LBL-30721
Preprint

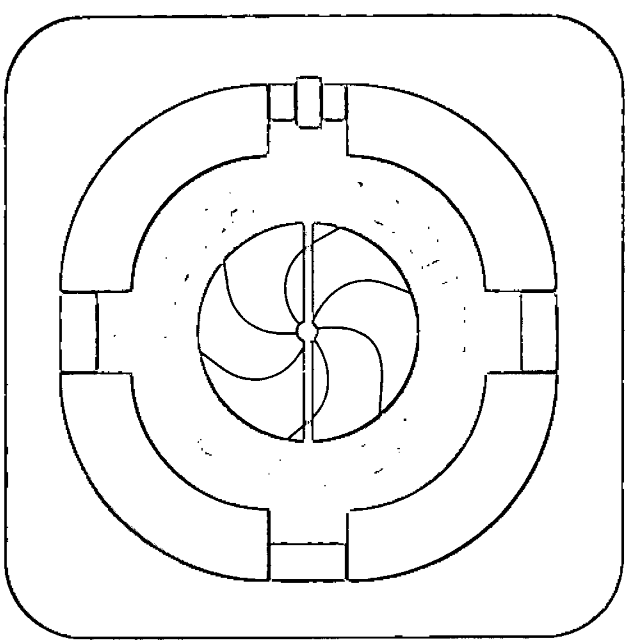
Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Physics Letters B

Beta-Delayed Two-Proton Decay of ^{39}Ti

D.M. Moltz, J.C. Batchelder, T.F. Lang, T.J. Ognibene,
J. Cerny, P.E. Haustein, and P.L. Reeder

April 1991



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

LBL - 30721

D. M. Moltz, J.C. Batchelder, T.F. Lang, T.J. Ognibene and Joseph Cerny
Department of Chemistry and Nuclear Science Division
Lawrence Berkeley Laboratory,
University of California, Berkeley, California 94720, USA

P.E. Haustein
Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973

P.L. Reeder
Battelle Memorial Institute, Pacific Northwest Laboratories, Richland, WA 99352

Beta-delayed Two-Proton Decay of ^{39}Ti

April, 1991

Abstract

The beta-delayed two-proton decay of the $T_z = -5/2$ nuclide ^{39}Ti has been observed. The ^{39}Sc isobaric analog state has been calculated to lie at 8.82 MeV using the measured two-proton sum energy of 4750$\pm$ 40KeV for its decay to the ^{37}K ground state. Combining this excitation energy with a Coulomb displacement energy calculation has lowered the energy available for ground state two-proton emission of ^{39}Ti from 760 to 530 KeV.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S.Department of Energy under Contract DE-AC03-76SF00098

Studies of nuclei near the proton drip line permit examination of very exotic decay modes and analysis of specific nuclear structure problems not addressable nearer stability. Of course at the drip line there exists the potential for proton emission ($S_p < 0$) on a timescale sufficiently long to be classified as radioactivity. To date, only four examples of this ground state decay mode have been discovered [1], ^{151}Lu, ^{147}Tm, ^{113}Cs and ^{109}I. Of equal interest would be the decay of a nuclide for which $S_p > 0$ and $S_{2p} < 0$ via the simultaneous emission of two protons. Ground state two-proton decay was first predicted by Gol'danskii [2,3], but is as yet unobserved. In principle, many candidates exist [4,5]. However, the exponential dependence of the half-life on the available decay energy creates a very narrow window between beta decay as the dominant decay mode and the nuclide being totally unbound. An experimentally accessible candidate for which these criteria appear to be favorable is ^{39}Ti [4,5].

The most important input parameter in making this choice is the selection of an atomic mass prediction [6]. Since, however, these predictions vary widely, for very neutron deficient light nuclei we employ the charge-symmetric Kelson-Garvey mass relation [7]. The predicted decay scheme for ^{39}Ti shown in Fig. 1 has utilized this Kelson-Garvey approach and the recently measured 28 ms half-life at GANIL [8,9]. This "long" half-life indicates that ^{39}Ti will decay primarily via beta decay. In addition to depicting the two-proton decay channel, Fig.1 shows the numerous particle-decay channels energetically allowed following super-allowed beta decay to the isobaric analog state (IAS). These particle-decay channels include p, 2p, 3p, α and αp. In fact, because the beta daughter (^{39}Sc) is unbound to proton emission by 600 keV [10,11], any beta decay branch of ^{39}Ti necessarily is followed by particle emission.

Prior to learning of the GANIL results [8,9], we had undertaken several experiments to search for ground state two-proton decay from ^{39}Ti. We collected recoil products from the 110 MeV $^3He^{2+}$ + ^{nat}Ca reactions in 200 $\mu g/cm^2$ Al catcher foils located on our fast rotating wheel [12]. Utilizing our recently developed low-energy proton detectors [13] with 250 keV proton thresholds permitted us to search for this decay mode in the 100 μs to 10 ms half-life range. That these searches were unsuccessful is in agreement with GANIL [9].

