resonance is separated by only 24 keV from the ^{88}Y γ ray of 1836.09 keV, while at the upper resonance the two-escape peak of the 3697-keV γ ray is separated by 60 keV from the full-energy peak of the ^{228}Th 2614.58-keV γ ray. Energy values for the observed γ-ray peaks from the ^{40}Ca$(p,\gamma)^{41}$Sc reaction were obtained by a polynomial fitting procedure using the 898.02- and 1836.09-keV ^{88}Y γ-ray peaks and the full-energy, one-escape, and two-escape peaks associated with the 2614.58-keV γ ray of ^{228}Th.

The measurements at the two resonances resulted in γ-ray energies of 2882.6 ± 0.3 keV and 3696.9 ± 0.5 keV. These values may be combined with the resonant energies of Youngblood, Aldridge, and Class[12] to determine the Q value of the ^{40}Ca$(p,\gamma)^{41}$Sc reaction. For the lower resonance at $E_p = 1841.7 \pm 1.5$ keV the resulting Q value is 1085.8 ± 1.5 keV, while for the upper resonance at $E_p = 2676.6 \pm 2.0$ keV the Q value is 1085.6 ± 2.1 keV. These separate results are in excellent agreement and we adopt $Q = 1085.7 \pm 1.4$ keV for the ^{40}Ca(p,γ)-^{41}Sc reaction. By using the masses of ^{40}Ca and p from the tables[9] it follows that the mass excess of ^{41}Sc is −28 642.2 ± 1.7 keV. This agrees with the value −28 641 ± 5 keV given in the tables but the accuracy has been improved by a factor of 3 as a result of the present work. These data, combined with the mass excess of ^{41}Ca from the tables, give a maximum positron kinetic energy in ^{41}Sc decay of 5472.9 ± 2.0 keV.

Information on possible ^{41}Sc branches to excited states of ^{41}Ca was not very sharp so we sought such branches by standard β-γ coincidence techniques using an NE102 plastic scintillator for the β rays on one side of the target and a 13 × 13-cm NaI(Tl) γ-ray detector on the other side, each detector being at about 2.5 cm from the target. The coincidence γ-ray spectrum was stored for two successive 1-sec intervals in separate analyzer sections following a chopped-beam irradiation of a thick Ca target with 3-MeV protons. No γ-ray peaks decaying with the half-life of ^{41}Sc were observed above the background of long-lived activities. Since the first excited state of ^{41}Ca is at 1.94 MeV one would expect γ rays of at least that energy to be in coincidence with β branches to excited states. From the upper limit on the intensity of any γ-ray peak between 2 and 3 MeV that could be associated with ^{41}Sc decay, together with the known absolute photopeak efficiency of the detector, the upper limit on a corresponding β branch is $<2\times10^{-3}$ per decay. For γ rays of >3 MeV the upper limit on β branching is $<2\times10^{-4}$ per decay. The calculated orbital electron-capture decay of ^{41}Sc is of very small intensity.

Our ^{41}Sc decay energy yields $f=4778\pm9$ and this, together with the above-adopted half-life, ignoring any competing β branch and applying the small calculated EC correction, gives $ft=2849\pm9$ sec.

ANALYSIS

In the previous section we have extracted the two ft values:

^{39}Ca $ft=4283\pm25$ sec,

^{41}Sc $ft=2849\pm9$ sec.

We must now split the β decay into its Fermi and Gamow-Teller parts. This we do in the way recently described in detail,[2] viz., using

$$ft=\frac{(6162\pm14)(1-3.67\times10^{-4}Z+1.30\times10^{-5}Z^2)\text{ sec}}{(0.995\pm0.003)\,\langle1\rangle^2+(1.565\pm0.023)\langle\sigma\rangle^2_{\text{exp}}}.$$

The first term in the numerator of this expression is the strength of pure Fermi decay at $Z=0$; the second term represents Z-dependent radiative corrections through order $Z^2\alpha^3$. In the denominator $\langle1\rangle^2$ is as given above; the numerical factor multiplying it accounts for the isospin symmetry breaking. The numerical factor multiplying the desired Gamow-Teller $\langle\sigma\rangle^2_{\text{exp}}$ is the free nucleon $(g_A/g_V)^2$.

Combining this expression for ft with the above ft values gives, without regard to sign:

^{39}Ca $\langle\sigma\rangle_{\text{exp}}=0.531\pm0.007$,

^{41}Sc $\langle\sigma\rangle_{\text{exp}}=0.863\pm0.007$.

DISCUSSION

We may now compare our $\langle\sigma\rangle_{\text{exp}}$ with the single-particle expectations, without regard to sign:

^{39}Ca $\langle\sigma\rangle_{\text{s.p.}}=\sqrt{\tfrac{3}{5}}=0.775$,

^{41}Sc $\langle\sigma\rangle_{\text{s.p.}}=3/\sqrt{7}=1.134$.

Our data then read:

^{39}Ca $\langle\sigma\rangle_{\text{exp}}/\langle\sigma\rangle_{\text{s.p.}}=0.685\pm0.009$,

^{41}Sc $\langle\sigma\rangle_{\text{exp}}/\langle\sigma\rangle_{\text{s.p.}}=0.761\pm0.006$.

These reductions of the $\langle\sigma\rangle_{\text{exp}}$ below the $\langle\sigma\rangle_{\text{s.p.}}$ are very considerable; they are substantially greater than the reductions expected from core polarization,[4] namely 15% or so, or from mesonic renormalization estimated through the nuclear Adler-Weisberger sum rule,[3] namely 10% or so. It is unlikely that the correct explanation is the summation of these effects since the situation in the lighter nuclei, where data have been analyzed in detail over a wide range of A values,[1,2] does not suggest that this summation should be made. In more direct support of this conclusion we quote the comparable cases at the closing of the $1p$ shell[2]:

^{15}O $\langle\sigma\rangle_{\text{exp}}/\langle\sigma\rangle_{\text{s.p.}}=0.882\pm0.009$,

^{17}F $\langle\sigma\rangle_{\text{exp}}/\langle\sigma\rangle_{\text{s.p.}}=0.877\pm0.008$.

Near $A=16$ neither the core-polarization effect nor the mesonic effect is expected to differ greatly from its value near $A=40$. A more likely explanation for the present results may appear to be the incompleteness of the double-shell closure at ^{40}Ca which blurs the $(2s,1d)/1f_{7/2}$ boundary and leaves ^{39}Ca and ^{41}Sc as rather poor single-particle nuclei. A realistic nonperturbative estimate of $(2s,1d)/1f_{7/2}$ mixing in this boundary region is much to be desired.

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