NEW DELAYED-PROTON EMITTERS: Ti^{41}, Ca^{37}, AND Ar^{33} †

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(Received 13 November 1964)

Three new nuclides, Ti^{41}, Ca^{37}, and Ar^{33}, have been observed to be delayed proton emitters of the type that undergo beta decay to proton unstable states of daughter nuclei. These nuclides extend to higher mass the series of known delayed proton emitters with even Z and $A = 2Z-3$: S^{29},[1] Si^{25},[2] Mg^{21},[2] Ne^{17},[3,4] and O^{13}.[5] The beta decay of Ca^{37} is of particular interest[6] with regard to the proposed solar neutrino experiment.[7,8] This isotope is the mirror nucleus of Cl^{37}, and thus, knowledge of the half-life of Ca^{37} is of help in estimating[8] the neutrino capture rate in Cl^{37}.

The nuclides were produced by the $(He^3, 2n)$ reaction in the external beam of the Bookhaven 60-in. cyclotron. The maximum energy of the beam was 31.8 MeV and the average intensity was about 0.1 microampere. The beam was pulsed by means of a mechanical chopper with a frequency that could be varied to suit the half-life of the nuclide being studied. The gaseous targets, Ar^{36} and H_2S for producing Ca^{37} and Ar^{33}, respectively,[9] were contained at $\frac{2}{3}$ of an atmosphere in a brass cell. The beam windows of the cell consisted of 0.25-mil Ni and the proton window parallel to the beam was 0.25 or 1.0-mil Mylar. The solid targets, Ca and S for producing Ti^{41} and Ar^{33}, respectively, were vacuum-deposited to a thickness of 1 mg/cm^2 on 0.1-mil Ni backing foils. The target foils were oriented at 10° to the He^3 beam in order to increase the path of the beam through the target material. Two detectors were mounted side by side, perpendicular to the target. Surface barrier detectors three cm^2 in area and 7000 to 8000 ohm-cm resistivity were used. Proton energy spectra as a function of time were recorded between beam pulses by a two-parameter analyzer normally having 255 energy channels by 16 time channels. Data for many beam pulses were accumulated by means of a repetitive electronic timer which controlled the beam chopper and initiated the analyzer.

The data were processed by a computer, using a least-squares program for fitting decay curves. For the determination of a half-life, the counts in the proton peaks in each energy spectrum were summed before the decay curve analysis was performed. The half-lives obtained for the three new nuclides are presented in Table I. In the case of Ti^{41}, which has several prominent proton peaks, analysis of each peak yielded a half-life which agreed within the errors with that obtained from the integrated spectrum. To obtain an energy spectrum resolved from background, each energy channel of the original data was analyzed with the half-lives of Table I. The resulting proton spectra for Ti^{41} and Ca^{37} are plotted in Figs. 1 and 2, as initial counting rate versus energy channel. The width of the time channel is indicated in the ordinate. A peak resulting from a calibrated 60-cps pulser is shown dashed on the high-energy side of each spectrum. The center-of-mass energies, which have been corrected for energy loss in the target material and in the window of the gas cell, are shown above the proton peaks and in Table II. The proton spectrum for Ar^{33} is similar to that for Ca^{37}

Table I. Half-lives of delayed proton emitters.

Target	Product	Half-life (msec)
S	Ar^{33}	182 ± 5
Ar^{36}	Ca^{37}	170 ± 5
Ca	Ti^{41}	90.5 ± 2

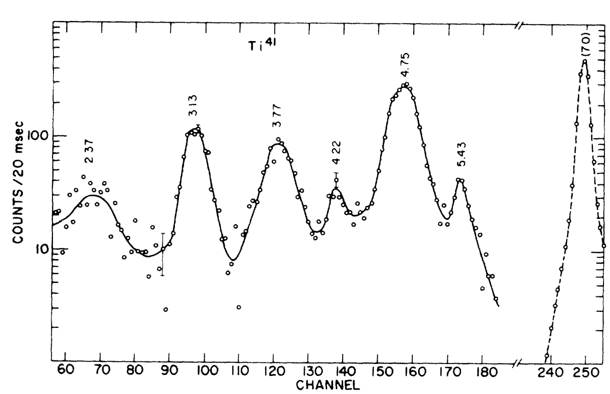

FIG. 1. Proton spectrum following the decay of Ti^{41} taken at 30-V bias. The 5.43-MeV protons penetrated beyond the depletion layer of the detector. The energy indicated for this peak was obtained from other spectra taken at higher bias.

