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# Development of Low-Energy Proton Detector Telescopes

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# Development of Low-Energy Proton Detector Telescopes

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## Abstract

Detector telescopes capable of observing and identifying low-energy protons with energies down to 250 keV in a high radiation environment have been developed. These telescopes employ either one or two gas $\Delta E$ detectors followed by a silicon E detector and have been utilized in various beta-delayed proton and beta-delayed two-proton measurements.

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## 1. Introduction

The study of nuclei far from beta stability has long been advanced by the development of new observational techniques. Sometimes these techniques include detectors specifically designed for a particular decay mode. Beta-delayed particle emission experiments led to the development of thin wafer silicon detectors suitable for use as differential energy counters in a ΔE-E silicon telescope. This differential energy loss can be combined with the E signal to produce a particle identification (PI) spectrum based upon the empirical relationship:

$$PI = (\Delta E+E)^{1.73} - E^{1.73}$$

Studies of beta-delayed proton emission in the A=4n+1, $T_z = -3/2$ series of nuclides {1} have been primarily accomplished by utililizing this type of detector and identification technique. A typical delayed proton spectrum from one of these emitters, $^{25}$Si, is shown in fig. 1 ( from reference {2} ). This $^{25}$Si spectrum collected with a 10 μm ΔE and a 250 μm E telescope has a typical energy range of 0.7 to 5.4 MeV for identified protons.

The low energy limit shown in Fig. 1 represents a best case scenario - a thin silicon ΔE with a very small active area in an arrangement which still yields a reasonable solid angle (~ 2% of 4 π ). If the area of the thin silicon detector increases, the capacitance also increases thereby significantly decreasing the resolution. Additionally, dependent upon the solid angle and ΔE thickness, the effective efficiency does not reach the full value for some initial energy range; this effect is caused by the varying thickness with particle incidence angle.

For measuring protons below the lowest typical cut-off energy of ~700 keV, other techniques were used. Figure 2 shows the low-energy proton spectrum ( from ref. {3} ) arising from $^{25}$Si beta-delayed proton decay. This spectrum was obtained by utilizing a 14 μm silicon detector as an E detector followed by a thicker silicon detector as a reject detector, thereby eliminating almost all beta particles. Peaks in such spectra are identified on a peak-by-peak basis by observing the energy shift with and without a thin degrader foil. Protons and alphas can therefore be distinguished only on a peak-by-peak basis. Since many interesting experiments near the proton drip line involve searching for low-energy proton emitters with low production cross-sections, this technique proves wholly inadequate. If such studies were to continue, it was imperative to develop a detector technique which could identify low-energy protons on an event-by-event basis.

## 2. Gas Detectors

At the time we intended to pursue the development of low-energy proton telescopes, epitaxially grown thin silicon counters were just becoming available. However, it was decided that the much larger capacitances associated with these counters would make them unacceptable as ΔE detectors. The only logical alternative was a gas based system for the first detector. Gas counters can be operated in three normal modes: ionization, proportional and avalanche. There exist many examples of all three types, but because particle identification was the most important function, the proportional mode was the only choice.

Figure 3 depicts the typical configuration of a silicon-backed proportional gas counter used primarily for particle identification. Particle trajectories are in the Z- direction. Since the signal is generated via charge collection at the anode, this process can take significantly long times of from 5 to 20 μs. Additionally, good particle identification can only be obtained with the use of relatively large gas pressures of 100-1000 Torr. This type of detector works very well for the identification of heavy-ion fragmentation reaction products ( see ref. {4} for example ) because they have sufficiently high energy ( > 5 MeV/nucleon ) to traverse the entire gas volume. By using the higher gas pressures, one obtains a strongly definitive proportional signal which has little recombination ( signal decrease ) or electron knockout ( signal increase ). This last feature is highly desirable in a gas counter, but the low-energy threshold for such a high pressure detector ( including the appropriately thick window ) would be unacceptably high. Additionally, the long charge collection times associated with the perpendicular ( to the particle direction ) electric field makes this type of gas detector incompatible with silicon detectors, even if the gas pressure is significantly reduced to ~10 Torr.

