Observation of the First $T_z = -\frac{5}{2}$ Nuclide, ^{35}Ca, via Its β-Delayed Two-Proton Emission

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The decay of the $T=\frac{5}{2}$ isobaric analog state in ^{35}K at 9053 ± 45 keV, fed by the superallowed β decay of 50 ±30-ms ^{35}Ca, results in two-proton emission to both the ground and the first excited states of ^{33}Cl. The measured energy correlations between the two decay protons indicate a sequential-decay mechanism. From the isobaric-multiplet mass equation, a mass excess of 4453 ± 60 keV can be predicted for the ground state of ^{35}Ca.

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As experiment defines the proton drip line in the light nuclei, current interest centers on investigating those nuclides with $T_z=(N-Z)/2=-\frac{5}{2}$ which are predicted to undergo β decay but which are yet to be observed. Previous studies have reported the decays of most of the proton-rich light nuclei, through $T_z \geqslant -2$ and with $Z \leqslant 20$, which are stable to rapid ground-state proton emission. In particular, $T_z=-2$ nuclei in both the even-even mass series[1,2] and the odd-odd mass series[3] have been observed and represent the current limits of our knowledge. Nuclei in both mass series decay by beta-delayed proton emission and those in the latter series (^{22}Al, ^{26}P) additionally decay by the new mode of beta-delayed two-proton emission.

Four exotic light nuclei with $Z \leqslant 20$ and $T_z=-\frac{5}{2}$ are predicted by the updated Kelson-Garvey charge-symmetry approach[4,5] to be bound to ground-state proton emission: ^{23}Si, ^{27}S, ^{31}Ar,[6] and ^{35}Ca. All four nuclides are expected to have relatively strong superallowed decay branches to the $T=\frac{5}{2}$ isobaric analog state in their daughter nuclei; decay from these analog states by both single-proton and two-proton emission is energetically allowed.

We wish to report the observation of ^{35}Ca, detected via its beta-delayed two-proton emission. By exploitation of this relatively unusual decay mode, it is possible to observe light nuclei very far from stability, even though produced in quite low yield, whose decay by other modes would be difficult to detect without on-line mass separation. Calcium-35, with a predicted half-life of 35 ms and a two-proton decay energy of 4.2 MeV,[7,8] to be produced via the reaction ^{40}Ca(^{3}He, $\alpha 4n$) was also chosen for this study because of the expected absence in our spectra of other possible "contaminant" beta-delayed two-proton emitters. First, the nearest odd-odd, $T_z=-2$ nuclei ^{30}Cl, ^{34}K, and ^{38}Sc are all predicted to be proton unbound by more than 600 keV.[4] Second, the $T_z=-\frac{5}{2}$ nuclide ^{31}Ar, if produced and decaying via this mode, is not observable in our experimental approach (rare-gas activities are not detected in our helium-jet experiments). Finally, the heavier $T_z=-\frac{5}{2}$ nuclide ^{39}Ti is almost certainly unbound to ground-state two-proton emission. Since an earlier lower-energy bombardment of ^{40}Ca with the 110-MeV ^{3}He beam did not show evidence for ^{35}Ca,[8] a higher energy (135 MeV) was chosen for this work.

Calcium-35 nuclei were produced by bombarding a 2-mg/cm^2-thick natural-calcium target with 135-MeV ^{3}He beams of 3–7-μA intensity from the 88-inch cyclotron at the Lawrence Berkeley Laboratory. Recoiling product nuclei were slowed down in 1.4 atm helium and transported through a 60-cm-long and 1.27-mm-diam capillary via NaCl aerosols into a counting chamber pumped by a high-speed Roots blower as discussed in Ref. 3. A total average delay time of 25 ms was achieved with this setup. The activity was collected on a slowly rotating catcher wheel directly in front the two-proton detector system.

This specially constructed detector system consisted of three elements: either 10- or 16-μm ΔE_1, 250-μm ΔE_2, and 500-μm E detectors. The surface contacts of the ΔE detectors were divided on one side along the center line, thereby providing two two-element (ΔE_1 and ΔE_2) telescopes capable of detecting low-energy protons in coincidence. Particle-identified proton-proton coincidences could be observed with a timing resolution better than 40 ns. The E detector, combined with either of these two-counter telescopes, was used as a means to detect high-energy single-proton groups as ΔE_1-ΔE_2-E coincidences or as a beta-proton pileup rejection counter. The energy calibration of the various telescopes was provided by the β-delayed single-proton emitters ^{41}Ti, ^{37}Ca, and ^{29}S. The angular acceptance covered by the two low-energy telescopes ranged from $\sim 0°$ to $\sim 50°$ with each side subtending $\sim 2\%$ of 4π. This "small-angle" setup was chosen to detect two-proton coincidences, whether from sequential proton emission (which is expected to result in a roughly isotropic pattern[3]) or emitted as a ^{2}He nucleus, the latter being confined only to small angles. This setup also discriminated effectively against false two-proton coincidences caused by protons from neutron-induced reactions traversing both telescopes.

