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Authors

Reiff, J.E.
Hotchkis, M.A.C.
Molt, D.M.

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J.E. Reiff, M.A.C. Hotchkis, D.M. Moltz,
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A FAST IN-BEAM RECOIL CATCHER WHEEL AND THE OBSERVATION OF BETA-DELAYED TWO-PROTON EMISSION FROM ^{31}Ar

J.E. Reiff, M.A.C. Hotchkis*, D.M. Moltz, T.F. Lang,
J.D. Robertson, and Joseph Cerny

*Department of Chemistry and the Nuclear Science Division,
Lawrence Berkeley Laboratory, University of California, Berkeley, California, 94720, U.S.A.*

August, 1988

A fast in-beam recoil catcher wheel has been constructed to perform particle spectroscopy on very proton-rich nuclei. The wheel speed can be varied to study nuclides whose half-lives range from 100 μs to ~200 ms. Known beta-delayed proton emissions from the A = 4n + 1, $T_z = -3/2$ nuclides ^{17}Ne, ^{21}Mg, and ^{25}Si as well as the beta-delayed two-proton decay from ^{22}Al ($t_{1/2} = 70$ ms) were measured to test the wheel. Subsequently, a beta-delayed two-proton branch from ^{31}Ar ($t_{1/2} = 15$ ms) was observed.

1. Introduction

Light, proton-rich nuclei far from the valley of beta stability, in general, have short half-lives (≤ 150 ms) and are produced in reactions with relatively small cross sections (~10 nb to 100 μb). As a result, exotic nuclei must often be detected in the presence of the primary beam and/or in the presence of more abundantly and simultaneously produced reaction products which lie closer to the valley of beta stability.

One traditional method for studying exotic nuclei is the helium-jet transport technique [1]. With this approach, an accelerator beam passes through a pressurized target chamber. Reaction products recoiling from the target are thermalized in helium and transported on the surface of, e.g., NaCl clusters (~0.1 μm in size) through a capillary to a low background collection and detection chamber. The transport efficiency of this system is typically on the order of 50%. Using this arrangement, the first cases of beta-delayed two-proton radioactivity were observed in the decays of the $T_z = -2$ nuclei ^{22}Al and ^{26}P [2]. Later, the first $T_z = -5/2$ nuclide, ^{35}Ca [3], was discovered using the same helium-jet system.

Despite its high transport efficiency, the helium-jet technique has two limitations. First, the minimum transport time of our helium-jet system [2] is 25 ms. This transport time makes it impossible to observe low yield nuclei whose half-lives are substantially below 10 ms. Second, noble gases do not adhere to the clusters in the helium thereby preventing the observation of their radioactive decays. It has thus become of interest to construct a new system which overcomes these limitations in order to continue our studies of light, proton-rich nuclei, since our long range goal is the observation of direct ground state proton and two-proton emitters whose half-lives range from 100 μs to 10 ms.

2. Alternatives to the helium-jet transport technique

Depending on the decay mechanism, the relative angle between the two protons in direct and beta-delayed two proton emission can vary from 0^o to 180^o. As such, it is imperative that the new system have the ability to detect particles in coincidence over a large angular range. Three general alternative methods were considered which attempt to be fast and chemically universal and, at the same time, cover a range of angles.

The first method, which is currently in use, is the annular gas detector system developed by Gillitzer *et al.* [4] for studying proton radioactivity in the tin region. This apparatus uses Bragg curve spectroscopy as its means of particle identification. A second available method is a pulsed-beam target counting system similar to that used by Cerny *et al.* [5] in detecting the proton radioactivity from ^{53m}Co. The third option is an in-beam rotating wheel which would collect recoil nuclei from the target on catcher foils located around the circumference of a wheel. All three of the systems are chemically universal and each meets the half-life requirements.

The annular gas detector system is the fastest of the three alternatives considered with the ability to measure activities down to 10 ns. The detector subtends a solid angle of 7% of 4π which is quite reasonable when looking for single particle emission; however, in order to measure two protons in coincidence, the detector would need to be split, thereby yielding a geometry of 3.5% of 4π for each side. Although the target counting system could measure activities down to 100 μs and coincidence events at either wide or narrow angles, the maximum solid angle that could be obtained for each telescope was only 2% of 4π . The rotating catcher wheel, which can also detect activities down to 100 μs, offers the best opportunity for detecting two coincident protons with a solid angle of approximately 19% of 4π per telescope.