## 3. Low-Energy Proton Detectors

The basic concept for our design of low-energy gas ΔE- silicon E proton telescopes was the utilization in the ΔE of an electric field collinear with the particle trajectory. A schematic diagram of this detector is shown in fig. 4. In this telescope the active gas region was clearly defined by two ground planes surrounding the anode (held at positive high voltage) from which the signal was processed in a specially designed AC coupled preamplifier with a high-voltage sparkdown protection network {5}. Although, in principle, the silicon surface could be used as a ground plane, it was decided that avalanches could be generated (instead of the desired proportional gas signal) that would be dependent upon the voltage applied to the silicon detector. The ground grids as shown in fig. 4 consist of parallel 10 μm gold coated tungsten wires with a 1 mm spacing. Initially, a similar grid was utilized for the high voltage application, but for all gas types studied, a thin metal foil was found to give much better charge collection. Nickel was chosen for this electrode material because of the commercial availability {6} of foils down to ~50 $\mu g/cm^2$. Although several thicknesses of foils were tried, all detectors finally used ~ 100 $\mu g/cm^2$ Ni foils. These thin foils are manufactured on a thin Cu backing. Construction of all high voltage foils was accomplished by first attaching the Ni side of the foil to copper clad PC board with a non-shrinking slow-cure epoxy before etching off the copper with a solution of ammonium trichloroacetate in a concentrated aqueous ammonia bath. The etching process can be readily observed because of the formation of the dark blue $Cu^{+2} (NH_3)_4 \cdot 2H_2O$ complex. (Note that the PC board Cu is protected by the epoxy layer. ) It is also important to note that these foils are extremely delicate and can easily by broken by the surface tension of the solution or very small air currents. This inherent delicacy, however, is offset by the dramatic gain increase afforded by the more uniform electric field.

The gas detector depicted in fig. 4 was tested with several gases. Many pressures and voltages were utilized, but each gas had a characteristic pulse shape and maximum total integrated charge collected. Figure 5 presents the pulse shapes typical of several gases used in these gas counters. These pulses were uniform in the 10-30 Torr range tested ( only the applied voltage needed to be varied. ) All of the results shown in fig. 5 are for 1 μs amplifier shaping times. The small pulse [a] in fig. 5 corresponds to signals generated with methane ( $CH_4$ or 90% Ar, 10%. $CH_4$). The large pulse [b] with the long tail is typical for hydrocarbons such as propane or isobutane. Use of 4-5 μs shaping times makes this peak look more like the typical Gaussian shown for the third gas [c] - tetrafluoromethane ( $CF_4$ - also known by the trade name Freon-14. ) Since we were interested in a system capable of handling count rates of ~100 kHz, use of the shorter shaping times was very important. Based primarily upon this criterion, we have subsequently only utilized $CF_4$ - it is non-flammable and non-toxic thus requiring no special handling procedures and it can operate at temperatures down to -40° C ( isobutane just condenses at this temperature. ) Low operating temperatures in the -10° - -40° C range are often necessary to permit the operation of neutron damaged silicon detectors, a common occurence with the many light ion beams we employ at the 88-Inch Cyclotron.

The telescope depicted in fig. 4 was tested with alphas, protons, and beta particles. Alpha particle tests were performed with $^{241}$Am, $^{148}$Gd and milked $^{228}$Th alpha sources. Beta tests were performed with both positron sources made in cyclotron induced reactions and with a $^{207}$Bi electron source degraded to energies between 100-1000 keV. Proton tests were performed utilizing two proton sources. The first source was beta-delayed protons from $^{25}$Si ( $E_p = 380 - 5400$ keV ) {2,3}. The second source was the 12 MV tandem at Lawrence Livermore National Laboratory. Low-energy protons from the tandem were elastically scattered from a thin carbon foil at various angles. Changing the lowest proton energies for these tests was accomplished by varying the scattering angle.

