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RADIOACTIVITY $^{53}Co^m$; measured direct proton E_p, $T_{1/2}$; deduced partial half-life, γ_p^2; searched for second proton decay branch.

FURTHER RESULTS ON THE PROTON RADIOACTIVITY* OF $^{53}Co^m$

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Abstract

Additional studies on the proton radioactivity of the 247 ± 12 msec isomer $^{53}Co^m$ lead to an improved estimate of ∿ 17 sec for its partial half-life for emission of 1.59 ± 0.03 MeV protons to the ^{52}Fe ground state. An upper limit of 1/250 for the ratio of direct proton decay to the $^{52}Fe^*$(2+, 0.84 MeV) state relative to decay to the ^{52}Fe(g.s.) can be set.

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1. Introduction

This report arises from an extension of our studies[1-2] on the proton decay of $^{53}Co^m$. In particular the earlier work has shown a) that this isomer is the mirror of the well known $^{53}Fe^m$(3.04 MeV, 19/2$^-$, T = 1/2) isomer[3-4] which arises from the $(f_{7/2})^{-3}$ configuration and is another example of the so-called "spin-gap" isomers[5]; b) that the dominant decay mode of 247 ± 12 msec $^{53}Co^m$ appears to be superallowed positron emission to $^{53}Fe^m$; and c) that a weak branch--not in coincidence with positrons--arising in the decay of $^{53}Co^m$ is the direct emission of 1.59 ± 0.03 MeV (center-of-mass, c.m.) protons to the ground state of ^{52}Fe. [This half-life and energy are "best values" arising from the analysis of both the previous and the present data.]

Two improvements in the results from this earlier work are of interest. First, we have searched for a further proton decay group of ∿ 0.75 MeV (c.m.) leading to the first excited state of ^{52}Fe, since neither of the earlier experiments could have detected such a branch. Second, since an indirect approach (employing in part statistical model calculations to determine relative cross-sections) was required in estimating the absolute branching ratio for the 1.59-MeV proton decay group, it appeared worthwhile to improve the earlier estimate[1]) through use of the spin-dependent nuclear evaporation model of Grover and Gilat[6]).

2. Experimental Procedure

External proton beams of various energies from the Berkeley "88-inch" cyclotron were used to produce $^{53}Co^m$ via the $^{54}Fe(p,2n)$ reaction on a separated isotope target (840 μg/cm^2). The experimental setup used for these measurements was also employed in our earlier work[2]) and is illustrated in fig. 1. Since high beam currents--typically 3-8 μA--were utilized, it was necessary to shield the detectors during the bombardment period.

As is shown in fig. 1, the two detector-telescopes were protected by a 3.2-mm-thick slotted tantalum wheel driven at a constant velocity. The two large slots rotate in front of the detectors during the beam-off period. Both a long and a very short narrow slit can also be seen in the plane view of this wheel. A light shining through the long slit generated signals from a photodiode which modulated the cyclotron dee voltage to control the duration of the beam-on interval. In addition, the signal from the photodiode aligned with the short slit, which appears immediately following the blocking of the beam-on signal, was used to generate an "inspect" pulse. This inspect pulse triggered a rate meter with a pre-set threshold, which was fed by signals from one of the detectors; should the beam fail to cut off (or drop away too slowly), a signal from the rate meter blocked all the electronics for that bombardment cycle. For these experiments the bombardment period was ∿ 670 msec, followed by a counting period of ∿ 750 msec.

Two semi-conductor detector telescopes feeding Goulding-Landis particle identifiers were used in these measurements. Both telescopes employed Ortec surface barrier ΔE-detectors and phosphorus-diffused silicon E- and E_{reject}-detectors; the E- and E_{reject}-detectors were cooled to -40°C. Telescope #1, mounted at 35.5° to the beam axis, used an 8-μm ΔE and a 50-μm E detector (due to the thickness of this ΔE detector, telescope #1 was primarily used as a monitor in the search for the 0.75 MeV (c.m.) proton group). Telescope #2, at 70.5°, employed a 4-μm ΔE and a 50-μm E detector. Because of the very high capacitive noise of this 4-μm (and 50-mm^2) detector, a special pre-amplifier was used which incorporated two liquid-nitrogen-cooled, field-effect transistors in parallel in its input stage. Telescope #2 could detect and identify protons ranging from ∿ 440 keV to 2.1 MeV. An energy-analyzed beam of 3.39-MeV H_2^+ ions scattered from a thin Au target was used for the energy calibration.

