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^{53}Co^{m}: A PROTON-UNSTABLE ISOMER[*]

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A 1.53 ± 0.04 MeV proton activity with a 245 ± 20 msec half-life has been observed in the reaction of ^{16}O on ^{40}Ca. The most plausible origin of this activity is the proton radioactivity of ^{53}Co^{m}, although the decay of this isomer by beta-delayed proton emission remains as a possibility.

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A recently reported experiment [1] has demonstrated the feasibility of using heavy-ion induced reactions to produce new nuclides of the $A = 4n + 1$, $T_Z = \frac{N-Z}{2} = -\frac{3}{2}$ series of beta-delayed proton emitters. Protons emitted from the lowest $T = 3/2$ state in ^{49}Mn were observed following the ^{40}Ca(^{12}C,3n)^{49}Fe reaction. As a natural extension of this program a similar experiment was designed to produce ^{53}Ni via the ^{40}Ca(^{16}O,3n) reaction. This communication reports an unforeseen result of these experiments--the observation of a proton activity for which the most plausible explanation is direct proton decay of an unbound isomer in ^{53}Co produced in the ^{40}Ca(^{16}O,2np) reaction.

In the initial experiments designed to produce ^{53}Ni, a natural calcium target was bombarded with a pulsed beam of ∿ 0.5 μA of ^{16}O(4+) ions at energies up to 81 MeV produced by the Harwell variable energy cyclotron. Delayed protons were detected and their lifetimes measured with the same system as that described in ref. 1 except that the semiconductor telescope consisted of a 23 μm ΔE counter followed by a 100 μm E detector and these fed a particle identifier [2]. As shown in fig. 1(a), the identified proton spectra from this reaction were dominated by a strong group near the minimum energy (∿ 1.3 MeV) required for reliable detection. (Higher energy protons expected from the decay of ^{53}Ni were in fact observed at the higher bombarding energies but their production cross section was roughly an order of magnitude lower than that found for producing ^{49}Fe.) In order to obtain energy spectra unaffected by the telescope cutoff, this low energy activity was also measured using a single 50 μm, totally depleted, silicon detector as shown in fig. 1(b).

Both detection systems always gave identical results for this activity which can be summarized as follows: (a) the energy of the protons after correction for energy loss in the target is 1.53 ± 0.04 MeV and their half-life is 245 ± 20 msec; and (b) their excitation function indicates a threshold below an ^{16}O bombarding energy of 39 MeV with a peak cross section ∿ 8 μb occurring in the region of 53 MeV (laboratory). The low threshold eliminates ^{53}Ni as a source of these protons and irradiation of other targets indicated that the observed activity could not be attributed to any likely contaminant.

In order to investigate further the reactions of ^{16}O on ^{40}Ca, delayed gamma-ray spectra were recorded with a Ge(Li) detector following the bombardment of a calcium target with pulses of ^{16}O ions at energies below 50 MeV produced by the coupled injector and EN tandem facility at Oxford. As was anticipated, prominent peaks were observed corresponding to the known [3] cascades in ^{54}Fe and ^{50}Cr following β^+-decay of the high-spin isomers $^{54}Co^m$ and $^{50}Mn^m$. These isomers were populated via the (^{16}O,pn) and (^{16}O,αpn) reactions with cross-sections of ∿ 0.8 mb and ∿ 4 mb, respectively, at a mean bombarding energy of 47 MeV. At this energy, however, the observed intensities of γ-rays of energies 0.701, 1.011, 1.328 and 2.339 MeV indicated a cross-section of ∿ 50 mb for the (^{16}O,2pn) reaction leading to $^{53}Fe^m$ - a 2.5 min isomer at an excitation of 3.04 MeV [4]. This isomer is presumed to be 19/2-, T = 1/2 on the basis of its observed properties and shell model predictions for high spin states with the configuration $(f_{7/2})^{-3}$.