Results from all of these tests can best be summarized by considering the two-dimensional plot of the gas signal versus silicon energy shown in fig. 6. This experiment observed products of the 40 MeV $^3He^{2+}$ + $^{nat}$ Mg reaction as transported by the helium-jet technique {7}. Betas ( negatrons or positrons ), protons and alphas are clearly seen as separate bands. Individual proton and alpha groups have a large gas energy spread due to both recombination and Landau tailing. This latter phenomenon also causes a small fraction of the betas to tail into any nominal proton gate in the approximate ratio of $1:10^4$. This ratio can be reduced by cutting into the true proton events. The electron source tests demonstrated nearly a 100% efficiency for detecting betas, making this a potential problem for any low-energy proton searches. The Rutherford scattering measurements proved that with sufficient gas gain, the detection efficiency is constant in the 250-6000 keV proton energy range. Figure 7 shows the one-dimensional energy spectrum (from the silicon E) projected from the proton band in fig. 6 and represents the most complete single measurement of $^{25}$Si beta-delayed protons {7}.

## 4. Next Generation Detectors

The gas $\Delta$E-Si E telescope depicted in fig. 4 is extremely useful for measurement of high yield beta-delayed proton emitters such as $^{25}$Si. The physical size of this telescope, however, precluded the use of several of these telescopes either to increase the available solid angle (from a typical value of 5% of $4\pi$) or to measure multiparticle coincidences such as is needed in studying beta-delayed two-proton emission {8}. In order to study very short-lived beta emitters ($t_{1/2} \leq 20$ ms) and to search for ground state one- and two-proton emission in light nuclei, we constructed a rapidly rotating wheel suitable for studying nuclides with half-lives down to 500 μs ( in some special cases, 100 μs ). More details can be found elsewhere {9}. We constructed two, mirror image six-fold gas $\Delta$E-Si E telescopes in an arrangement fit around the wheel near the target and beam. This setup was utilized in the unsuccessful search for ground state proton decay of $^{65}$As {10} in products of the $^{28}$Si + $^{40}$Ca reaction. However, tests during this measurement demonstrated that these gas $\Delta$E detectors could not operate in a very high radiation field such as that produced in high intensity light ion bombardments often used in the production of light proton rich nuclei.

Although the single gas $\Delta$E- Si E telescope does not work in very high radiation fields, it works very well for helium-jet and on-line mass separator studies. In these types of experiments, however, small proton decay branches can be masked by the intrusion of the beta background into the low-energy proton gates. This problem has been solved by designing a two gas ΔE, Si-E telescope which is depicted in fig. 8. The two ΔE detectors shown in fig. 8 have been designated as "filter" and "trigger" detectors. These designations are artificial with respect to the way they are used in data analysis. In general, a valid event is defined as a coincidence between the trigger ΔE detector and the silicon E detector. The filter ΔE detector is used as a gating condition during analysis. Since the Landau tailing is the predominant reason for the beta background in the low-energy proton gates and since this tailing is a random process, it was assumed that the addition of a second gas ΔE to make triple coincidences possible would dramatically reduce the number of beta background events. As stated previously, tests with a $^{207}$Bi conversion electron souce and the single gas counter telescope demonstrated a "beta contamination" level of ~ 1:$10^4$. Tests with the detector shown in fig. 8 have shown that this rate is <1:$10^6$ ( no events were observed with $10^7$ incident electrons. ) $10^7$ betas are typically recorded during a normal single shift of one of our experiments.

