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EXTENSION OF THE T_z = - 3/2 BETA-DELAYED PROTON PRECURSOR SERIES TO $^{57}Zn^*$

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Abstract:

Two new β^+-delayed proton precursors, ^{53}Ni and ^{57}Zn, have been produced by the $^{40}Ca(^{16}O,3n)$ and $^{40}Ca(^{20}Ne,3n)$ reactions, respectively. A single proton group (E_p(c.m.) = 1.94±.05 MeV, $T_{1/2}$ = 45±15 ms) was observed following the decay of ^{53}Ni, while three proton groups (E_p(c.m.) = 1.95±.05 2.58±.05, and 4.65±.05 MeV, $T_{1/2}$ = 40±10 ms) were observed following the decay of ^{57}Zn.

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The well-known series of A = 4n + 1, T_z = -3/2 β-delayed proton precursors has been completed from ^9C through ^{49}Fe [1] with the recent addition of ^{45}Cr [2]. Such studies both establish the decay properties of proton rich nuclei far from stability and, with the use of the isobaric multiplet mass equation, permit an excellent prediction of the precursor's mass. Although the β-delayed proton activity from the heavier nuclides in this series, through ^{41}Ti, has been produced in reasonable yield (∿30 -250 μb) by the (^3He,2n) reaction on T_z = 0 targets, extension of these

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studies further into the fp shell by employing the $^{32}S(^{16}O,3n)^{45}Cr$ [2] and $^{40}Ca(^{12}C,3n)^{49}Fe$ [3] reactions has been hampered by much lower cross sections (∿300–500 nb). We wish herein to report the observation of ^{53}Ni via the $^{40}Ca(^{16}O,3n)$ reaction at 65 MeV and of ^{57}Zn via the $^{40}Ca(^{20}Ne,3n)$ reaction at 70 MeV in which even lower yields were observed (∿25 and ∿60 nb, respectively).

Beta-delayed protons emitted from precursors retained in the target were detected in a semiconductor counter telescope subtending an effective solid angle of 0.24 sr. These precursors were produced by employing pulsed beams of $^{16}O^{+3}$ (60 and 65 MeV, ∿100 particle-nA) or $^{20}Ne^{+4}$ (62 and 70 MeV, ∿60 particle-nA) from the Lawrence Berkeley Laboratory 88-inch cyclotron in irradiations of natural calcium targets rotated to a target angle of 70°. A slotted rotating wheel system, similar to that described in ref. [4], controlled the pulsing of the beam and protected the detectors while the target was being irradiated. A typical timing cycle consisted of an irradiation period of 150 ms with an inspection interval of 15 ms (during which beam cessation was verified) followed by a counting period of 200 ms.

Several detector telescope combinations were used, ranging from 14 μm to 19 μm for the ΔE and 107 μm to 250 μm for the E detector. (Biasing the target to +2.5 kV proved to be essential in improving the detector lifetime, apparently by reducing radiation damage from electrons present throughout the system during target irradiation.) Events which met a ΔE-E coincidence (2τ = 60 ns) and which identified as protons were time-routed sequentially into eight 512-channel spectra, each 25 ms in duration. Setup and calibration were achieved with β-delayed protons originating from ^{25}Si [5] and ^{41}Ti [6] produced by (^{3}He,2n) reactions at 29.5 MeV on Mg and Ca targets, respectively.

Figure 1(a) represents the proton spectrum (summed over the eight time channels) observed following the bombardment of a 1.6 mg/cm^2 natural calcium target with 65 MeV ^{16}O ions for 16,400 μC (as 8+). The large group at 1.59 MeV (c.m.) is known to arise from direct proton radioactivity of ^{53m}Co [4] produced via the competing ^{40}Ca(^{16}O,p2n) reaction. Its half-life of 260±20 ms (determined in this experiment) agrees with the known half-life of ^{53m}Co(247±12 ms [4]). This proton group served as an additional energy calibration point to reduce target thickness uncertainties. In addition to ^{53m}Co, a previously unreported proton activity was observed with a low yield of ∿25 nb. After making target and detector dead layer energy loss corrections of 130 keV, its energy was determined to be 1.90 MeV (lab), which, with recoil correction, is 1.94±.05 MeV in the center of mass. The half-life of this group was determined to be 45±15 ms (see decay curve in the inset of fig. 1(a)). The experiment was repeated at a bombarding energy of 60 MeV at which this 1.94 MeV proton activity was again observed, but at slightly lower yield (∿15 nb), while the ^{53m}Co yield increased by a factor of two. In this latter experiment, protons up to 5.6 MeV could have been detected, but no significant activity above 1.94 MeV was observed.