Energy spectra of identified protons were stored as a function of time in a 4096-channel analyzer operating in an 8 × 512 channel mode. The time router indicated in fig. 1 supplied eight routing signals which permitted an initial time group of 50 msec followed by seven groups, each of 100 msec duration. In addition, half-life information on the 1.59-MeV proton group was also acquired using a 400-channel multi-scalar whose address was advanced by a quartz-crystal oscillator.

3. Results and Discussion

3.1. SEARCH FOR THE DECAY $^{53}Co^{m} \rightarrow {}^{52}Fe^{*}(2+) + p$

Figure 2 presents an identified-proton energy spectrum measured in telescope #2 arising from the decay of $^{53}Co^{m}$. A bombarding energy of 35 MeV was used in this experiment, corresponding to the observed peak of the (p,2n) excitation function. The maximum yield of the 1.59 ± 0.03 MeV (c.m.) proton group arising in the decay of the isomer to the ^{52}Fe(g.s.) is ≈ 450 nb. No evidence for an additional 0.75-MeV (c.m.) proton group leading to the $^{52}Fe^{*}$(2+, 0.84-MeV) state[7]) can be seen above the low background. These data set an upper limit of 1/250 for the ratio of protons populating the $^{52}Fe^{*}$(2+) state relative to those populating the ^{52}Fe(g.s.).

3.2. PARTIAL HALF-LIFE FOR THE DECAY $^{53}Co^{m} \rightarrow {}^{52}Fe(g.s.) + p$

The positron decay (and absolute yield) of $^{53}Co^{m}$ could not be determined due to its weak production and the much greater yield of other activities (e.g., ^{54}Co, ^{50}Mn) with similar half-lives and positron end-points (also see ref. [1])). However, an indirect estimate of the partial half-life for the 1.59-MeV proton decay branch of $^{53}Co^{m}$ can be obtained by comparing the experimental ratio of peak cross-sections for $^{54}Fe(p,pn)^{53}Fe^{m}/^{54}Fe(p,2n)^{53}Co^{m}$ [proton branch only] to the ratio predicted from the spin-dependent nuclear evaporation program GROGI-2 of Grover and Gilat[6,8]). Relative excitation functions for producing $^{53}Fe^{m}$ and $^{53}Co^{m}$ by the (p,pn) and (p,2n) reactions, respectively, were calculated with this code by following in detail the de-excitation of the compound nuclei via neutron, proton, α-particle and gamma-ray emission channels.

Based on a pre-selected sequence of emitted particles, GROGI-2 calculates the distribution in excitation energy (E) and spin (J) of the cross section populating successive daughter nuclei in the evaporation chain. Both the initial distribution of the excited population and the transmission coefficients for the emitted particles were supplied to the program by the optical-model code ABACUS-2[9]). Optical-model parameters were chosen following the approach of Hodgson[10]). The phase space available to the evaporating particles was constrained in part by the yrast levels (E_J) which were determined by a combinatorial calculation based on the full numerical level density calculation of Hillman and Grover[11]). Level density parameters were taken from ref. [12]) and the spin parameter R and pairing correction δ were then determined by a least squares fit of the function $E_J = \frac{(J + 1/2)^2}{aR} + \delta$ to the numerical yrast calculation. The probability for dipole radiation was normalized from extrapolated data of ref. [13]) and that for quadrupole emission was taken[14]) to be 10^{-3} Γ(dipole). Finally, level densities were calculated using the Lang prescription[15]) as discussed in ref. [8]).

Figure 3 presents calculated excitation functions for the ^{54}Fe(p,pn)^{53}Fe^m and ^{54}Fe(p,2n)^{53}Co^m reactions. In order to obtain relative cross-sections for populating these $J^\pi = 19/2^-$ isomers, the de-excitation of the final ^{53}Fe and ^{53}Co nuclei was terminated at the appropriate excitation energies (and spin). The theoretical cross-sections were normalized to experiment at the observed peak of the ^{54}Fe(p,2n)^{53}Co^m excitation function. Proton bombarding energies were measured with the high-resolution analysis magnet of the cyclotron; quite good agreement between the experimental and theoretical excitation functions for the production of ^{53}Co^m can be seen. (Although Eskola[4]) reports excitation function data for the ^{54}Fe(p,pn)^{53}Fe^m reaction, uncertainties in his absolute beam energy determinations preclude a similar comparison.)