Although the GANIL results determined the ^{39}Ti half-life via ßp emission, these results did not determine the location of the IAS in ^{39}Sc (from which one can estimate the mass of ^{39}Ti and hence an improved direct 2p decay energy). It was decided to search for the decay of ^{39}Ti via its beta decay to the ^{39}Sc IAS and subsequent 2p emission. Beta-delayed two-proton decay was first observed in ^{22}Al decay [14,15] and has now been observed in ^{26}P [15], ^{35}Ca [16], ^{31}Ar [12,17,18] and ^{27}S [19]. ß2p decay also has the distinct observational advantage of requiring the coincidence of two particles and thus it significantly reduces the background.

We chose to use the helium-jet transport method (short capillary transit time ~25 ms; see ref. [15]) in conjunction with an array of modified gas-Si proton telescopes (see ref. [12] for a description of the original proton telescope). A schematic diagram of one of these modified telescopes is shown in Fig. 2. The primary modification to the original telescope is the addition of a second gas-ΔE detector to create a gas-gas-Si telescope. These three detectors are used as a triple coincidence system for low energy (0.3–4 MeV) protons. Any particle which fires the trigger gas detector and the silicon detector constitutes a potentially valid event. Figure 3 shows the effect of the various gates on one sample calibration spectrum of beta-delayed protons arising from ^{25}Si decays. ^{25}Si was produced in the 40 MeV $^{3}He^{2+}$ + ^{nat}Mg reaction. Figure 3a represents a two-dimensional plot of the differential energy in the trigger detector (ordinate) and the energy in the silicon detector (abscissa). The proton band is clearly marked as are the regions containing betas and alpha particles (alphas are from ^{20}Na decay). A one-dimensional Si energy projection of events in the proton gate is given in Fig. 3b. The requirement that a particle also fire the filter detector (a valid 3-fold coincidence) and be identified as a proton utilizing the proton gate drawn in Fig. 3c (filter detector vs. silicon energy) yields the very low background ^{25}Si spectrum shown in Fig. 3d. In all cases the proton energy is determined from the measured pulse height in the silicon detector; the gas detectors are used only for identification and the small energy loss therein is compensated for in the silicon energy calibration. This type of energy calibration has been used for every separate experiment.

Titanium-39 was produced in the 110 MeV $^{3}He^{2+}$ + ^{nat}Ca reaction. At this energy, the statistical fusion evaporation code ALICE [20] predicts a total cross section of 40 nb. The $^{3}He^{2+}$ ions were ionized with the LBL ECR source and then injected into and accelerated by the 88-Inch Cyclotron. The 8 μA beam was pulsed on a 100 ms time scale (40 ms on and 60 ms off) by rapidly cycling (2 μs) electric field deflection plates in the ECR injection line. Data were collected only during the beam-off phase because the large neutron flux induced an intolerable background level (of real protons). Triple detector telescopes were placed on five faces of a cube (one face was used for collecting activity from the helium-jet). Although four telescopes were identical, a pair of telescopes was mounted in a single housing opposite the collection spot to permit the measurement of narrow angle coincidences so that there were six telescopes in all. Four of these telescopes subtended solid angles of ~3% of 4π whereas the remaining two telescopes (180^{o} from each other) subtended solid angles of only 1% of 4π. Three separate bombardments of approximately equal integrated beam current were obtained. All events which fired two telescopes and -for calibration purposes- 1/16 of all events which fired only one telescope were recorded in an event-by-event mode on magnetic tape for subsequent analysis.

Typical two-dimensional proton gates are shown in Fig. 3. Gates were refined as necessary for each run from the simultaneous, and copious, production of the beta-delayed proton emitters ^{37}Ca, ^{40}Sc and ^{41}Ti. All coincidence data were subjected to the following minimum requirements to be considered a nominal two-proton event: 1) a valid proton in <u>each</u> trigger gas-Si 2D spectrum and 2) either a) a valid 20 ns Si-Si TAC signal for both protons or b) a valid proton in the filter gas-Si 2D spectrum if Ep < 700 keV. All events which met these requirements were then subjected to detailed analysis of the original raw event (both pα and 3p events were looked for, but none were observed). Approximately 50% of these nominal two-proton events could then be eliminated, primarily by being shown to be beta particle-proton coincidences at the edge of the gates. (For example, an event with a 300-keV particle in one telescope at the lowest edge of the proton gate, a 3100-keV particle in the second telescope and a valid TAC was eliminated as a simple beta-proton coincidence arising from the principal decay group in ^{37}Ca.) The final two-proton sum-energy spectrum shown in Fig. 4. was generated by individually summing the energies of each separate proton (i.e., no 2p energy scale was utilized in the peak energy determination).

