Title

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Observation of the First $T_z = -5/2$ Nuclide, ^{35}Ca, Via its β-Delayed Two-Proton Emission*

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The decay of the T = 5/2 isobaric analog state in ^{35}K at 9053±45 keV, fed by the superallowed beta 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. Using 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 $T_z = (N-Z)/2 = -5/2$ which are predicted to beta decay but which are yet to be observed. Previous studies have reported the decays of most of the proton rich light nuclei, through $T_z \geq -2$ and with $Z \leq 20$, 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 $Z \leq 20$ and $T_z = -5/2$ 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 = 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 exploiting this relatively unusual decay mode, it is possible to observe light nuclei very far from stability, even though produced in quite low yield and 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 ^{40}Ca(^{3}He,α4n) reaction, 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 proton unbound by more than 600 keV[4)]. Second, the $T_z = -5/2$ 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 $T_z = -5/2$ nuclide ^{39}Ti is almost certainly unbound to ground state two-proton emission.

Calcium-35 nuclei were produced by bombarding a 2 mg/cm^2 thick natural calcium target with 135 MeV ^3He 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 diameter 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 set-up. The activity was collected on a slowly rotating catcher wheel directly in front of the two-proton detector system.

This specially constructed detector system consisted of three elements: either 10 or 16 μm ΔE1; 250 μm ΔE2 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 (ΔE1 and ΔE2) 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 ΔE1, ΔE2, E coincidences or as a beta-proton pile-up 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 ~0^o to ~50^o with each side subtending ~2% of 4π. This "small angle" set-up 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 ^2He, the latter being confined only to small angles. This set-up 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 $^{24}Mg(^3He, p4n)$ reaction 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 β2p decay of ^{22}Al to the first excited state of ^{20}Ne. Using 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 ~33^o 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.

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 magnesium impurities in the target had to be evaluated. An electron induced X-ray fluorescence analysis showed that less than 0.1% of magnesium was present in the target, an amount which would produce an insignificant contribution to the 4089 keV peak. (The next higher group in ^{22}Al $\beta 2p$ decay, proceeding to the ^{20}Ne second excited state, would lie at 1.7 MeV.)

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 clearly 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 due to 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.

Utilizing the above assumption, the observed laboratory single proton energies and the effective average detection angle of 33^{o} 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 = 5/2 $(1/2^{+})$ 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 = 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 expected energies 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 $T_z = -3/2$ nuclei make such observations extremely difficult.

Since this measurement provides the third member of the A = 35, T = 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= 5/2 state in ^{35}S has been determined by the ^{37}Cl(p,^{3}He) reaction to be -19692±10 keV, corresponding to an excitation energy of 9155± 10 keV[11]. (A second candidate for the lowest T = 5/2 state in ^{35}S at 8430 ± 10 keV, as given in Reference (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 -24844±4 keV for the ground state of T_z = +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 = 5/2) is calculated by 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 scheme a lower limit of ~6 nb can be deduced for the production cross section of ^{35}Ca.

In summary, beta-delayed two-proton decay of the first $T_z = - 5/2$ nucleus ^{35}Ca has been observed. Its disintegration has been found to proceed via sequential two-proton emission from the T = 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.

Footnotes and References

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Figure Captions

Fig. 1. Beta-delayed two-proton sum spectra of (a) ^{35}Ca and (b) ^{22}Al. Groups labelled 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 the ground state (a) and the first excited state (b) of ^{33}Cl.