Taking Eskola's value[4]) of ∿ 5 mb for the <u>peak</u> cross section of the ^{54}Fe(p,pn)^{53}Fe^m reaction (and our peak proton yield of 0.45 μb), one finds the ratio $\sigma(^{53}Fe^m)/\sigma$(proton activity) ∿ 11,000, while the theoretical result for $\sigma(^{53}Fe^{m})/\sigma(^{53}Co^{m})$ using peak cross sections is $\sim$ 165. This then leads to a partial branch of $\sim$ 1.5% for the observed proton decay or a partial half-life of $\sim$ 17 sec. Similar GROGI-2 calculations were performed to obtain the peak cross-section ratio $^{40}Ca(^{16}O,2pn)^{53}Fe^{m}/^{40}Ca(^{16}O,2np)^{53}Co^{m}$, which was then compared to the experimental results of ref. [1]. Though the large errors involved in determining absolute cross-sections for these heavy-ion induced reactions limit the usefulness of this comparison, it did give a partial half-life consistent with $\sim$ 17 sec.

3.3. $^{53}Co^{m}$ DECAY SCHEME AND REDUCED WIDTHS

Figure 4 presents our decay scheme for $^{53}Co^{m}$. The mass of the as-yet-unobserved ^{53}Co ground state is taken from the Coulomb displacement energy calculations of Harchol et al.[16]. As is discussed in ref. [1], the expected half-life for the isomer would be 350 msec based solely on the Fermi component of its superallowed β^{+}-decay; this reduces to 200 msec when the Gamow-Teller matrix element is included (assuming pure $(f_{7/2})^{-3}$ configurations). The observed 247 msec half-life agrees well with this estimate.

Since the $\sim$ 17 sec partial half-life for direct emission of a 1.59-MeV (c.m.) proton to the ^{52}Fe(g.s.) appears quite long, it is of interest to estimate the reduced width for this decay. A standard calculation for the penetration through the Coulomb and $\ell = 9$ centrifugal barriers (using $r_o = 1.4$ fm) leads to an expected half-life of $\sim$ 60 nsec for a reduced width $\gamma_p^2 = 1$. The observed half-life then implies that $\gamma_p^2 \sim 4 \times 10^{-9}$ for this complex decay. Since the barrier penetrability for the proton group populating the $^{52}Fe^{*}(2+)$ state (an $\ell = 7$ decay) is $\sim$ 6% of that to the ^{52}Fe(g.s.), our data set an upper limit for the relative reduced widths of

$$\frac{\gamma_p^2(g.s.)}{\gamma_p^2(2+)} > \frac{15}{1} \quad .$$

One estimate of the order of magnitude to be expected for the reduced width for proton decay to the ^{52}Fe(g.s.) has been performed by Peker *et al.*[17]), who find fair agreement with our value. The present results on the ratio of the reduced widths for proton decay to the ground and first-excited states of ^{52}Fe should provide an additional test of such theoretical calculations. Although proton radioactivity should be a widespread phenomenon for highly neutron-deficient nuclei[18]), it is quite possible that experimental considerations may cause the decay of many-particle isomeric states[17]) to be our richest source of studies of this new nuclear decay mode for some time.

We should like to thank Don Landis for his development work on several aspects of the overall electronic setup.