The data presented in Fig. 4 have been normalized to $\theta_L = 90°$ because 12 of the 15 detector permutations are at this angle. Only two features are noticeable: a cluster of 4 events at ~4.75 MeV and a larger cluster of 7 events at ~2.50 MeV. These two peaks can be attributed to the beta-delayed two-proton decay of ^{39}Ti. The only other beta-delayed two-proton emitters which could be produced in this reaction are ^{31}Ar and ^{35}Ca, both of which have been characterized [12,16,17,18]. Argon nuclei are not transported with the helium jet; the ground state β2p decay of ^{35}Ca would be observed at 4.1 MeV and could be present. Additionally, β2p emitters produced in reactions on the most plausible target contaminant (i.e., ^{24}Mg) can be discounted because the observed peaks do not correspond to the known β2p emitter ^{22}Al [15]. The peak labelled 1) in Fig. 4 has a measured energy of 4750 ± 40 keV and is 230 keV smaller than the predicted ground state β2p decay energy. This extra stability is consistent with the observation that ^{39}Ti decays primarily via beta decay [9]. If one assumes that peak 1) corresponds to β2p decay to the ground state of ^{37}K, then the arrows 2), 3) and 4) delineate where the next three groups of excited states in ^{37}K would fall in this spectrum (both 2) and 3) are doublets). Good agreement with 3) and our observed peak at 2480 keV is seen. (Unfortunately, which state in the doublet is populated is not known. Thus, this energy could not be used in determining the excitation energy of the IAS in ^{39}Sc.) This spectroscopic information has been used to construct the partial decay scheme given in Fig. 5. The paucity of statistics does not permit the assignment of the assumed sequential decay to intermediate states in ^{38}Ca.

The 4.87 MeV center of mass decay energy was used to determine the excitation energy of the T = 5/2 isobaric analog state in ^{39}Sc to be 8.82 MeV. By using Coulomb displacement energy calculations [21], the mass of ^{39}Ti can also be estimated and is shown in Fig. 5. When combined with the ground state mass of ^{37}Ca, the energy available for 2p decay is reduced to 530 ± 65 keV (the 40 keV error from this measurement has been added in quadrature to an estimated 50 keV error from the Coulomb displacement energy [21]). This result is also consistent with the recurring observation that masses predicted by the Kelson-Garvey relations [7] near the edge of stability are in fact better bound by 100-200 keV (KG 2p energy ~760 keV). Our measurement is also 130 keV better bound than the improved shell model prediction of Brown [5]. Although this mass does not preclude a small direct 2p decay branch, it constrains it to less than 0.1% (based on our mass plus upper error limit).

When these results are combined with recent calculations [22] predicting that the two proton/one proton decay ratios from the isobaric analog states of ^{31}Ar, ^{35}Ca and ^{39}Ti would be 3, 1 and 1, respectively, it is interesting to note that the observed ^{39}Ti yield in this reaction is consistent with those observed earlier for ^{35}Ca from the ^{40}Ca (^{3}He, α 4n) reaction at $E_{^3He}$ = 135 MeV [16] and for ^{31}Ar from the ^{32}S (^{3}He, 4n) reaction at $E_{^3He}$ = 110 MeV [12].

The beta-delayed two-proton decay of the T_z = -5/2 nuclide ^{39}Ti has been observed via its daughter isobaric analog state. Unfortunately, these data lead to a predicted ^{39}Ti mass with a S_{2p} of -530 ± 65 keV, which seriously restricts the partial half-life for ground state two proton emission in competition with its 28 ms beta decay. Following the general trend for greater than expected stability of highly proton rich nuclides near the drip line, this S_{2p} is 230 keV better bound than that predicted by the Kelson Garvey approach [7] and 130 keV better bound than shell model calculations by Brown [5] with the inclusion of some $f_{7/2}$ orbitals.

This work was supported by Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U. S. Department of Energy under Contracts DE-AC03-76SF00098 with Lawrence Berkeley Laboratory, DE-AC02-

76CH00016 with Brookhaven National Laboratory and DE-AC06-76RL0 1830 with Pacific Northwest Laboratories.

REFERENCES

‡Permanent address: UCSF Physics Research Laboratory, 389 Oyster Point Blvd., South San Francisco, CA 94080.

[1] S. Hofmann, in Particle Emission from Nuclei, edited by D.N. Poenaru and M.S. Ivascu (CRC Press, Boca Raton, FL, 1989) Vol. II, p. 25.

[2] V.I. Gol'danskii, Nucl. Phys. **19** (1960) 482.