Considering the observed yield of $^{53}Fe^m$ from the (^{16}O,2pn) reaction, it is reasonable to expect a lower but significant population of its isobaric analogue state in ^{53}Co from the (^{16}O,2np) reaction. The mass excess of the ^{53}Co ground state is predicted to be -42.64 MeV from the known mass of ^{53}Fe [5] and the Coulomb displacement energy calculations of Harchol *et al.*[6]. From the known mass of ^{52}Fe [7], the binding energy of a proton in ^{53}Co is then estimated to be

1.6 MeV and thus, $^{53}Co^{m}$, the isobaric analogue state of $^{53}Fe^{m}$, must be unbound. If the observed proton group is attributed to the direct decay of $^{53}Co^{m}$ to ^{52}Fe, one obtains a value of 8.42 MeV for the mass difference between the analogue isomers. This result is in adequate agreement with the value 8.30 MeV calculated in ref. [6] for the corresponding ground states [8]. The calculated threshold for the $^{40}Ca(^{16}O,2np)^{53}Co^{m}$ reaction is 33.0 MeV, consistent with the experimental observations, and its excitation function agrees well with that expected from simple statistical model calculations [9].

Based on $^{53}Co^{m}$ as the origin of the proton activity, the probable decay scheme presented in fig. 2 is consistent with our data. The observed 245 msec half-life implies that the dominant mode of decay is by positron emission to $^{53}Fe^{m}$. The partial half-life for the Fermi component alone of the superallowed β^{+}-decay can be calculated with considerable precision [10] to be 0.35 sec; if the Gamow-Teller matrix element is then included (assuming pure $(f_{7/2})^{-3}$ configurations), one obtains 0.2 sec as the anticipated half-life [11]--in reasonable agreement with observation.

Proton emission apparently arises only as a weak branch in the decay of $^{53}Co^{m}$. A rough order of magnitude estimate of the partial lifetime for this branch can be obtained from the statistical model calculations [9]: at an ^{16}O energy of <u>47 MeV</u> the predicted ratio of

$$\frac{\sigma(^{16}O,2pn)}{\sigma(^{16}O,2np)} \text{ is } \approx \frac{70}{1} ,$$

while the observed ratio of

$$\frac{\sigma(^{53}Fe^{m})}{\sigma\begin{pmatrix}\text{proton}\\ \text{activity}\end{pmatrix}} \text{ is } \approx \frac{15000}{1} ,$$

implying a partial half life $\approx$ 50 sec. Since penetration through the Coulomb and $\ell = 9$ centrifugal barriers [12] leads to an expected half-life of $\sim$ 0.3 μsec for $\gamma_p^2 = 1$, this rough estimation implies $\gamma_p^2 \approx 6 \times 10^{-9}$ for this very complex decay. A 0.7 MeV (c.m.) proton group leading to the first excited (2+) state [13] of ^{52}Fe is also energetically possible (with a barrier penetrability 50 times less) but could not have been observed in these experiments.

The best alternative explanation for this activity is of course to attribute it to beta-delayed proton emission. The only known nuclei expected to be more than very weak delayed-proton emitters and which could possibly be produced in the present experiments have $T_Z = -3/2$, $A = 4n + 1$. The measured half-life and energy spectrum are quite inconsistent with the known members of this series (^{9}C, ^{13}O, -- ^{41}Ti, and ^{49}Fe) and the observed threshold precludes production of the unknown $T_Z = -3/2$ nuclide ^{45}Cr.

In this vein one must also consider the ground states and isomers of all other nuclei for which the emission of beta-delayed protons of 1.53 MeV is energetically possible. Of these the most reasonable example follows the assumption that the parent nuclide is still the isomer ^{53}Co^{m}, but that its direct proton decay is too weak to be observed. One would then attribute the observed activity to delayed-proton emission following β^+-decay to a level in the region of 9.08 MeV in ^{53}Fe, as shown in fig. 2. In the unlikely event that such a state were populated by β^+-decay from ^{53}Co^{m} having a log *ft* as low as 3.8, such a branch would represent only 4×10^{-4} of all decays of the isomer. This would imply that the ratio $\sigma(^{53}\mathrm{Co}^m) / \sigma(^{53}\mathrm{Fe}^m)$ was at least one order of magnitude higher than expected on the basis of statistical model calculations [9]. Similar arguments and the excitation function data make it improbable that any other $T_Z = -1/2$ or -1 nuclide below ^{56}Ni--even if produced in a fission-type reaction--is the origin of this activity. However, as is obvious, our arguments rely upon the presently known systematics of the decay of such nuclei.