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

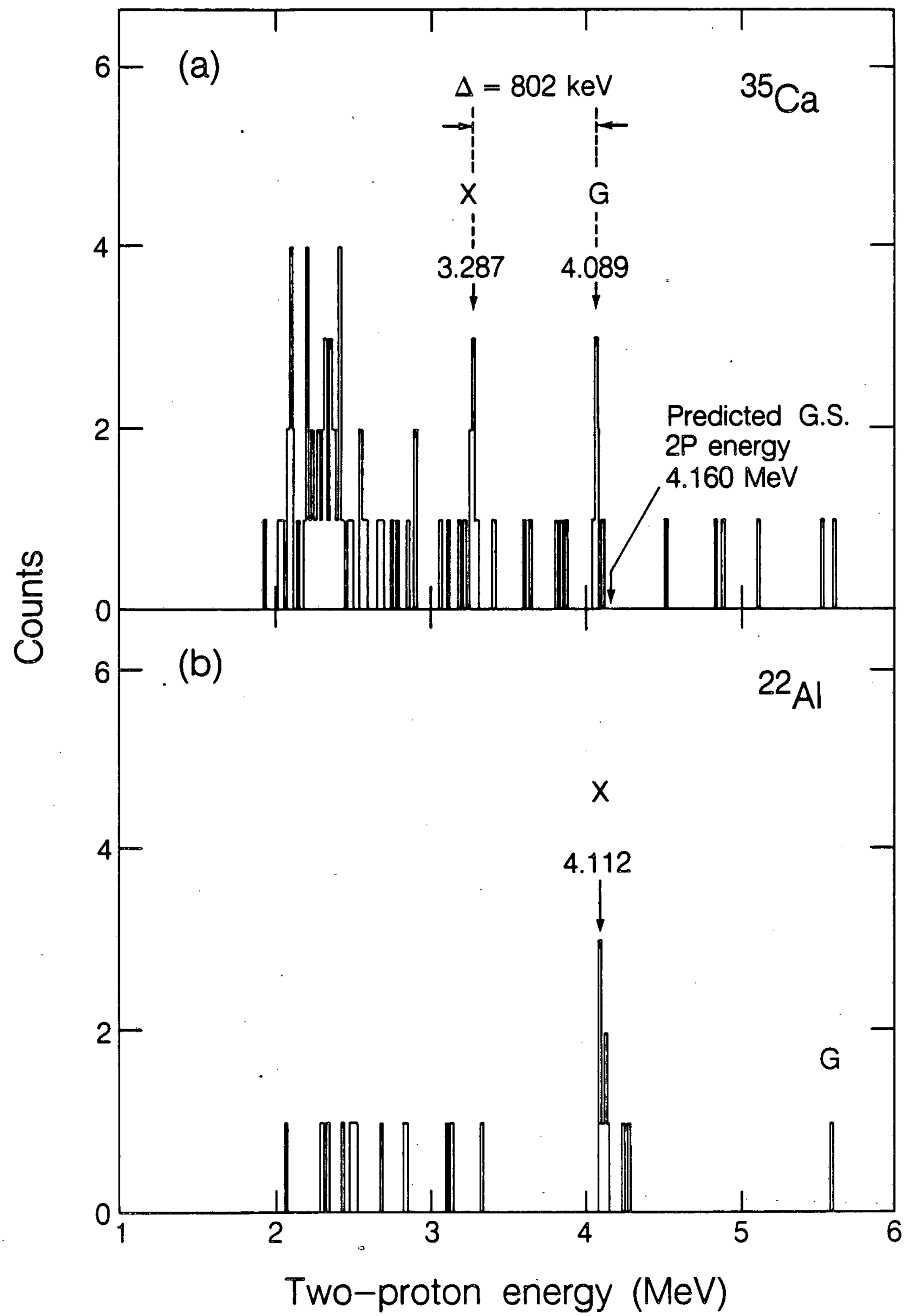

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Fig. 1.