Footnotes and References

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Figure Captions

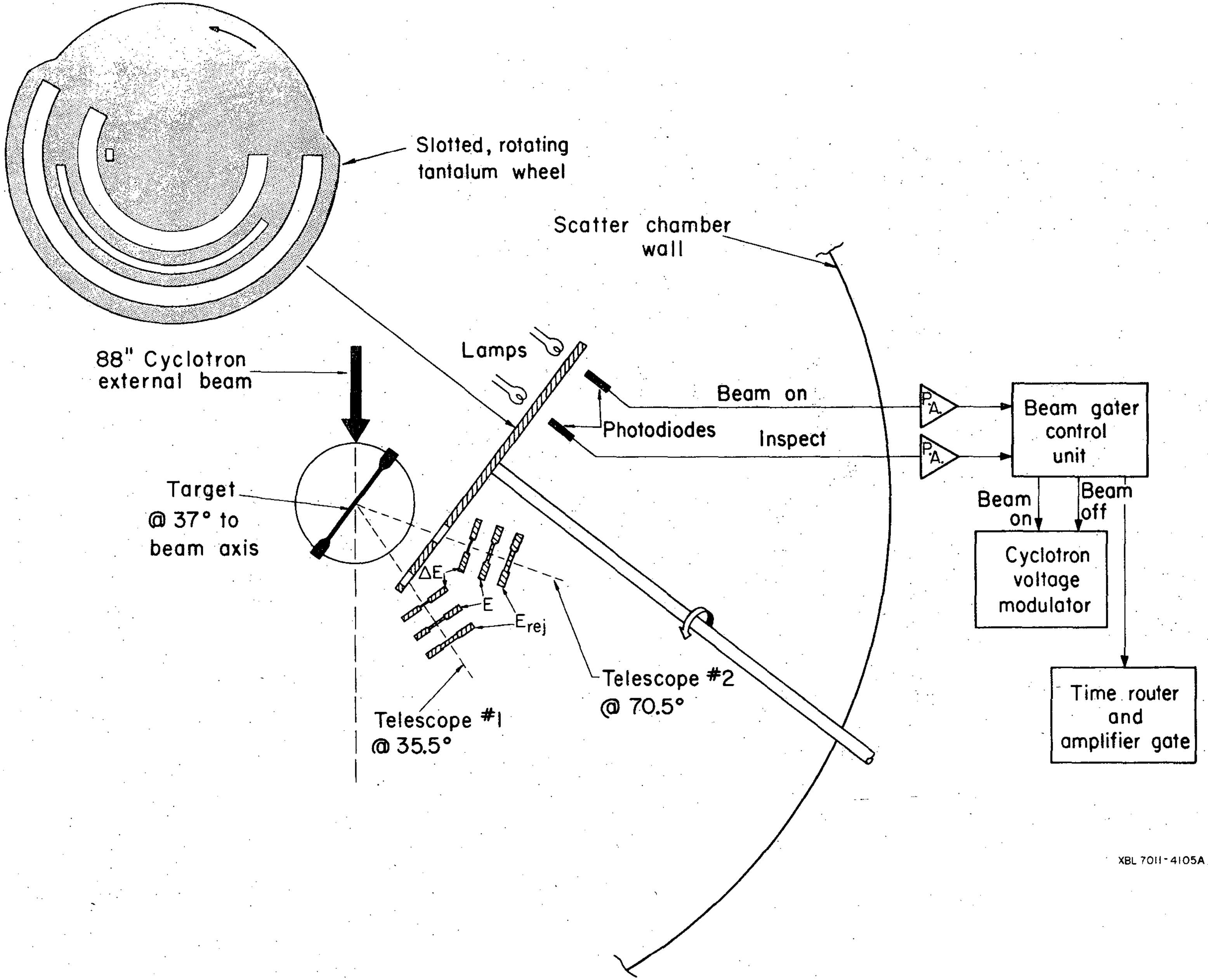
Fig. 1. A schematic diagram of the apparatus employed in these pulsed-beam, shielded-detector measurements.

Fig. 2. An identified-proton energy spectrum from the decay of $^{53}Co^m$ produced by the $^{54}Fe(p,2n)$ reaction induced by 35-MeV protons. The vertical arrows denote the energy region over which decay protons could be reliably observed, while the horizontal arrow indicates the location of any possible transitions to the $^{52}Fe^*(0.84\text{-MeV})$ state.

Fig. 3. Theoretical predictions for the excitation functions of $^{53}Fe^m$ and $^{53}Co^m$ employing the approach of Grover and Gilat (see text). The theoretical curves have been normalized to the experimental excitation function for the $^{54}Fe(p,2n)^{53}Co^m$ reaction.

Fig. 4. The decay scheme of $^{53}Co^m$.