The source of this weak activity cannot be attributed to pile-up events associated with ^{53m}Co, due to the very different observed half-life from that of ^{53m}Co and the independent variation in yield as a function of bombarding energy of the two activities. Further it cannot arise from the decay of the next lower $T_z = -3/2$ nuclide, ^{49}Fe [3], produced by the ^{40}Ca(^{16}O,α3n) reaction, because the effective threshold of this reaction (including Coulomb barrier) is ∿65 MeV. Finally, the only other possible source of β-delayed protons in this region would be the uncharacterized nuclide, ^{52}Co, which is the pertinent member of the A = 4n, T_z = -1 series of <u>weak</u> β-delayed proton and/or alpha emitting nuclei. Though ^{52}Co can be produced by the ^{40}Ca(^{16}O,p3n) reaction (threshold

$\sim$51.4 MeV), it is extremely improbable that this is the source of the observed activity since its calculated relative β^+-proton yield is estimated to be 50 times smaller than that expected for ^{53}Ni. (This estimate is based on a Monte Carlo compound nuclear evaporation code [7], which predicts a cross section ratio $\sigma(^{52}\text{Co})/\sigma(^{53}\text{Ni})$ $\sim$10/1, coupled with an estimated branch of $\sim$0.09% (assuming a log <u>ft</u> = 4.5) for allowed β-decay of ^{52}Co to an unknown ^{52}Fe state at $\sim$9.3 MeV, which would be necessary to account for this activity, and an estimated branch of $\sim$45% for superallowed β-decay of ^{53}Ni to ^{53}Co - see below.) It is also of interest to note that the observed cross section ratio, $\sigma(^{53m}\text{Co})/\sigma(^{53}\text{Ni})$, at 65 MeV agrees well with the earlier calculation [4] for the ^{16}O + ^{40}Ca system performed with the spin-dependent evaporation code GROGI-2. Based on the 1.5% proton branch for ^{53m}Co and the β-branch estimated for ^{53}Ni, the calculated ratio was $\sim$7600/1, while the observed ratio is $\sim$6500/1.

The most reasonable source of the 1.94 MeV activity is β-delayed proton emission following the decay of ^{53}Ni produced via the ^{40}Ca(^{16}O,3n) reaction (threshold $\sim$47.8 MeV based on Kelson-Garvey type mass predictions [8,9]). As shown in fig. 2(a), the best explanation is that these protons arise from the superallowed β^+-decay of ^{53}Ni to its analog state in ^{53}Co which in turn decays by isospin-forbidden proton emission to the first excited state of ^{52}Fe (a pattern similar to that observed in the decays of ^{45}Cr and ^{49}Fe); hence the lowest T = 3/2 state in ^{53}Co lies at 4.39±.06 MeV, in good agreement with the known energy of its analog state in ^{53}Fe of 4.256±.015 MeV [10]. No evidence for proton decay of this T = 3/2 state to the ground state of ^{52}Fe was observed (see fig.1(a)); an upper limit of 5% can be set for this branch. If a log <u>ft</u> value of 3.3 [11] is assumed for the superallowed β-transition to the analog state in ^{53}Co, the observed protons would account for roughly 45% of the total decay of ^{53}Ni.

The proton spectrum resulting from the 70 MeV ^{20}Ne bombardment of a 1.8 mg/cm^2 calcium target for 20,000 μC (as 10^+) is shown in fig. 1(b). Again, ^{53m}Co arising from the competing ^{40}Ca(^{20}Ne,αp2n) reaction was observed. Three proton groups at energies of 1.95±.05, 2.58±.05, and 4.65±.05 MeV (c.m.) were observed, corresponding to a total delayed-proton yield of ∿60 nb. The half-life of each group is consistent with the 40±10 ms value determined from the sum of all three groups. Observation of the proton spectrum at a bombarding energy of 62 MeV again resulted in the appearance of these three groups with the same relative intensities, energies, and half-life.