3. The catcher wheel

An aluminum alloy wheel with twelve removable catcher foils around its circumference has been constructed and installed at an angle of 20^o with respect to the beam. This presents an effective catcher foil 2.9 times thicker than the material the emitted protons must traverse, maximizing the catching efficiency of the foils while minimizing the recoil range effect on particle resolution. The target ladder, which holds up to six targets, and the detector telescopes, which are placed to the side of the target ladder, are also inclined at 20°. The wheel, driven by an external, variable speed motor, can be rotated at speeds ranging from 20 to 5000 RPM. A schematic diagram of the experimental setup is shown in fig. 1.

The beam must be pulsed as the wheel rotates to prevent the irradiation of the spokes of the catcher foil frames. This pulsing is accomplished by placing electrostatic deflection plates on the injection line between the electron cyclotron resonance (ECR) ion source [6] and the 88-Inch Cyclotron at the Lawrence Berkeley Laboratory. Since the ECR extraction voltage is ~10 kV, the beam can be completely deflected before entering the accelerator by applying only 700 volts to one plate while the other remains at ground potential. Turning the voltage on or off requires ~2 μs. The wheel has twelve equally spaced slots permitting a lamp and photodiode to generate the signal for pulsing the beam. The beam-on time is set equal to the beam-off time because the distance between the beam and the detectors is such that the activated portion of the foils just reaches the detectors as the beam is turned off. The detector electronics must be disabled during the beam pulse to eliminate the observation of beam related events. The timing is typically set such that the beam comes on 100 μs after the electronics are disabled, and is deflected 200 μs before the counting period begins. To minimize the effects of radiation damage suffered by the detectors due to the intensity and proximity of the beam, the ion implanted detectors are cooled to -35° C with thermoelectric coolers or cold nitrogen.

4. Testing the wheel setup

In order to confirm that the wheel and pulsing system were working properly, we measured beta-delayed protons produced in a 110 MeV ^{3}He bombardment of a 2.0 mg/cm^2 natural magnesium target. The beta-delayed proton spectrum obtained from this reaction is shown in fig. 2. The most prominent peaks belong to the $A = 4n + 1$, $T_z = -3/2$ nuclei ^{17}Ne ($t_{1/2} = 109$ ms), ^{21}Mg ($t_{1/2} = 120$ ms), and ^{25}Si ($t_{1/2} = 220$ ms). For these tests 500 μg/cm^2 aluminum catcher foils were installed around the wheel and the wheel speed was set at 20 RPM, corresponding to a complete pulsing period of 250 ms (125 ms beam on, 125 ms beam off). Two, two-element solid state detector telescopes each consisting of a 20 μm ΔE detector and a 500 μm E detector were placed above and below the wheel. The observed peak width at half the height (FWHM) of 140 keV is due primarily to the 500 μg/cm^2 catcher foils. After the 125 ms transit time to the telescopes, 55% of the ^{17}Ne had decayed, 51% of the ^{21}Mg had decayed, and 33% of the ^{25}Si had decayed. Although a substantial fraction of the activity had disintegrated before the counters were turned on, the relatively large solid angle of the detector system enhanced the observation rate.

5. The search for the beta-delayed two-proton decay of ^{31}Ar

As a prelude to the search for the beta-delayed two-proton decay of ^{31}Ar, a 2.0 mg/cm^2 natural magnesium target was bombarded with 135 MeV ^{3}He^{2+} ions to look for the beta-delayed two-proton emission from ^{22}Al ($t_{1/2}$ = 70 ms). The experimental setup consisted of using 500 µg/cm^2 aluminum catcher foils and a wheel speed of 50 RPM. This corresponded to a pulsing period of 100 ms (50 ms beam on, 50 ms beam off). The two, two-element telescopes, each comprised of a 20 µm ΔE detector and a 300 µm E detector, were set up as depicted in fig. 1. These telescopes were sensitive to proton pairs whose relative angles ranged from 40° to 180°.