[3] V.I. Gol'danskii, Usp. Fiz. Nauk. **87** (1965) 255, (Sov. Phys. Usp., **8** (1966) 770.

[4] D.M. Moltz, J.D. Robertson, J.E. Reiff, T.F. Lang and J. Cerny, in Proceedings of the Symposium on Exotic Nuclear Spectroscopy, Miami Beach, FL, Sept. 1989, in press.

[5] B.A. Brown, Phys. Rev. C **43** (1991) R1513.

[6] P.E. Haustein, At. Data Nucl. Data Tables **39** (1988) 185.

[7] I. Kelson and G.T. Garvey, Phys. Lett. **23** (1966) 689.

[8] M. Lewitowitcz *et al.*, in Proc. of the Bormio Nuclear Physics Workshop, Bormio, Italy, Feb., 1989.

[9] C. Detraz *et al.*, Nucl Phys. **A519** (1990) 529.

[10] C.L. Woods, W.N. Catford, L.K. Fifield and N.A. Orr, Nucl. Phys. **A484** (1988) 145.

[11] M. F. Mohar *et al.*, Phys. Rev. C **38** (1988) 737.

[12] J.E. Reiff, M.A.C. Hotchkis, D.M. Moltz, T.F. Lang, J.D. Robertson and J. Cerny, Nucl. Instr. Meth. **A276** (1989) 228.

[13] J.D. Robertson, J.E. Reiff, T.F. Lang, D.M. Moltz and J. Cerny, Phys. Rev. C **42** (1990) 1922.

[14] M.D. Cable, J. Honkanen, R.F. Parry, S.H. Zhou, Z.Y. Zhou and J. Cerny, Phys. Rev. Lett. **50** (1983) 404.

[15] M.D. Cable, J. Honkanen, E.C. Schloemer, M. Ahmed, J.E. Reiff, Z.Y. Zhou and J. Cerny, Phys. Rev. C **30** (1984) 1276.

[16] J. Äystö, D.M. Moltz, X.J. Xu, J.E. Reiff and J. Cerny, Phys. Rev. Lett. **55** (1985) 1384.

[17] D. Bazin *et al.*, in Proc. of the Workshop on Nuclear Structure of Light Nuclei Far From Stability, Experiment and Theory, Obernai, France, Nov. 17–29, 1989, p. 21.

[18] M.J.G. Borge *et al.*, Nucl. Phys. **A515** (1990) 21.

[19] V. Borrel *et al.*, Obernai Proc. *Op. Cit*, p. 3.

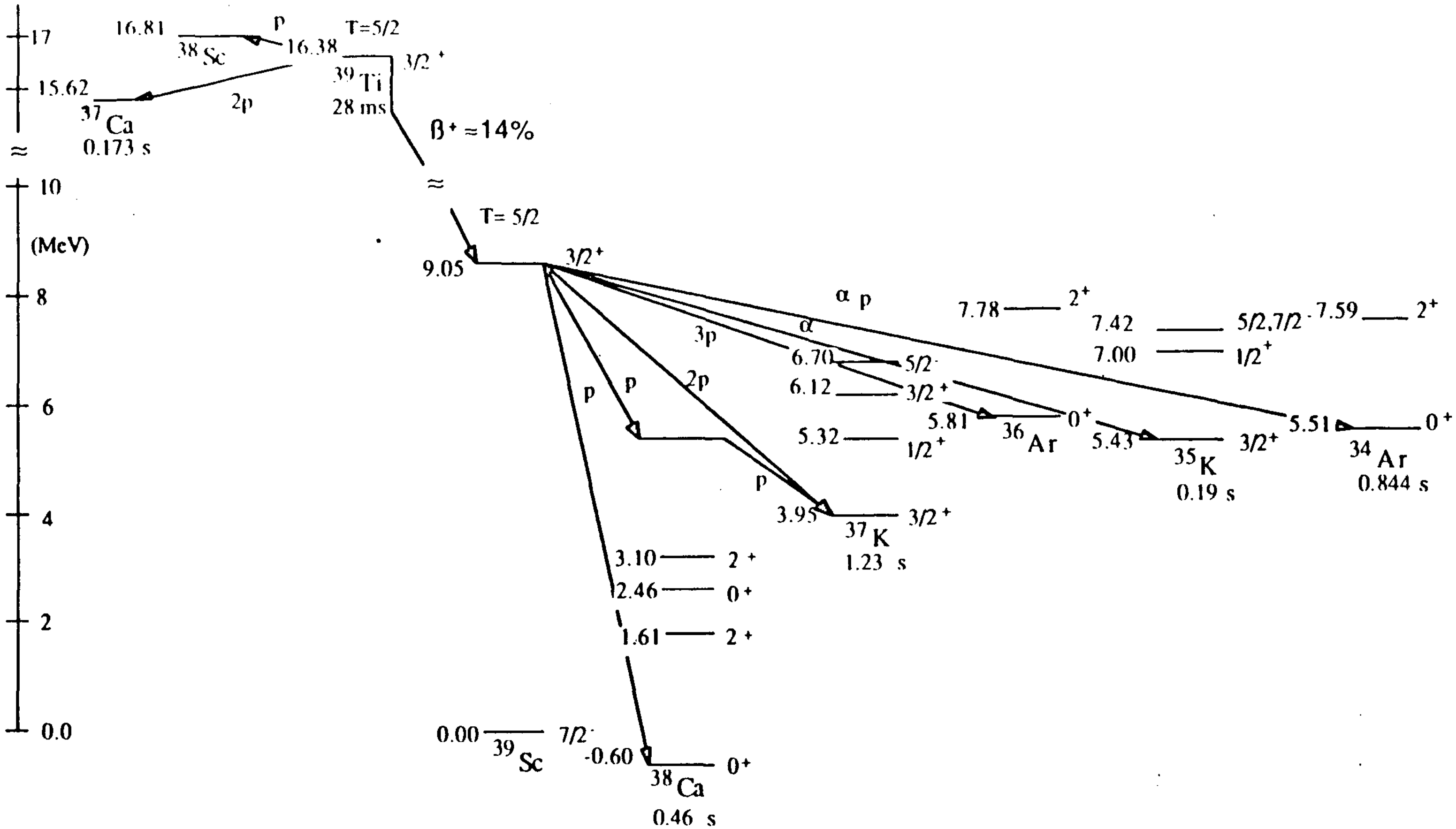
[20] M. Blann and J. Birplinghoff, Lawrence Livermore National Laboratory Report No. UCID-19614, 1982 (unpublished).