The overall performance of the experimental system was established in the same experiment by observing the β-delayed two-proton decay[3] of ^{22}Al which was produced via the reaction ^{24}Mg(^{3}He,$p4n$) at 135 MeV. The two-proton sum spectrum shown in Fig. 1(b) arose from a bombardment with an integrated beam current of 86 mC; the two-proton peak at 4112 keV agrees well with earlier observations for the $\beta 2p$ decay of ^{22}Al to the first excited state of ^{20}Ne. With use of the observed two-proton energy, the corresponding individual proton spectra from the two telescopes, and the well-known center-of-mass energy for this decay, an effective average angle of $\sim 33°$ between the telescopes was determined.

The two-proton coincidence spectrum collected during the bombardment of a Ca target for 2.1 C is shown in Fig. 1(a). Two sum peaks are evident with laboratory energies of 4089 ± 30 keV and 3287 ± 30 keV. A half-life of 50 ± 30 ms was estimated for both groups by comparison with the ^{22}Al yield at two different catcher-wheel speeds. The assignment of the observed groups to ^{35}Ca is based on excellent agreement with the predicted decay energy for the higher sum peak populating the ^{33}Cl ground state[4,8] and with the known energy difference for decays to the ground (G) and the first excited (X) states at 811 keV in ^{33}Cl. Further, the half-life is consistent with the prediction for ^{35}Ca and no other new beta-delayed two-proton emitters (e.g., ^{27}S), if produced, are expected to have these two-proton sum energies.

Figure 2 presents the superimposed individual proton spectra corresponding to the decays to the ground state (G) and the first excited state (X) at 811 keV of ^{33}Cl. The distribution of individual proton energies suggests a sequential decay process via intermediate states in ^{34}Ar. (If the two protons were emitted via a single-step ^{2}He emission, a continuum of individual proton energies centered at $E_{p1} = E_{p2}$ would be expected.) Derivation of the corresponding center-of-mass decay energies requires knowledge of the order in which the protons are emitted, since as a result of

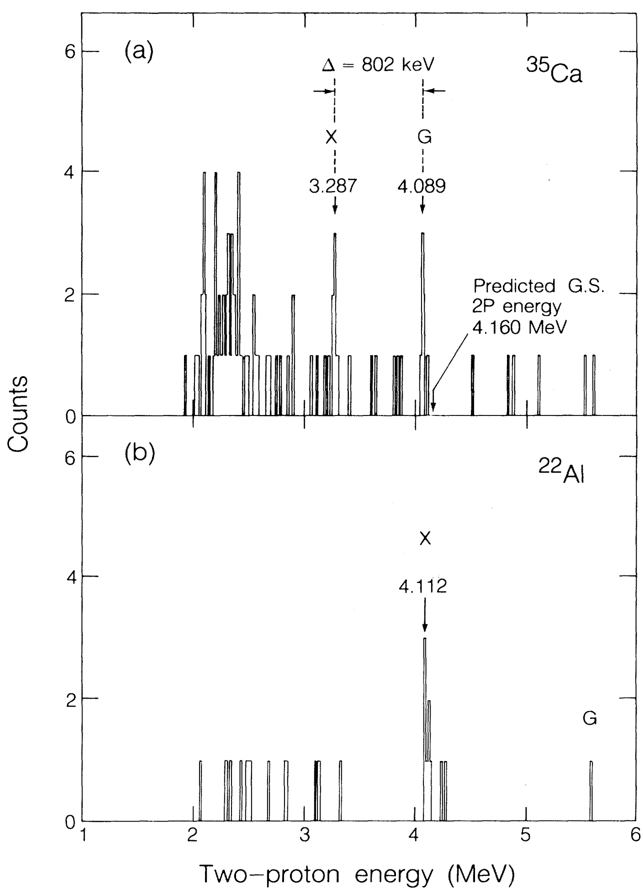

FIG. 1. Beta-delayed two-proton sum spectra of (a) ^{35}Ca and (b) ^{22}Al. Groups labeled by G and X are related to the two-proton transitions to the ground and first excited states in the daughter nuclei, respectively. Part of the continuum in the spectra below 3 MeV is due to positron scattering between the detector wafers.