Figure 3(a) shows the beta-delayed two-proton spectrum obtained from the decay of ^{22}Al; the coincidence requirement for the two protons was 20 ns. Two distinct groups are evident in this spectrum: a peak at 4.2 MeV and a peak at 5.9 MeV. The FWHM of these peaks are 220 keV and 340 keV, respectively. These results, which are consistent with previous observations [2], can be shown to correspond to two, two-proton transitions which proceed to the first excited and ground states of ^{20}Ne, following the beta decay of ^{22}Al to its T = 2 isobaric analog state in ^{22}Mg. The center-of-mass energies for these transitions are 4.48 MeV and 6.12 MeV [2].

The observed isotropy of the beta-delayed two-protons from ^{22}Al [7] indicates a predominantly sequential decay mechanism. A drawback of any system designed to detect two sequentially emitted particles over a broad angular range is the kinematic effects on the sum of the laboratory energies of the coincident particles. As described in ref. 2, the observed sum of the energies of two sequentially emitted particles is dependent upon the angle between them; the larger the angle, the higher the observed energy. In fig. 3(a), virtually all of the observed peak widths are due to this kinematic broadening.

Upon successfully observing the beta-delayed two-proton decay of ^{22}Al, the search for a similar decay branch of ^{31}Ar was initiated. The decay of ^{31}Ar is unobservable with the helium-jet transport system because it is a noble gas. Its half-life has very recently been measured as 15 ± 3 ms [8] from its beta-delayed proton decay branch. A 2.5 mg/cm^2 ZnS target on a 1.5 mg/cm^2 aluminum backing was bombarded with 135 MeV ^{3}He ions to produce ^{31}Ar via the ^{32}S(^{3}He, 4n)^{31}Ar reaction. 500 µg/cm^2 aluminum catcher foils were used with a wheel speed of 130 RPM, corresponding to a 38 ms pulsing period (19 ms beam on, 19 ms beam off).

The two-proton sum spectrum obtained from this bombardment is shown in fig. 3(b). The known peaks from ^{22}Al and ^{26}P are indicated. At about 7.5 MeV there is a cluster of events which we assign to the beta-delayed two-proton decay of ^{31}Ar. This assignment is based on the close agreement with the predicted beta-delayed two-proton decay energy, the fact that ^{31}Ar has the highest available beta-delayed two-proton decay energy of any nuclide possibly formed in this reaction, including ^{22}Al, ^{26}P, ^{27}S, and ^{23}Si, and on the ratio of the number of events of ^{22}Al and ^{26}P to the number of events of ^{31}Ar.