The decay of ^{53}Ni, produced via the ^{40}Ca(^{20}Ne,α3n) reaction, can not contribute to the activity at 1.95 MeV since the effective threshold (including Coulomb barrier) for this reaction is ∿66 MeV. Furthermore, the unknown T_z = −1 nuclide ^{56}Cu (a possible weak β^+-proton precursor), which could be produced via the ^{40}Ca (^{20}Ne,p3n) reaction (threshold ∿52.3 MeV), is a highly improbable source of these three groups, based on analogous arguments to those discounting ^{52}Co in the previous ^{53}Ni discussion. These activities are, however, very compatible with the β-delayed proton emission expected from ^{57}Zn whose predicted threshold via the ^{40}Ca(^{20}Ne,3n) reaction is ∿50.0 MeV (assuming a mass excess of −32.77 MeV, calculated using the Kelson-Garvey charge symmetry relations [8] and two predicted T_z = −1/2 masses from ref. [12]). The proposed ^{57}Zn decay scheme is given in fig.2(b).

The groups observed at 4.65 MeV and 1.95 MeV can be assigned to the isospin-forbidden proton decay of the lowest T = 3/2 state of ^{57}Cu to the ground state and first excited state of ^{56}Ni, respectively. This energy difference of 2.70±.07 MeV agrees very well with the known separation between these ^{56}Ni states of 2.702±.003 MeV [13]. Based on these two groups, the excitation energy of the lowest T = 3/2 state of ^{57}Cu, 5.35±.04 MeV (assuming the ground state mass excess of ^{57}Cu is -47.31_4 MeV [12]), compares well with its known analog state in ^{57}Ni at 5.23±.01 MeV [14]. The group at 2.58 MeV could be attributed to isospin-allowed proton decay of a T = 1/2 state at 3.28±.05 MeV in ^{57}Cu. Assuming, as before, a log ft value of 3.3 for the superallowed β-transition, the relative log ft value for decay to this state is calculated to be 4.3, which is reasonable for an allowed β-transition. (In the foregoing, we have assumed that γ de-excitation of the analog state is negligible; should it be appreciable this allowed relative log ft value would become larger.) Since the spin and parity of ^{57}Zn are expected to be $7/2^-$ (based on its mirror, ^{57}Co), allowed β-decay limits the spin and parity of the 3.28 MeV state to $5/2^-$, $7/2^-$, or $9/2^-$; hence this state is potentially the mirror of one of the two known $7/2^-$ states in ^{57}Ni at 3.23±.02 and 3.36±.02 MeV [14].

If the mass excesses of the lowest T = 3/2 states in the T_z = -1/2 nuclei ^{53}Co (-38.26±.06 MeV) and ^{57}Cu(-41.97±.04 MeV), together with those of the corresponding T = 3/2 states in the T_z = +3/2 and +1/2 members of each multiplet, are used in the isobaric multiplet mass equation (IMME), the predicted mass excesses for ^{53}Ni and ^{57}Zn are -29.41±.18 MeV and -32.63±.13 MeV, respectively. For ^{53}Ni, good agreement between this prediction and the Kelson-Garvey type mass prediction [9] of -29.69 MeV or the Coulomb energy calculation of -29.65 MeV [15] is found. Similar agreement is obtained between the IMME result for the mass excess of ^{57}Zn and the Kelson-Garvey prediction (described earlier) of -32.77 MeV.

Surveying the β-delayed proton decay of the $J^\pi = 7/2^-$, T_z = -3/2 nuclei from ^{45}Cr to ^{57}Zn, we see that only in the case of ^{57}Zn has isospin-forbidden proton decay from the analog state (in the emitter) to the ground state of the T_z = 0 residual nucleus been observed, a result which may largely be due to the enhanced stability of the doubly magic ^{56}Ni. On the basis of penetrability calculations alone, an intensity ratio for proton decay from the ^{57}Cu (T = 3/2) state to the ground state (0^+) relative to the first excited state (2^+) in ^{56}Ni of ∿28/1 would be expected. The observed ratio of ∿0.6/1 indicates that the reduced width for (isospin-forbidden) proton decay to the ground state is ∿1/45 of that for decay to the first excited state. Such a reduced width ratio is consistent with the limits observed [2,3] in the proton decays of the analog states in ^{45}V, ^{49}Mn, and ^{53}Co, which indicate $\gamma_p^{\ 2}(0^+)/\gamma_p^{\ 2}(2^+) < 1/8$. Theoretical estimates of the expected reduced widths for the isospin-forbidden proton decay of the isobaric analog states in these fp shell nuclei would be particularly welcome.

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Figure Captions

Fig. 1. Proton spectra observed following the bombardment of calcium with (a) 65 MeV ^{16}O and (b) 70 MeV ^{20}Ne. Dashed vertical arrows indicate the energy region in both spectra over which protons could be reliably observed. The precursor and the center of mass energy are labeled above each proton group. The horizontal arrows in (a) designate the energy region where proton decay to the ground state of ^{52}Fe would be expected (see text). Decay curves for the ^{53}Ni group and the sum of the three ^{57}Zn groups are shown in the insets.