LBL-626



Slotted, rotating tantalum wheel
Scatter chamber wall
88" Cyclotron external beam
Lamps
Photodiodes
Beam on
Inspect
P.A.
P.A.
Beam gater control unit
Beam on
Beam off
Cyclotron voltage modulator
Time router and amplifier gate
Target @ 37° to beam axis
ΔE
E
E rej
Telescope #1 @ 35.5°
Telescope #2 @ 70.5°
XBL 7011-4105A

Fig. 1

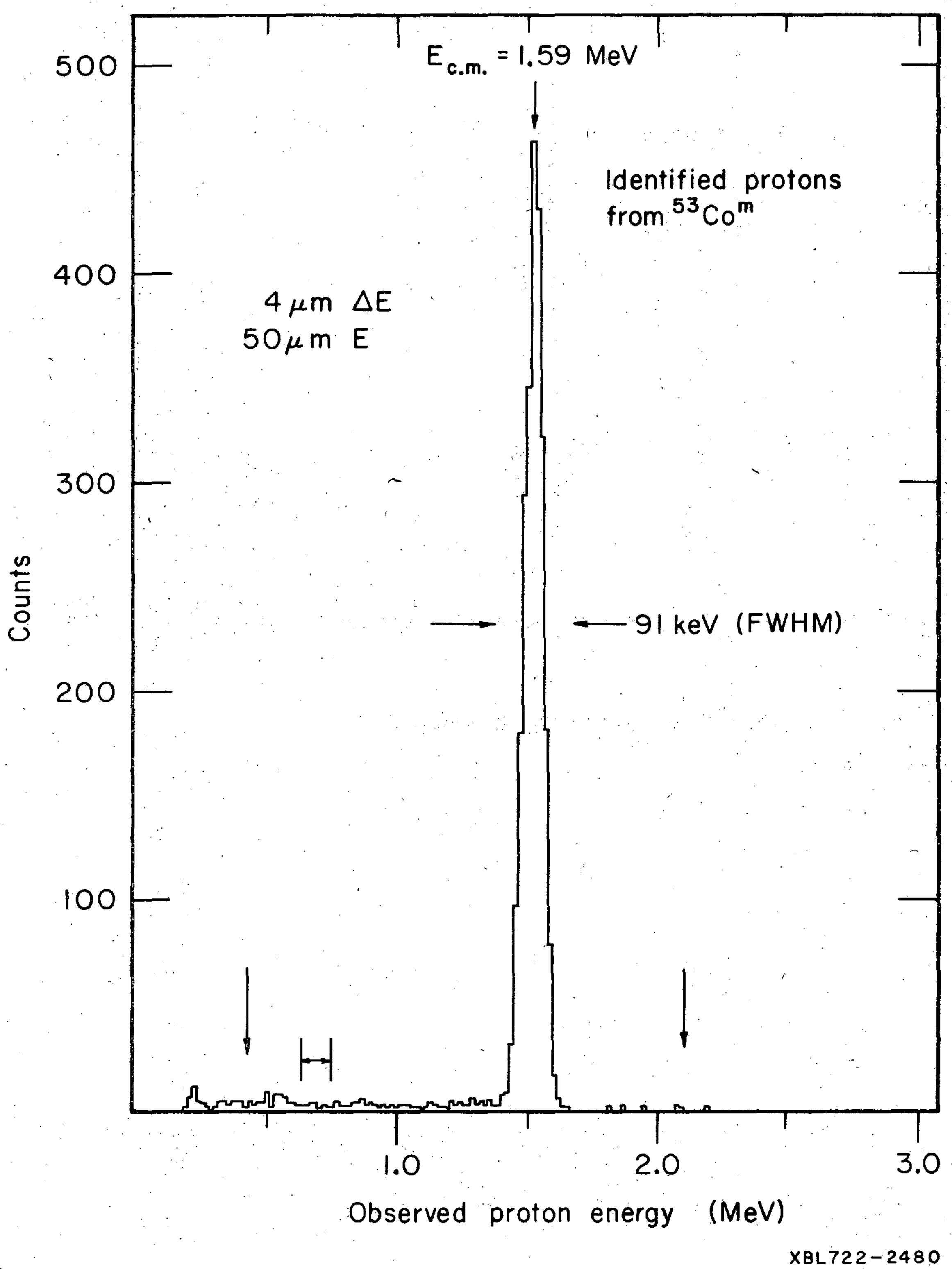

E c.m. = 1.59 MeV
Identified protons from 53Co m
4 μm ΔE
50 μm E
91 keV (FWHM)
Counts
500
400
300
200
100
1.0
2.0
3.0
Observed proton energy (MeV)
XBL722-2480