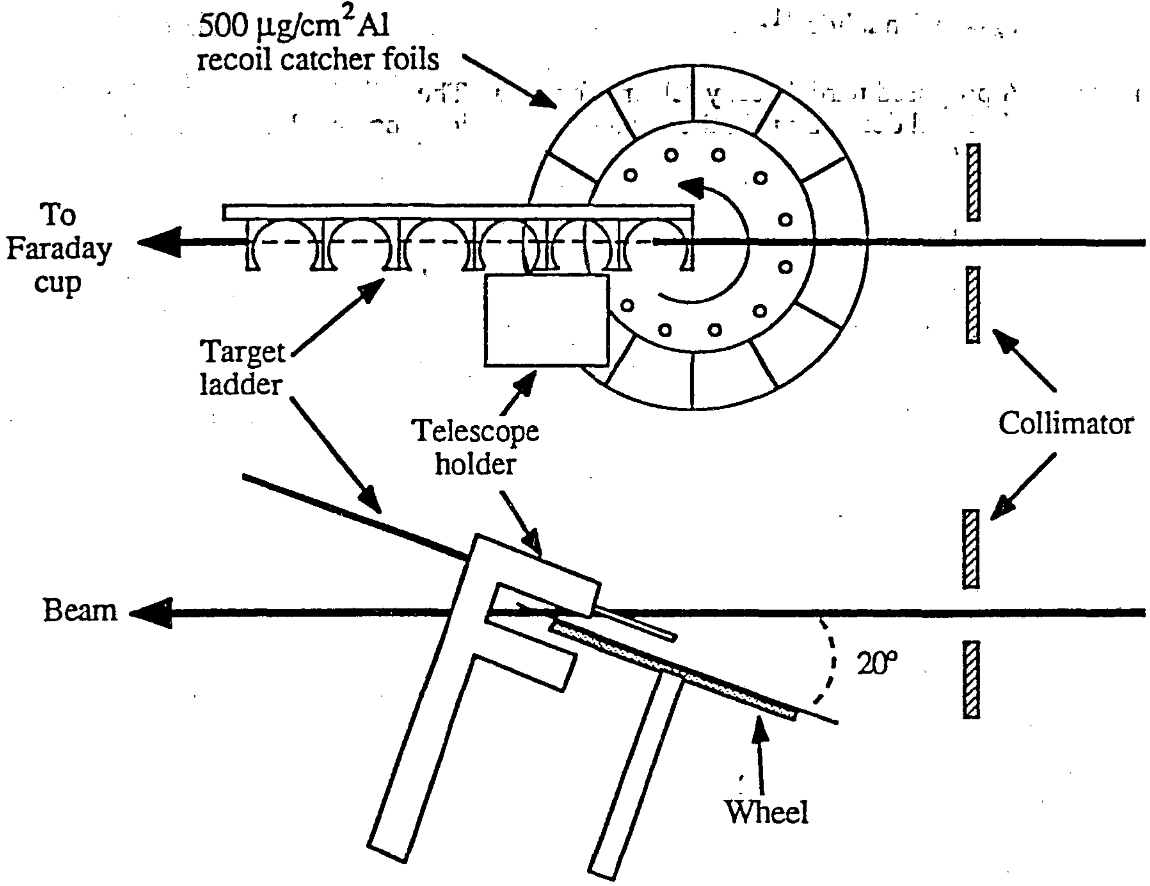
Using the Kelson-Garvey mass relation [9], the mass excess of ^{31}Ar has been deduced to be 11.65 ± .07 MeV; this gives a Q_{EC} for ^{31}Ar of 18.71 ± .10 MeV. Input masses for this calculation were taken from the 1986 Audi-Wapstra Mid-Stream Mass Evaluation [10]. The isobaric analog state in ^{31}Cl, which can decay by two-proton emission, has a calculated excitation energy of 12.49 ± .10 MeV. This was deduced by using a formula for Coulomb displacement energies derived from a fit to data [11]. Two protons emitted from the $T = 5/2$ isobaric analog state in ^{31}Cl to the ground state of ^{29}P are thus expected to have a sum center-of-mass energy of 7.81 ± .11 MeV and a laboratory energy of 7.6 MeV at our average angle of 110°. Our observed sum group at a laboratory energy of 7.0 - 7.7 MeV is consistent with the assignment of the two protons as arising from the beta-delayed two-proton decay of ^{31}Ar. Analogous calculations for ^{27}S and ^{23}Si yield beta-delayed two-proton energies in the center-of-mass of 6.59 ± .07 MeV and 5.86 ± .17 MeV, respectively. According to the statistical model fusion-evaporation code ALICE [12], ^{22}Al and ^{26}P have production cross sections 15 and 50 times higher than that of ^{31}Ar in this reaction. After correcting for the difference in half-lives, this is approximately the ratio that is seen in fig. 3(b). A proposed partial decay scheme for ^{31}Ar is shown in fig. 4.

6. Summary

We have constructed a fast in-beam recoil catcher wheel in order to observe the decays of very short lived nuclei near the proton drip line. This wheel permits us to detect the decays of nuclei whose half-lives are between 100 μs and ~200 ms. Its speed can be adjusted both to maximize the yield of the nuclide in question and to determine its half-life. With this approach, we have observed the known beta-delayed proton decays of several $T_z = -3/2$ nuclei and the known beta-delayed two-proton decays of the $T_z = -2$ nuclides ^{22}Al and ^{26}P. Furthermore, we have discovered a beta-delayed two-proton decay branch of the $T_z = -5/2$ nucleus ^{31}Ar.

Future experiments planned for the wheel include extending the $A = 4n + 1$, $T_z = -3/2$ series of known beta-delayed proton precursors through ^{69}Kr, searching for the ground state proton emissions from ^{65}As and ^{69}Br, and detecting the first case of ground state two-proton emission from the $T_z = -5/2$ nuclide ^{39}Ti.