[21] M.S. Antony, J. Britz and A. Pape, At. Data and Nucl. Data Tables **34** (1986) 279.

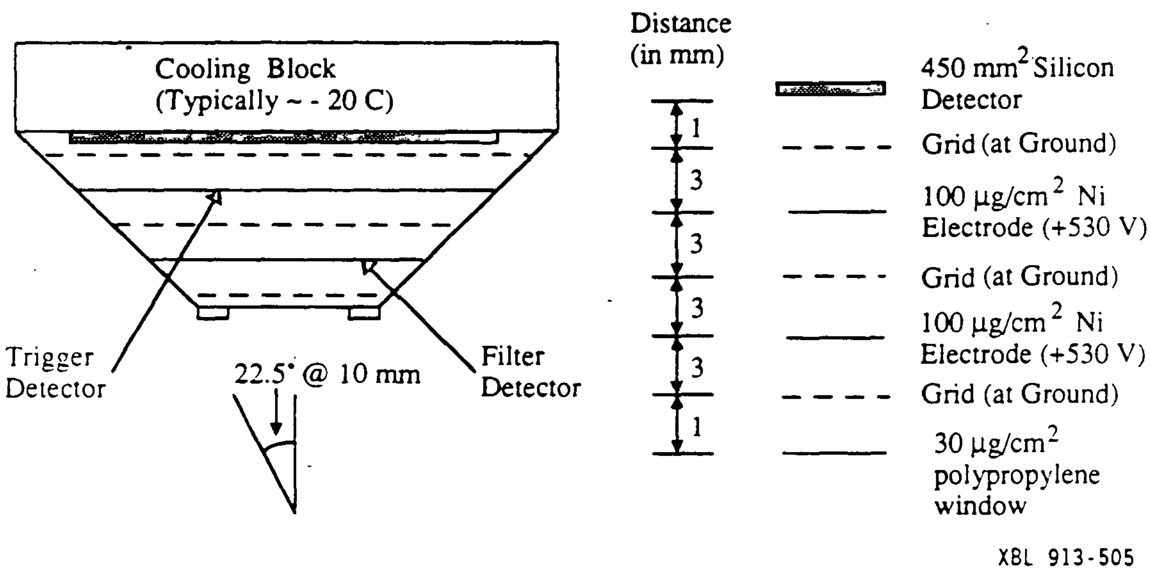
[22] C. Detraz, submitted to Z. Phys. A, Sept. 1990.