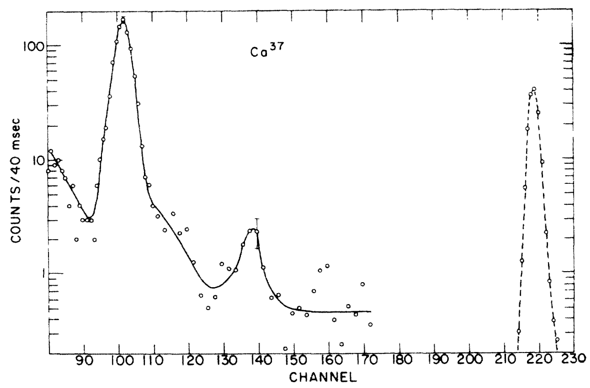

FIG. 2. Proton spectrum following the decay of Ca^{37}.

and is also summarized in Table II. The peaks were shown to be due to protons and not alpha particles from variation of gas pressure and window thickness, and from the narrowness of the peak widths for the target thicknesses used. Also, in the case of Ar^{33} the peak energies derived from the solid and gas targets were the same. In order to relate the center-of-mass energies to energy levels in the daughter nucleus resulting from beta decay, one has to add the proton-separation energy from the daughter nucleus. The values used[10] (in MeV) were 2.285 ± 0.012 for Cl^{33}, 1.876 ± 0.041 for K^{37}, and 1.082 ± 0.012 for Sc^{41}. The resulting energy levels of the daughter nucleus are listed in Table II.

Table II. Proton energies.

Nuclide	$E_{c.m.}$ (MeV)	$E_{c.m.}+S_p$ (MeV)	Relative intensity[a] (%)
Ar^{33}	3.256 ± 0.030	5.54 ± 0.03[b]	98
	3.90 ± 0.10	6.19 ± 0.10	2
Ca^{37}	3.172 ± 0.030	5.05 ± 0.05[b]	99
	4.00 ± 0.10	5.9 ± 0.1	1
Ti^{41}	2.37 ± 0.1	3.45 ± 0.1	8
	3.13 ± 0.03	4.21 ± 0.03	17
	3.77 ± 0.03	4.85 ± 0.03	16
	4.22 ± 0.05	5.30 ± 0.05	4
	4.75 ± 0.03	5.83 ± 0.03[b]	50
	5.43 ± 0.05	6.51 ± 0.05	5

[a]Intensities as percent of protons observed for each isotope.
[b]Energy of the lowest $T = \frac{3}{2}$ state in the daughter nucleus.

Evidence for the identification of these nuclides was obtained from measurements of excitation functions. The excitation function observed for Ca^{37} has a threshold at 20 ± 2 MeV which is consistent with the predicted threshold of 19.4 MeV for the $(He^3, 2n)$ reaction.[6,8] The (He^3, n) reaction is exothermic and the $(He^3, 3n)$ has a threshold at 33 MeV and these reactions are thus inconsistent with the observed excitation function. The energetic threshold for the production of Ar^{33} by the reaction $Ar^{36}(He^3, 2n\alpha)$ is 26.5 MeV. However, inclusion of a Coulomb barrier for the emission of the α particle would raise the effective threshold to about 32 MeV. Thus our results for Ca^{37} have no contribution from the very similar isotope Ar^{33}. The only reactions with thresholds similar to $Ar^{36}(He^3, 2n)$ are the reactions $Ar^{36}(He^3, n\alpha)Ar^{34}$ and $Ar^{36}(He^3, t)K^{36}$. From the masses predicted[11] for these products it can be shown that the amount of energy available for beta decay is insufficient to give rise to the 3-MeV protons which we have observed. The predicted $(He^3, 2n)$ thresholds for producing Ti^{41} and Ar^{33} are quite similar to that for Ca^{37}. The measured excitation functions, although cruder, are consistent with the predicted thresholds. Similar arguments concerning competing reactions apply to these nuclides also.