The actual construction of these telescopes was a complicated compromise between the nuclear physics goals and mechanical and fiscal realities for gas-based detector telescopes. Ideally, one would like a 4π detector with large granularity. Maintenance considerations for individual telescopes suggested a modular design. This modularity necessarily generated a system with a large mechanical overhead. Using reasonable dimensions for proximity to a collected source, one obtains a detector telescope which subtends ~4% of 4π solid angle. This solid angle is derived from a detection system with a 22.5° cone ( half-angle ). This 22.5° active cone required a mechanical package with a 45° cone ( half-angle ). Thus, the closest packing arrangement for individual segments is a cube of 5 telescopes ( one side must be left open for introduction of samples ). In principle, the increased solid angle coverage ( relative to a double telescope system with similar solid angles for each telescope ) would be X2.5 for singles and X10 for coincidences utilizing these five triples telescopes. The most important feature of this system of five gas ΔE-gas

$\Delta$E -Si E telescopes is the large increase in coincidence yield and confidence in the identification of observed protons.

To demonstrate the effectiveness of this new system, fig. 9 shows the two dimensional plots of the filter and trigger gas counter signal versus Si signal for products of the 40 MeV $^3$He$^{2+}$ + Mg reaction. Betas, beta-delayed protons from $^{25}$Si and beta-delayed alphas from $^{20}$Na are all clearly visible. A one-dimensional projection of the proton bands utilizing a two-dimensional gate only on the trigger detector still shows a significant beta background. This spectrum has significantly more beta contamination than that shown in fig. 7 This difference is due to the greater gas thickness in the single gas $\Delta$E based telescope ( reduces tailing) and to the incomplete electrical isolation of the two detectors by the common ground grid ( increases signal spread; this problem has been solved in the next detector design. ) Requiring the second coincidence with the filter detector yields a proton spectrum essentially devoid of any beta background. Even with the greater tailing in the trigger and filter detectors relative to that observed with the single gas detector, the double coincidence still reduces the beta contamination by several orders of magnitude. This cubic array of six triples telescopes was used in the successful observation of the beta-delayed two-proton decay of the $T_z$ = -5/2 nuclide, $^{39}$Ti {11}.

## 5. Conclusions and Future Directions

The construction of gas $\Delta$E based detector systems which are capable of observing protons down to ~250 keV for the single gas counter telescope (~300 keV for the double gas counter system ) has been presented. Despite the successes of these detectors in studies of $^{25}$Si {7}, $^{39}$Ti {11} and $^{65}$As {10}, there still exists several areas for improvement. The thermal cycling that occurs because of the necessary cooling of the silicon detectors to -20°C causes a significant failure rate in the thin nickel electrodes; it is important to reduce this failure rate, particularly in the two-gas $\Delta$E system. Although the two gas $\Delta$E counters are modular, they are extremely difficult to assemble because of the extraordinarily delicate nickel electrodes. Because there are several experiments such as the search for ground state two-proton emission which require the ability to observe very low-energy protons, it is desirable to reduce the lower proton threshold for the two gas ΔE counter to ~150keV. Many experiments can be done, however, with these single and double gas ΔE - Si E detector telescopes.

## Acknowledgements

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{5} N.A. Madden, LBL, private communication.

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## Figure Captions

Fig. 1. Beta-delayed protons from $^{25}$Si ( peaks 1-24 ) measured with a traditional silicon ΔE-E telescope. The lower threshold is ~ 0.7 MeV. See text.

Fig 2. Low-energy beta-delayed proton peaks measured as single events in a 14 μm Si detector. Events which passed through this detector were rejected by a second thick silicon detector. It is important to note that these are not identified as protons on an event-by-event basis. The low bombarding energy precludes the production of any low-energy beta-delayed alpha emitters. See text.

Fig 3. Schematic diagram of a gas ΔE-Si E telescope utilized for heavy ion detection. Particles are incident in the Z- direction.

Fig 4. Cross section of the single gas ΔE - Si E low-energy proton telescope.