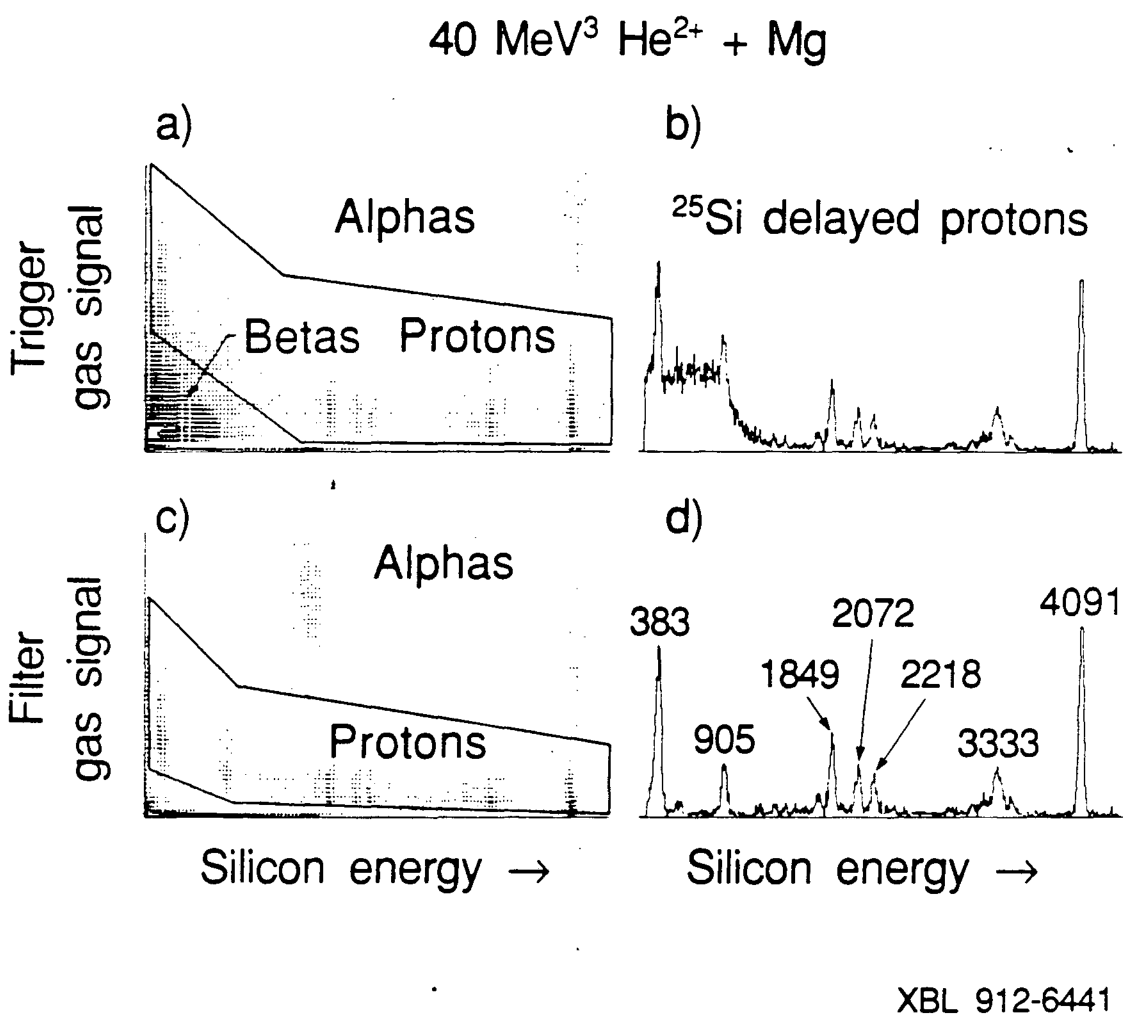
FIGURE CAPTIONS

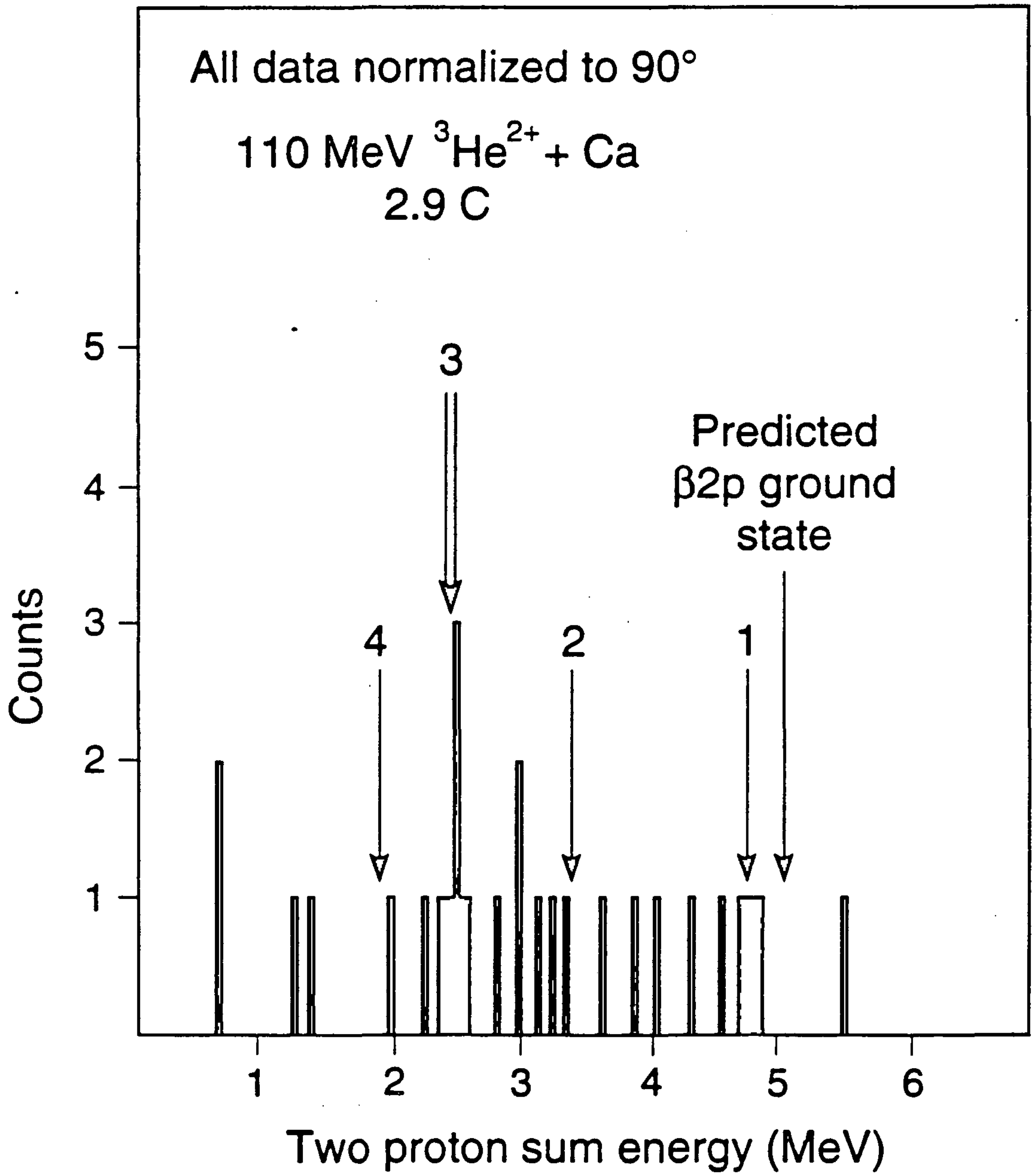
1. Calculated partial decay scheme for ^{39}Ti.
2. Cross-section of one gas-gas-silicon three-element telescope.
3. Delayed proton spectra from ^{25}Si decay. a) Two-dimensional (trigger gas vs. silicon energy) spectrum showing the alpha, proton and beta bands. b) One-dimensional Si energy projection of the proton gate in a). c) Two-dimensional (filter gas vs. silicon energy) spectrum showing the same particle bands. c) is necessarily a subset of a). d) One-dimensional Si energy projection of the proton gate in c). Energies are in keV.
4. Two-proton sum energy spectrum resulting from the bombardment of a ^{nat}Ca target with 2.9C of 110 MeV $^{3}He^{2+}$ beam. See text.
5. Proposed partial decay scheme for ^{39}Ti. The intermediate state in ^{38}Ca is not known. See text.


(MeV)
17
10
8
6
4
2
0.0
16.81
p
38 Sc
16.38
T=5/2
3/2 +
39 Ti
28 ms
15.62
37 Ca
0.173 s
2p
β+ ≈14%
T= 5/2
9.05
3/2+
α p
α
3p
2p
p
p
p
7.78
2+
7.42
5/2,7/2 -
7.59
2+
7.00
1/2+
6.70
5/2-
6.12
3/2 +
5.81
0+
36 Ar
5.32
1/2+
5.43
3/2+
35 K
0.19 s
5.51
0 +
34 Ar
0.844 s
3.95
3/2 +
37 K
1.23 s
3.10
2 +
2.46
0 +
1.61
2 +
0.00
7/2-
39 Sc
-0.60
0+
38 Ca
0.46 s