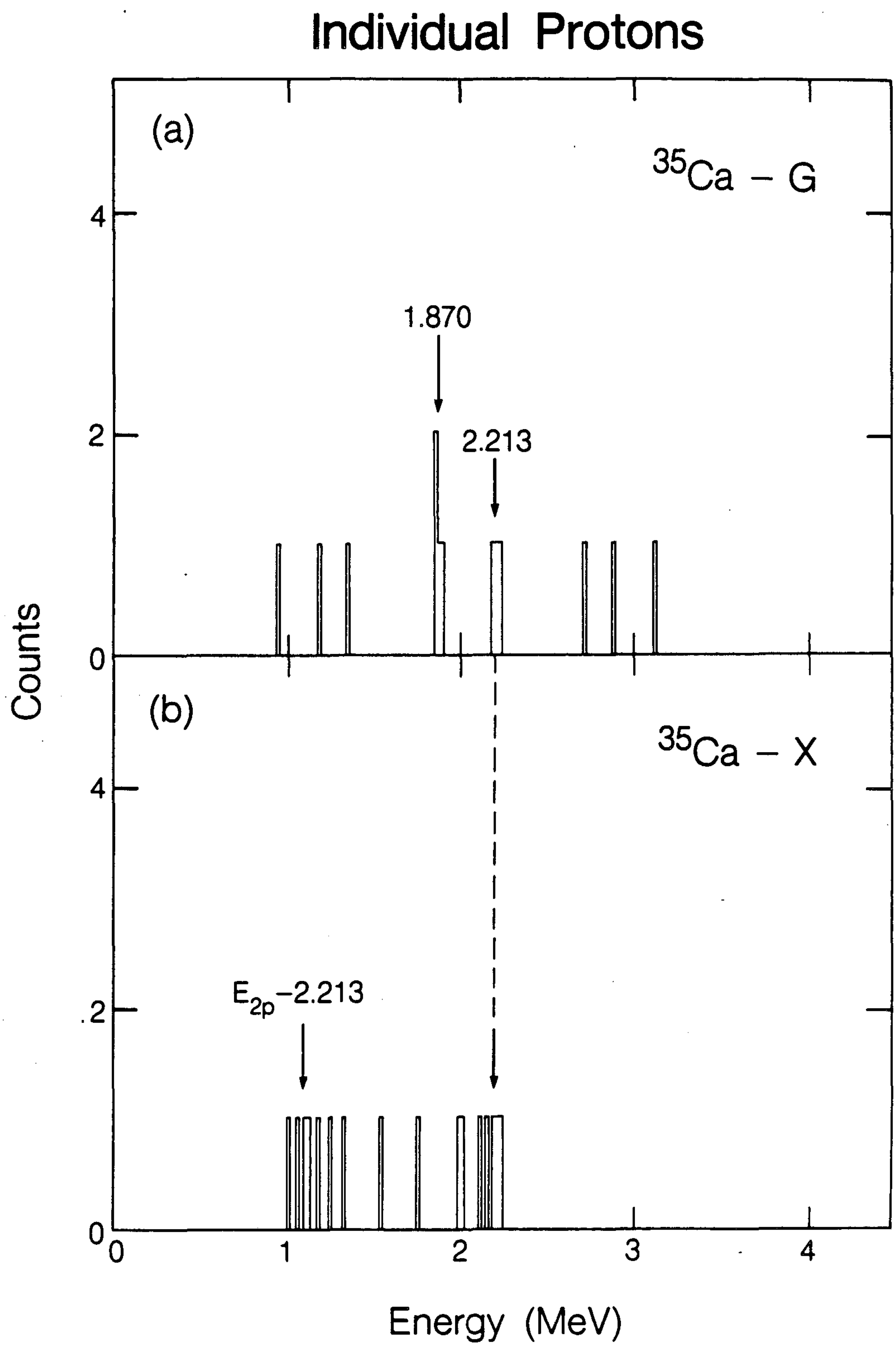

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Fig. 2.

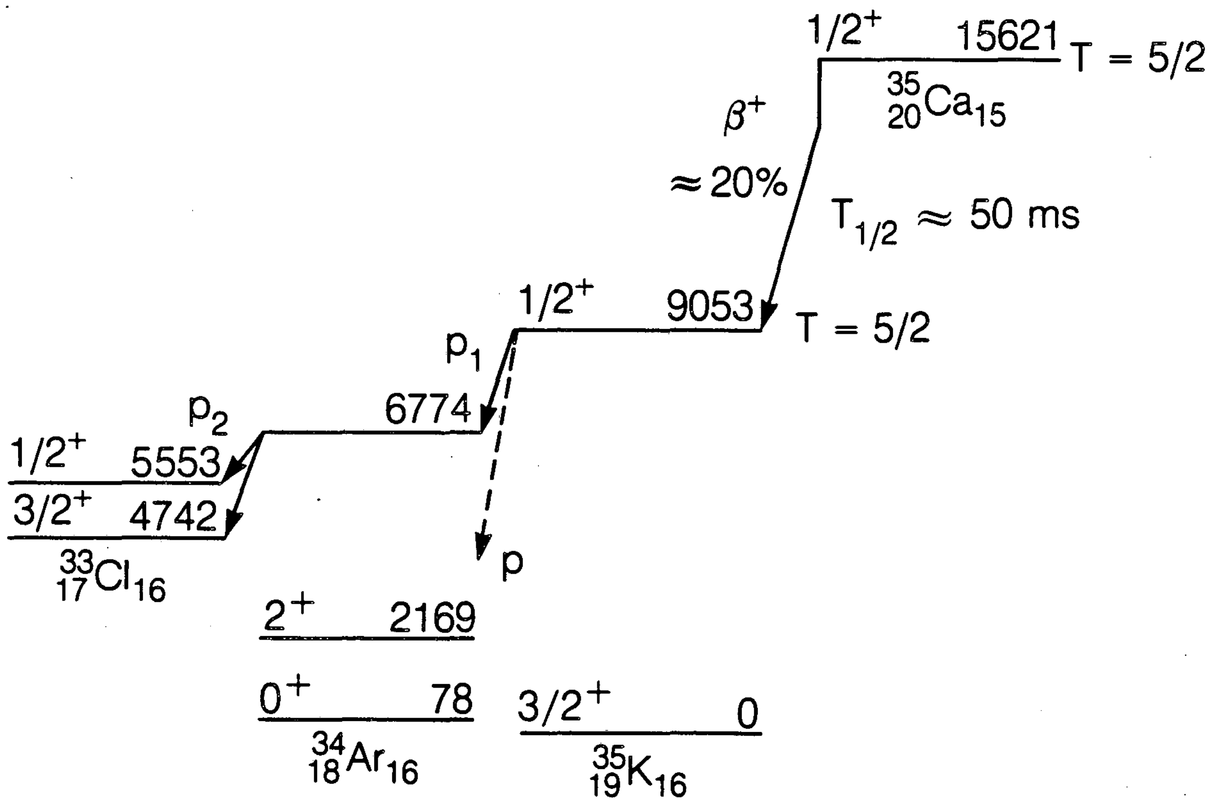

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Fig. 3.

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