Rapidly-Rotating Recoil Catcher Wheel



XBL 887-2661

Fig. 1

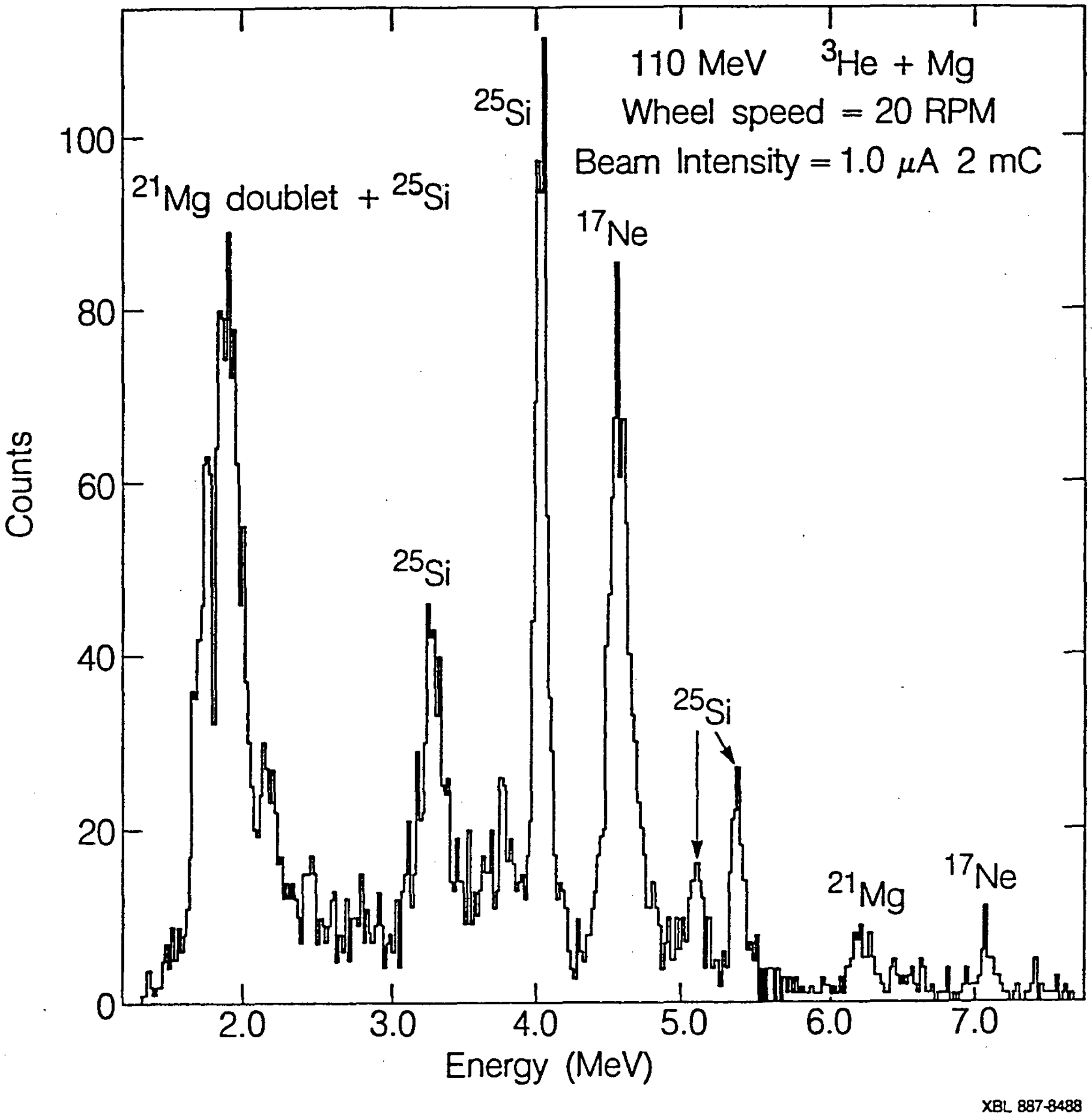

110 MeV ^{3}He + Mg
Wheel speed = 20 RPM
Beam Intensity = 1.0 μA 2 mC
^{21}Mg doublet + ^{25}Si
^{25}Si
^{17}Ne
^{25}Si
^{25}Si
^{21}Mg
^{17}Ne
Counts
0
20
40
60
80
100
2.0
3.0
4.0
5.0
6.0
7.0
Energy (MeV)
XBL 887-8488