Each of the proton spectra, particularly in the case of Ca^{37} and Ar^{33}, is dominated by a peak due to a superallowed beta transition to a daughter state which is the analog of the parent nucleus ground state.[2] The excitation energies of these levels in the daughter nuclides, the lowest energy $T = \frac{3}{2}$ states, are indicated by footnote b in Table II. The masses of the parent nuclides may be estimated[11] by adding a Coulomb correction ($1.2Z/A^{1/3}$ MeV) to the energy of the analog state and subtracting the neutron-hydrogen mass difference (0.78 MeV). Using this method we calculate the Q_β values shown in Table III. Using Wilkinson's method[12]

Table III. Calculated values of Q_β in MeV.

Nuclide	From Coulomb correction to analogue state	From Wilkinson
Ti^{41}	12.70	12.58
Ca^{37}	11.46	11.46
Ar^{33}	11.49	11.40

and known ground-state masses[10] of the three other members of the isobaric quartet, we obtain the values shown in the last column of Table III. The good agreement supports our assignment of the analog-state proton peaks.

For Ca^{37}, the energy of the analog state agrees within the errors with that predicted by Bahcall[6,8] while the observed half-life is slightly longer than the 0.13-sec value predicted by him. However, the observation of Ca^{37} with properties so close to those predicted supports the estimation of the neutrino-capture cross sections for the solar-neutrino experiment.

We wish to acknowledge helpful discussions with R. Davis, Jr., G. Friedlander, and R. McPherson, and assistance from R. W. Stoenner.

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†Research performed under the auspices of the U. S. Atomic Energy Commission.

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RESTRICTED $\Delta Q/\Delta S = -1$ WEAK CURRENTS, CP, AND THE R(8) EXTENSION OF SU(3) †

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(Received 15 October 1964)

The exploration of $\Delta Q = -\Delta S$ hadron leptonic decays seems to have established an upper limit on their occurrence[1]; this limit implies that the coupling of the corresponding hadron current to the lepton current is at least one order of magnitude lower than in the $\Delta Q = \Delta S$ case. Some positive evidence for their existence seems to have been supplied,[2] e.g., the observation of one Σ^+ beta decay. Lately, the breakdown of CP invariance in K_2^0 decay has been explained by Wolfenstein[3] within the framework of the current-current theory as a result of an out-of-phase $\Delta Q = -\Delta S$ current. In this Letter, we would like to show how this result can be reconciled with the SU(3)-based description of the weak interaction, including the Gell-Mann–Cabibbo[4] version of universality of the weak vector current. This implies extending the parity-retaining symmetry into a badly broken R(8) system[5] derived from the $\underline{8}$ representation of SU(3).[6] Since R(8) starts at $\underline{8}$ and contains SU(3)/Z(3) but not SU(3), our picture would not allow for the existence of triplets (quarks, etc.). Thus, if the breakdown of CP invariance is verified and no new interactions be at work, and provided we keep the conventional weak Hamiltonian, one is led to definite conclusions with respect to the emergence of the eightfold way and the triality of its representations.

The small value of the $\Delta Q = -\Delta S$ coupling (also required by the Okun-Pontecorvo K_1^0-K_2^0 mass difference argument) allows us to regard it as one more term in a current

$$j_H^{\mu} = \bar{\psi}(1+\gamma_5)\gamma^{\mu}\{a(F_1+iF_2)+b(F_4+iF_5) + c(G_{19}+iG_{20})+\cdots\}\psi, \quad (1)$$

where

$$|a|^2+|b|^2+|c|^2+\cdots=1; \quad (2)$$

a and b are the $\cos\theta$ and $\sin\theta$ of Cabibbo's formulation, very slightly reduced so as to leave room for very small additional terms c, d, etc. The new current's fourth component, and its charge conjugate, generate an SU(2) through equal-time commutation. It should be connected with the isospin current by a unitary transformation. The operators[7] $(G_{19}+iG_{20})$ and (F_4+iF_5)