Fig. 2

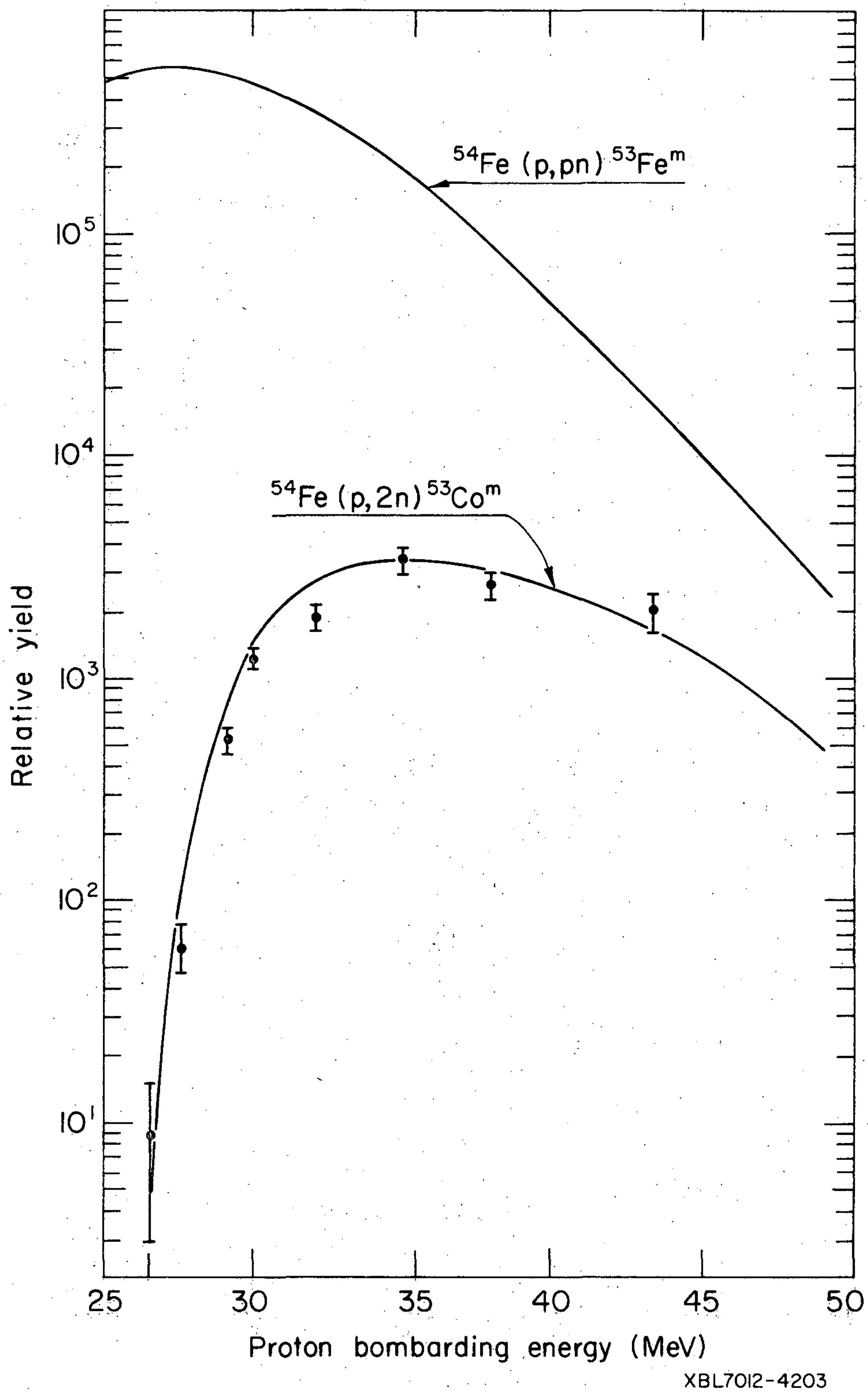
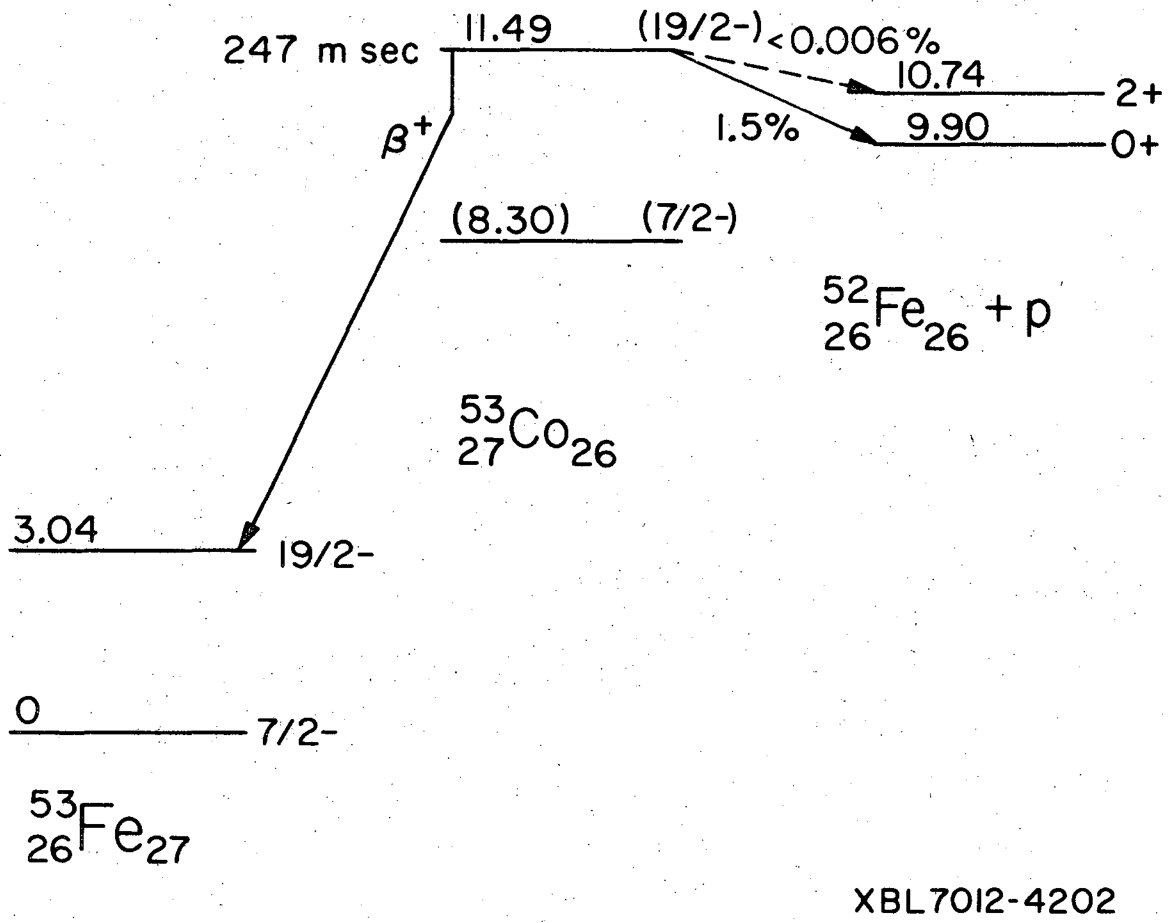

$^{54}Fe\,(p,pn)\,^{53}Fe^m$
$^{54}Fe\,(p,2n)\,^{53}Co^m$
Relative yield
10^5
10^4
10^3
10^2
10^1
25
30
35
40
45
50
Proton bombarding energy (MeV)
XBL7012-4203

Fig. 3



247 m sec
11.49
(19/2-)
< 0.006%
10.74
2+
1.5%
9.90
0+
β+
(8.30)
(7/2-)
$^{52}_{26}Fe_{26}$ + p
$^{53}_{27}Co_{26}$
3.04
19/2-
0
7/2-
$^{53}_{26}Fe_{27}$
XBL7012-4202

Fig. 4