Fig. 2. The proposed decay schemes for (a) ^{53}Ni and (b) ^{57}Zn. Decays which have not been directly observed are indicated with dashed lines. All energies are given in MeV relative to the ground state mass of the appropriate $T_z = -1/2$ nuclide. Predicted energies, assumed spin, parity, and isospin values and estimated branching ratios are shown in parentheses.

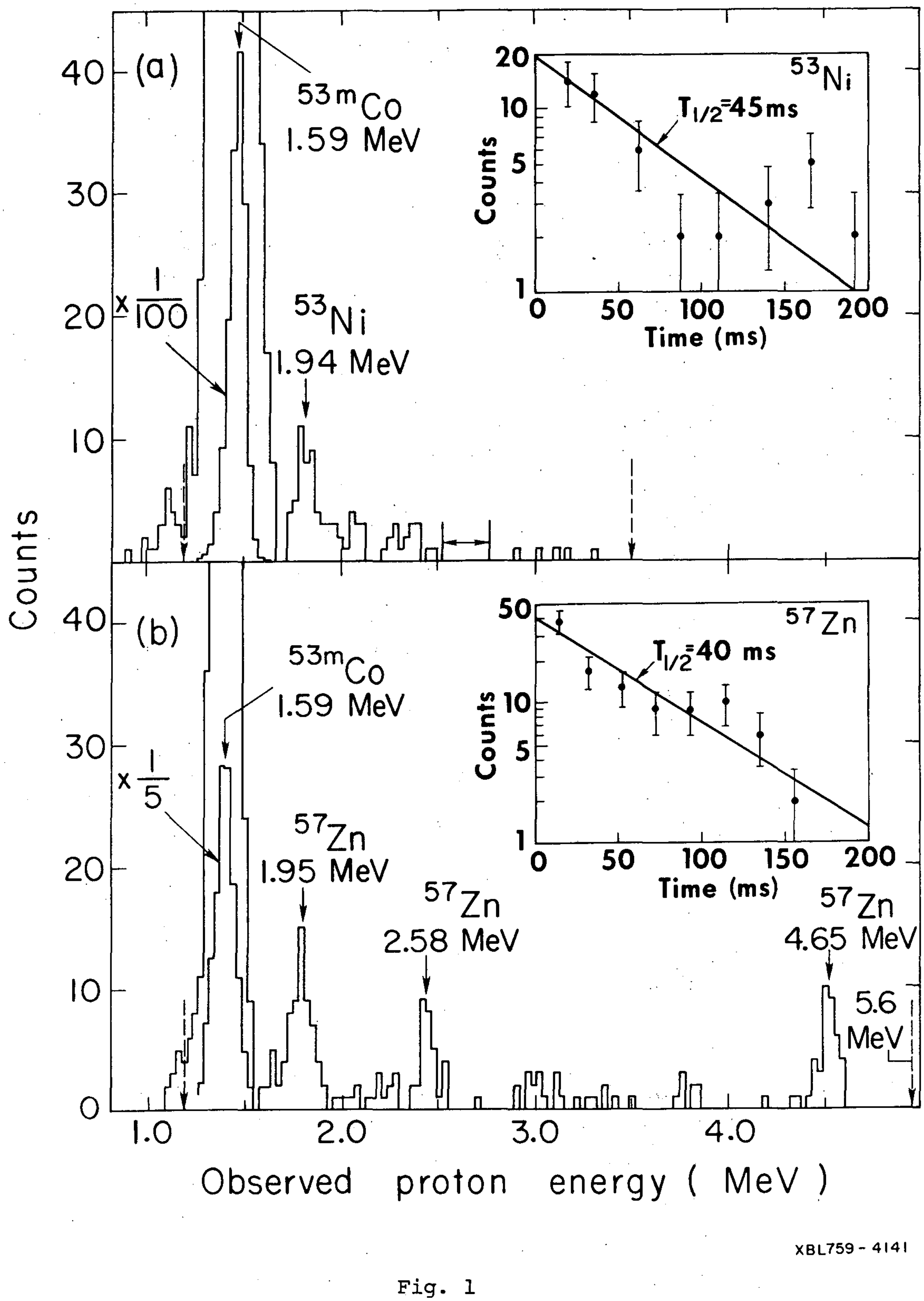