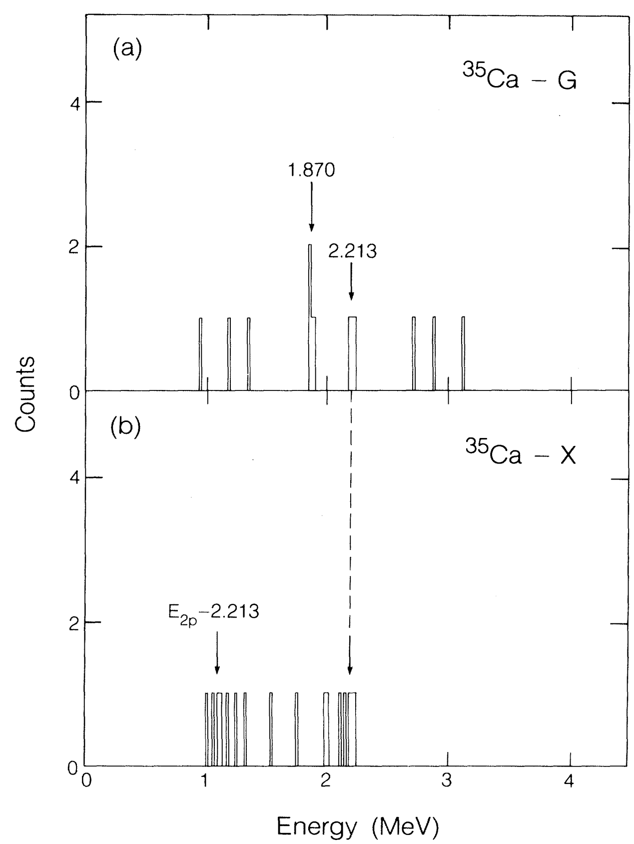

FIG. 2. Individual proton energy spectra from the beta-delayed two-proton decay of ^{35}Ca to (a) the ground state and (b) the first excited state of ^{33}Cl.

recoil effects the energy of the second proton depends on the relative emission angle.[3] Since both of the individual proton spectra, G and X, have a peak at the same energy, ~ 2.21 MeV, this suggests that a proton with this energy may be emitted first to an excited state in ^{34}Ar. This is also additional evidence for assigning the observed $\beta 2p$ groups to the same nucleus, ^{35}Ca.

Because of the expected similarity of the energy of the ^{35}Ca $\beta 2p$ ground-state sum group with that of the ^{22}Al $\beta 2p$ sum group shown in Fig. 1(b), possible interference from ^{22}Al had to be evaluated. The observed energy difference between these groups is 23 keV. Since most of the 30-keV absolute error given is due to a calibration extracted from the single telescopes, the determination of the ^{35}Ca and ^{22}Al $\beta 2p$ energies in the same experiment under identical conditions make the relative precision higher. Thus, the difference in the observed energies becomes larger than one standard deviation and excludes the contribution from ^{22}Al. Moreover, the 3.287-MeV $\beta 2p$ group assigned to ^{35}Ca cannot be due to the decay of ^{22}Al, because the next lower energy group in the $\beta 2p$ decay of ^{22}Al, proceeding to the ^{20}Ne second excited state, would be at 1.7 MeV. The evidence for the absence of ^{22}Al from the ^{3}He$+^{40}$Ca reactions is further reinforced by the fact that we did not observe the other well-known $\beta 2p$ emitter ^{26}P, which is expected to be produced in much higher yields in these reactions.[3] Further support is also provided by the observed very low yields of the β-delayed single-proton emitters ^{25}Si and ^{21}Mg, that necessarily accompany in large quantities the production of the more neutron-deficient nucleus, ^{22}Al. The same argument can also be used to reject the ^{22}Al production from possible contaminants in the target such as Mg. An electron-induced x-ray fluorescence analysis showed the target to contain less than 0.1% contaminants (including Mg), an amount which would produce an insignificant contribution.