Fig. 2

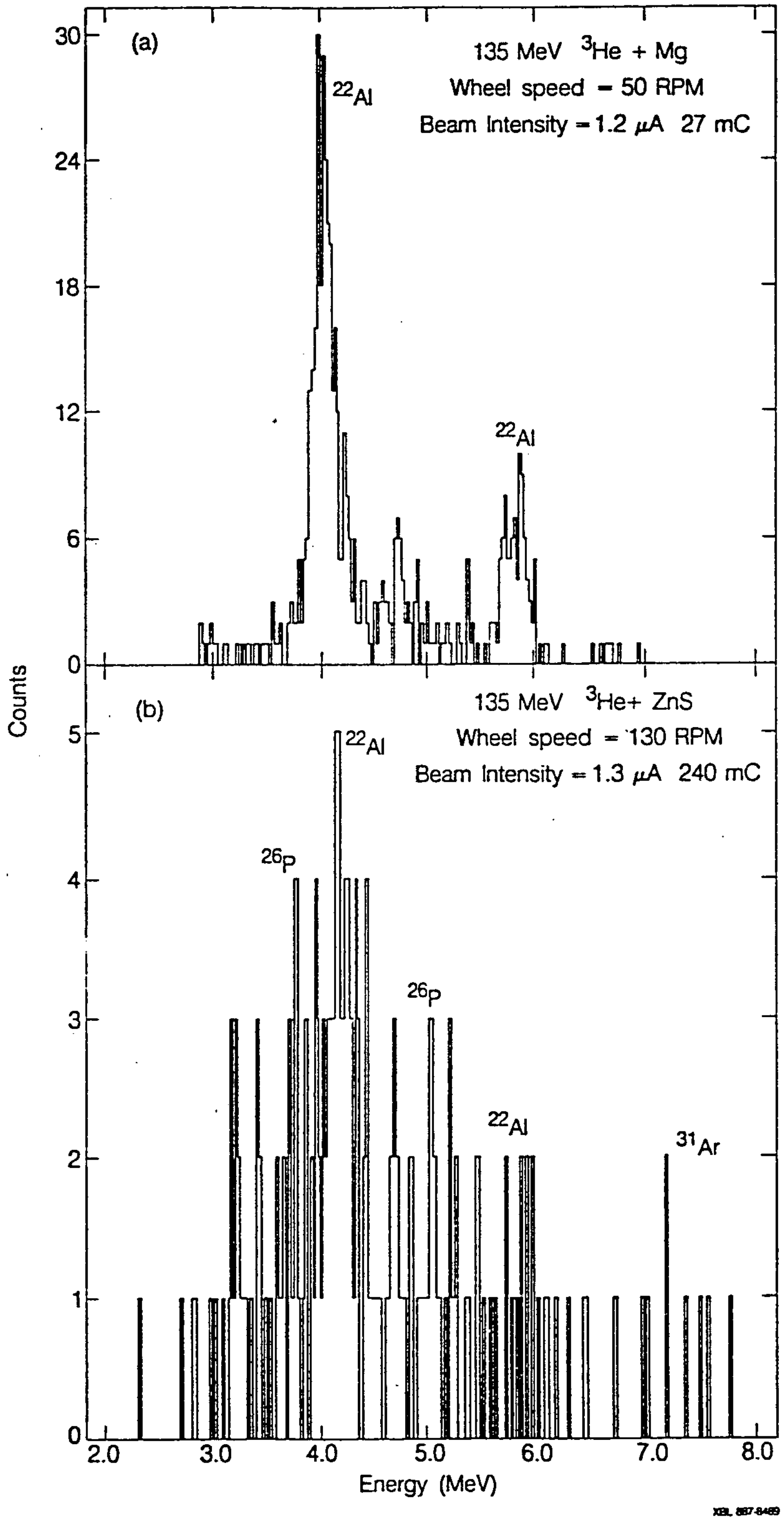

(a)
135 MeV 3He + Mg
Wheel speed = 50 RPM
Beam Intensity = 1.2 μA 27 mC
22Al
22Al
30
24
18
12
6
0
Counts
(b)
135 MeV 3He+ ZnS
Wheel speed = 130 RPM
Beam Intensity = 1.3 μA 240 mC
22Al
26P
26P
22Al
31Ar
5
4
3
2
1
0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Energy (MeV)
XBL 887-8469