It is our opinion that the best explanation for the origin of the observed activity is the weak proton radioactivity of $^{53}\mathrm{Co}^m$. Its origin as a beta-delayed proton radiation from $^{53}\mathrm{Co}^m$ can not, of course, be ruled out by the present data nor can the activity without question be attributed to this nuclide. Further experimentation is obviously needed to clarify these points. At the very least, however, it would appear that $^{53}\mathrm{Co}^m$ is the best presently known candidate to be an observable proton-radioactive nucleus [14].

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FIGURE CAPTIONS

Fig. 1. (a) An identified proton spectrum arising from the bombardment of calcium by ^{16}O at 49 MeV. Protons between 1.3 and 3.6 MeV could be linearly detected.

(b) A spectrum recorded in a single 50 μm detector of the activity arising from bombardment of calcium by 49 MeV ^{16}O. The center of mass energy shown results from assuming $^{53}Co^{m}$ to be the origin of this activity. Events below 0.6 MeV arise from the high β-background and those below 0.4 MeV are not shown.

Fig. 2. The proposed decay scheme for the proton unstable isomer $^{53}Co^{m}$. Energies are given in MeV. The probable decay modes are given by solid arrows while the less-likely production of beta-delayed protons is indicated by dashed lines.

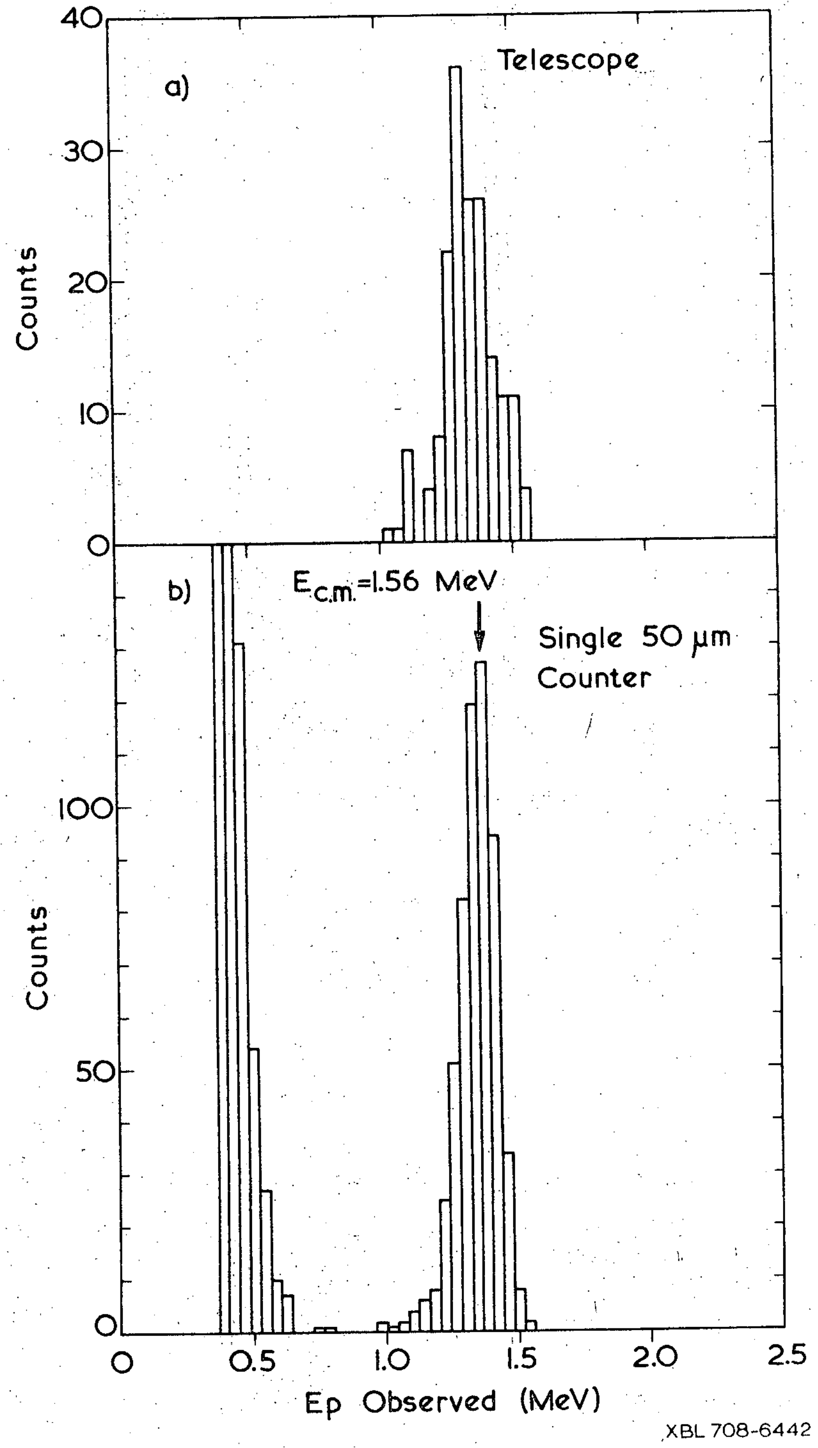
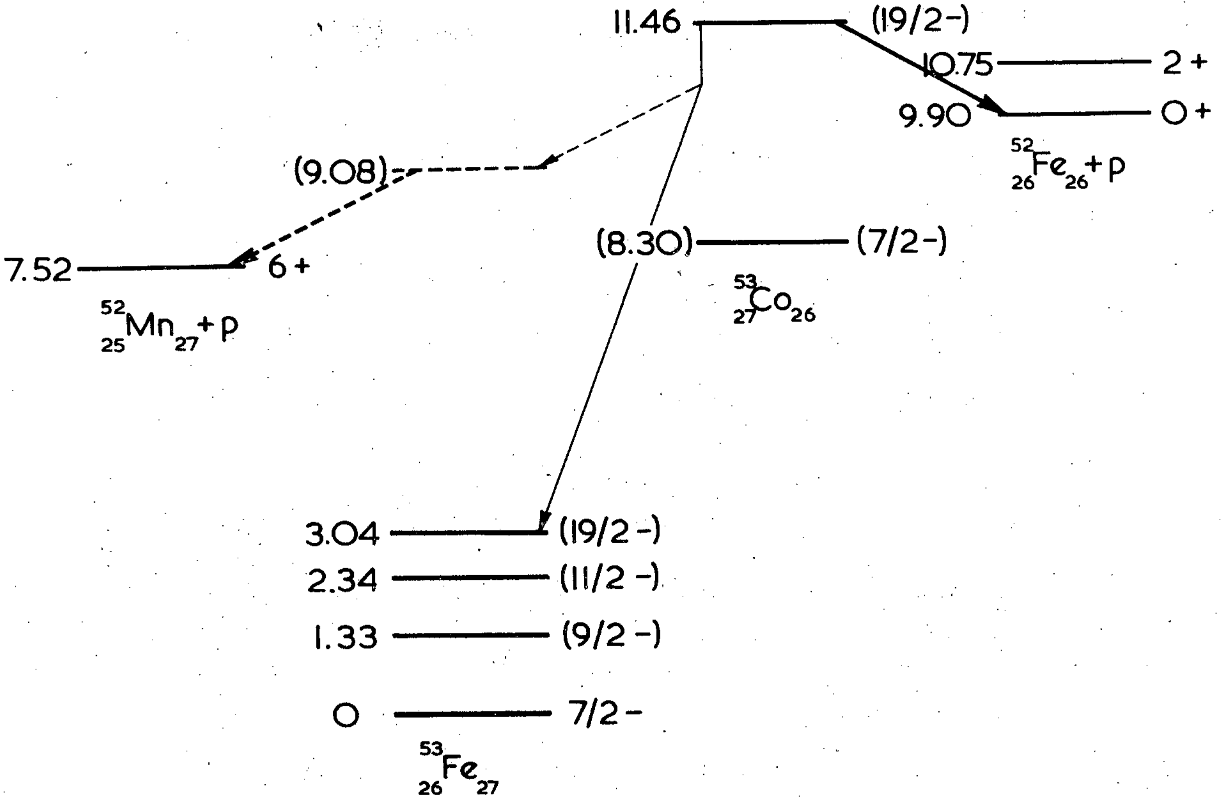

a)
Telescope
Counts
40
30
20
10
0
b)
$E_{c.m.}$=1.56 MeV
Single 50 μm Counter
Counts
100
50
0
0
0.5
1.0
1.5
2.0
2.5
Ep Observed (MeV)
XBL 708-6442

Fig. 1



XBL 708-6441

Fig. 2

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