By utilization of the assumption of a sequential decay, the observed laboratory single-proton energies, and the effective average detection angle of 33° obtained from the ^{22}Al data, a total center-of-mass energy of 4311 ± 40 keV is obtained for the two-proton decay of the $T=\frac{5}{2}$ $(\frac{1}{2}^+)$ isobaric analog state in ^{35}K. This value, taken together with the latest $2p$ binding energy and the mass excess of ^{35}K,[5] results in a mass excess of -2115 ± 45 keV and an excitation energy of 9053 ± 45 keV for the $T=\frac{5}{2}$ state. With regard to single-proton emission from this state, the high-energy single-proton spectra did not yield unambiguous evidence for any β-delayed proton groups at energies expected for ^{35}Ca. However, it should be noted that competition in the high-energy part of the single-proton spectra from high-energy proton groups and beta-proton pile-up events arising from the decay of the copiously produced $T_z=-\frac{3}{2}$ nuclei make such observations extremely difficult.

Since this measurement provides the third member of the $A=35$, $T=\frac{5}{2}$ isospin sextuplet, it is possible to use the isobaric multiplet mass equation to predict the mass of the ^{35}Ca ground state. If two-body forces are responsible for all charge-dependent effects in nuclei, the masses of analog states in an isospin multiplet can be related in first order by a quadratic relationship,[9] $M(A,T,T_z)=a(A,T)+b(A,T)T_z+c(A,T)T_z^2$, which has been found to be in excellent agreement with experiment on isospin quartets[10] and quintets.[2] The mass excess of the lowest $T=\frac{5}{2}$ state in ^{35}S has been determined by the reaction ^{37}Cl$(p,{}^{3}$He) to be $-19\,692 \pm 10$ keV, corresponding to an excitation energy of 9155 ± 10 keV.[11] [A second candidate for the lowest $T=\frac{5}{2}$ state in ^{35}S at 8430 ± 10 keV, as given in Ref. 11, can be eliminated because of its inconsistency with Coulomb-displacement-energy calculations and with the observed excitation of the analog state in ^{35}K.] The mass excess of $-24\,844 \pm 4$ keV for the ground state of $T_z=+\frac{5}{2}$, ^{35}P was obtained as a weighted average of four measurements.[12] The quadratic mass relation could then be used to predict a value of 4453 ± 60 keV for the ground state of ^{35}Ca. This mass for ^{35}Ca is in good agreement with that predicted by the updated Kelson-Garvey relations[4,5] and is 233 keV better bound.

The proposed partial decay scheme for ^{35}Ca is shown in Fig. 3. The branching of the superallowed β^+ decay to the isobaric analog state $(T=\frac{5}{2})$ is calculated by our assuming a Fermi decay with $\log ft=3.09$. The ground-state spin for ^{35}Ca is taken from its mirror nucleus ^{35}P.[13] Only the isospin-forbidden two-proton decay via the intermediate state in ^{34}Ar is shown. Based on this partial decay sheme a lower limit of ~ 6 nb can be deduced for the production cross section of ^{35}Ca. This value is twice the earlier upper limit obtained at 110-MeV ^{3}He energy[8]; this increase in the cross section is consistent with the evaporation calculations done with the code ALICE.[14]

In summary, beta-delayed two-proton decay of the first $T_z=-\frac{5}{2}$ nucleus ^{35}Ca has been observed. Its disintegration has been found to proceed via sequential two-proton emission from the $T=\frac{5}{2}$ analog state in ^{35}K fed in superallowed β^+ decay. This mechanism of sequential decay has also been observed for the other known beta-delayed two-proton emitters ^{22}Al and ^{26}P. In addition, the present study has demonstrated that specific detection of beta-delayed two-proton decay can also be an effective tool in searches for new and exotic nuclides near the proton drip line.

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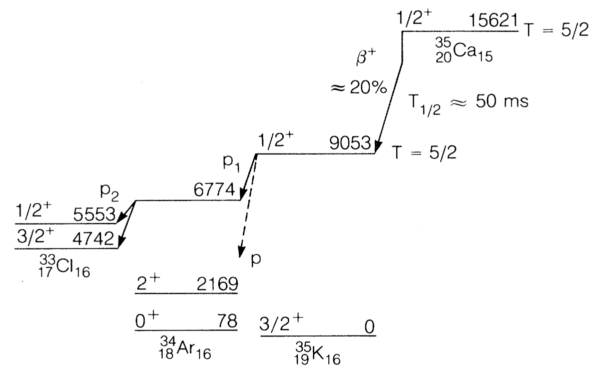

FIG. 3. Proposed partial decay scheme for the beta-delayed two-proton emission of ^{35}Ca.

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