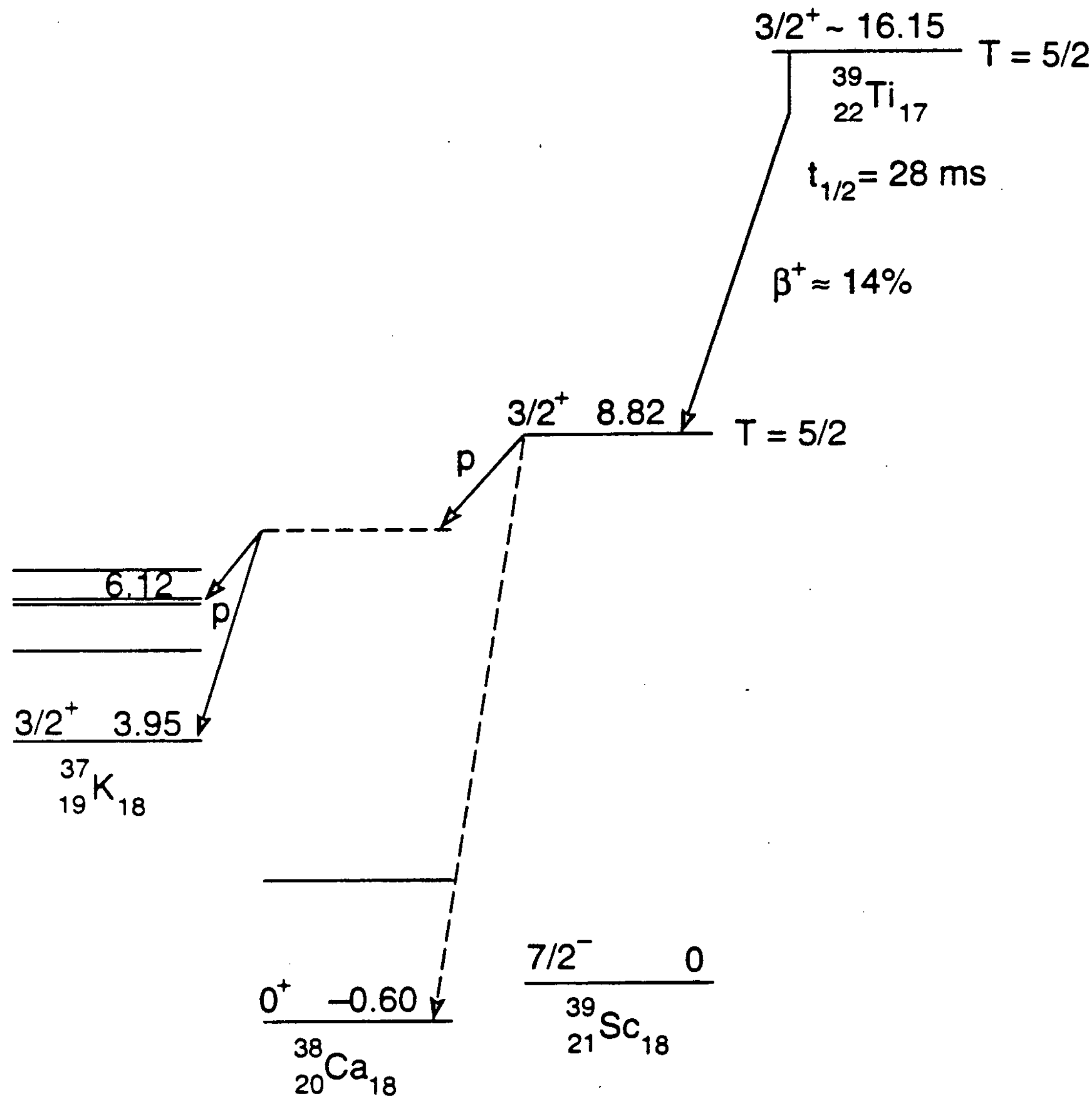
XBL 914-861


Cooling Block
(Typically ~ - 20 C)
Trigger Detector
22.5° @ 10 mm
Filter Detector
Distance
(in mm)
1
3
3
3
3
1
450 mm² Silicon Detector
Grid (at Ground)
100 µg/cm² Ni
Electrode (+530 V)
Grid (at Ground)
100 µg/cm² Ni
Electrode (+530 V)
Grid (at Ground)
30 µg/cm²
polypropylene
window
XBL 913-505


40 MeV 3 He2+ + Mg
a)
b)
Alphas
25Si delayed protons
Trigger gas signal
Betas
Protons
c)
d)
Alphas
Filter gas signal
383
2072
4091
1849
2218
905
3333
Protons
Silicon energy →
Silicon energy →
XBL 912-6441


All data normalized to 90°
110 MeV $^3He^{2+}$ + Ca
2.9 C
Predicted
β2p ground
state
3
4
2
1
Counts
5
4
3
2
1
1
2
3
4
5
6
Two proton sum energy (MeV)

XBL 912-6440


3/2+ ~ 16.15
T = 5/2
39 22 Ti 17
t1/2= 28 ms
β+ ≈ 14%
3/2+ 8.82
T = 5/2
p
6.12
p
3/2+ 3.95
37 19 K 18
7/2− 0
39 21 Sc 18
0+ −0.60
38 20 Ca 18

XBL 912-6439