Fig. 3

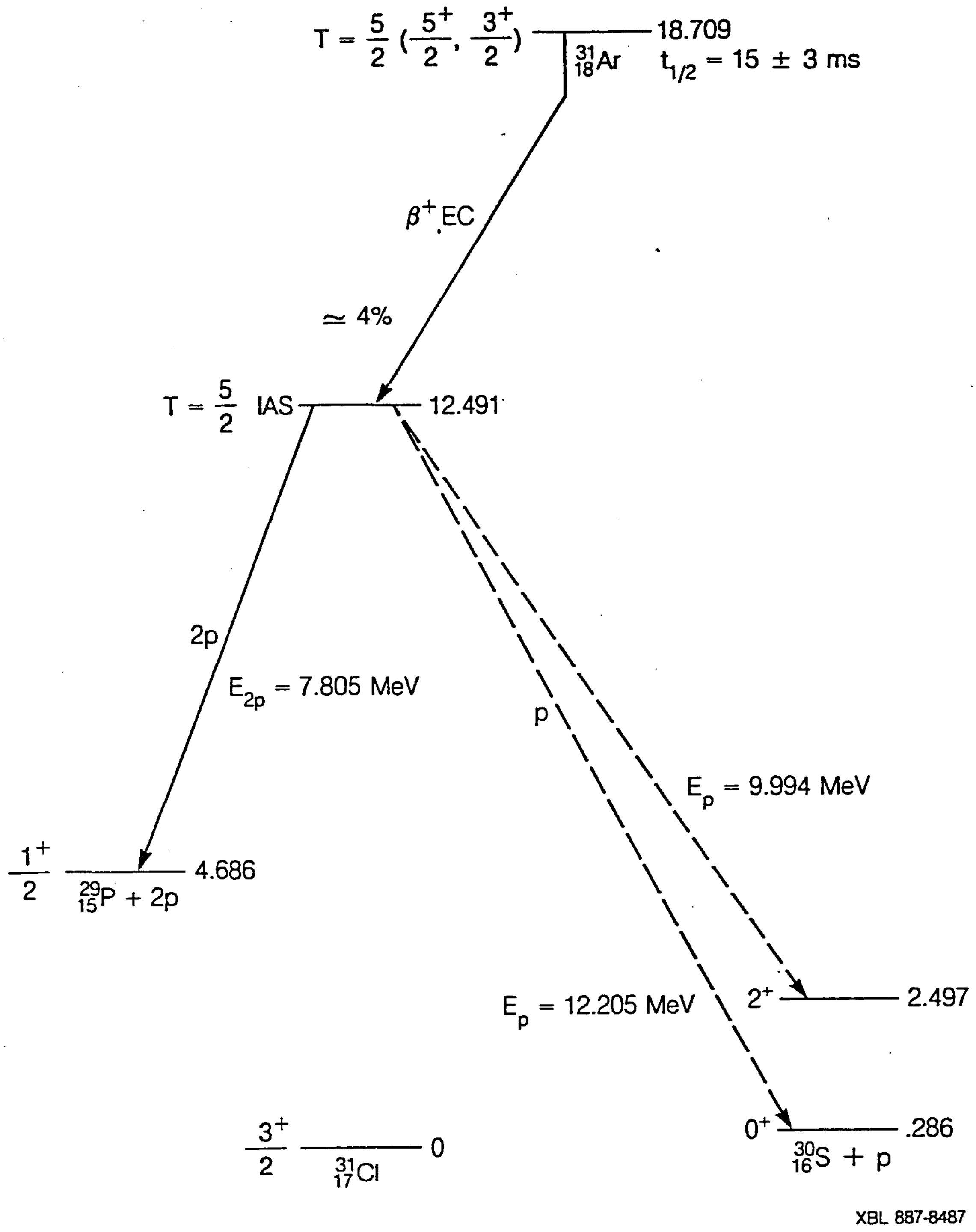

T = 5/2 (5+/2, 3+/2)
18.709
$^{31}_{18}$Ar
$t_{1/2}$ = 15 ± 3 ms
β+ EC
≃ 4%
T = 5/2 IAS
12.491
2p
E_{2p} = 7.805 MeV
p
E_p = 9.994 MeV
1+/2
4.686
$^{29}_{15}$P + 2p
2+
2.497
E_p = 12.205 MeV
0+
.286
$^{30}_{16}$S + p
3+/2
0
$^{31}_{17}$Cl
XBL 887-8487

Fig. 4

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720