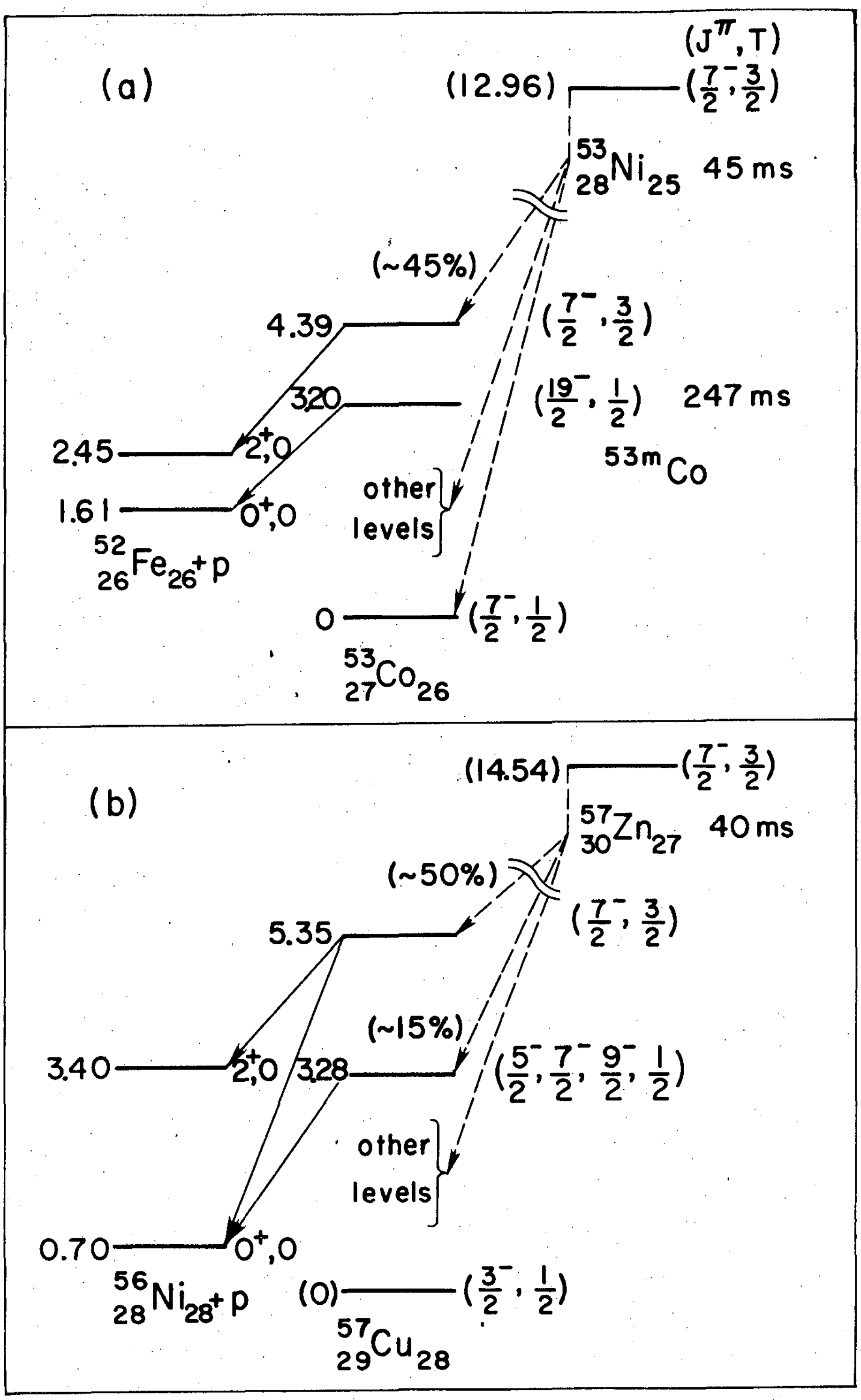

(a)
53m Co
1.59 MeV
x 1/100
53 Ni
1.94 MeV
53 Ni
T1/2=45ms
Counts
Time (ms)
(b)
53m Co
1.59 MeV
x 1/5
57 Zn
1.95 MeV
57 Zn
2.58 MeV
57 Zn
4.65 MeV
5.6 MeV
57 Zn
T1/2=40 ms
Counts
Time (ms)
Counts
Observed proton energy (MeV)
XBL759-4141

Fig. 1



XBL 759-4142

Fig. 2

U U 0 0 4 4 0 3 9 4 4

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