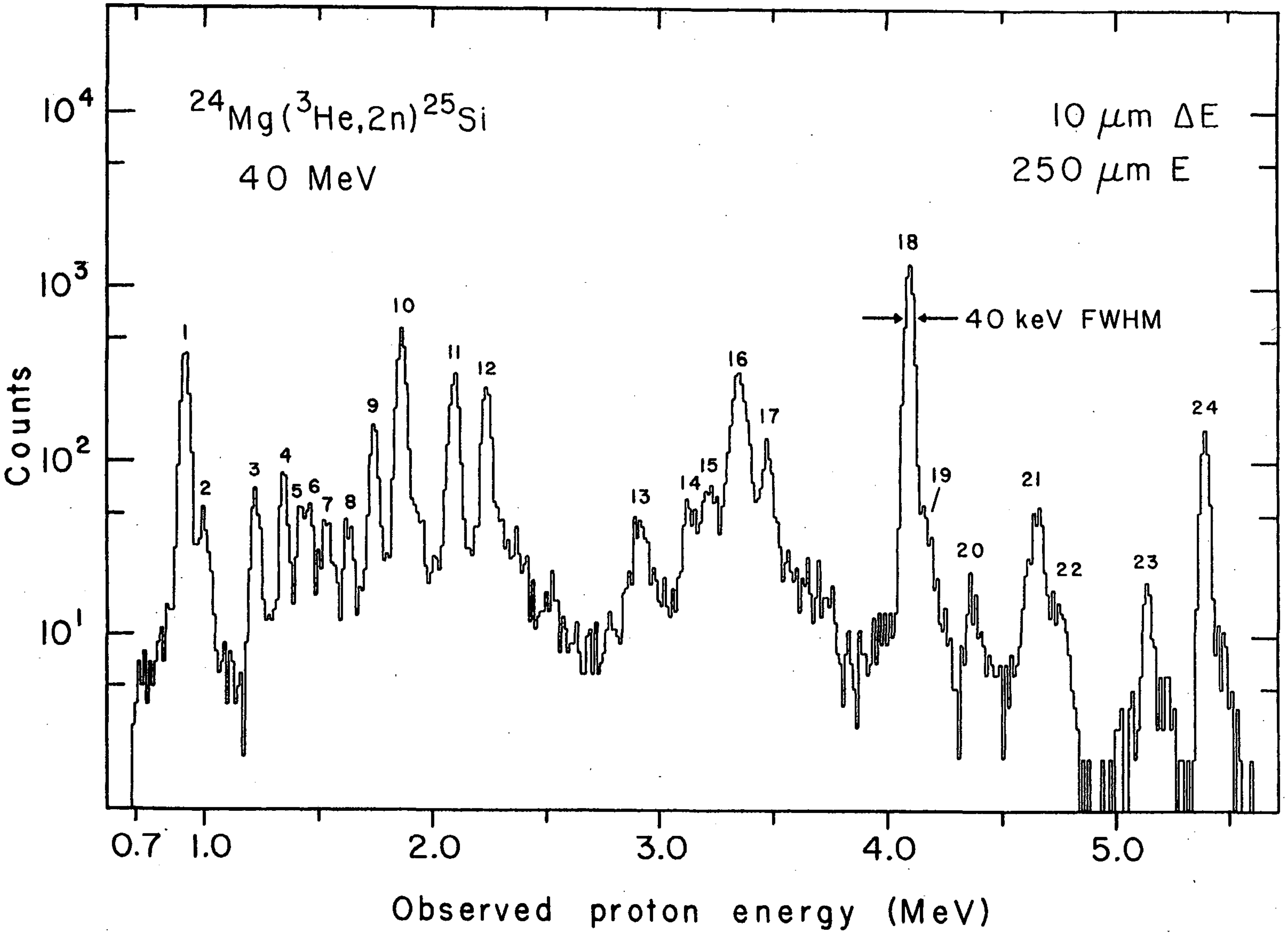
Fig 5. Plot of typical pulse shapes from the final shaping amplifier for a) methane, b) isobutane and c) tetrafluoromethane gases. See text.

Fig 6. Two-dimensional plot of the measured energy in the silicon E detector versus the differential energy gas signal. The beta, proton and alpha groups are clearly shown (alphas arise from $^{20}$Na and $^{8}$B beta-delayed alpha decay.) In order to accurately represent the normal color logarithmic scale in black and white, a small and uniform background subtraction has been utilized.

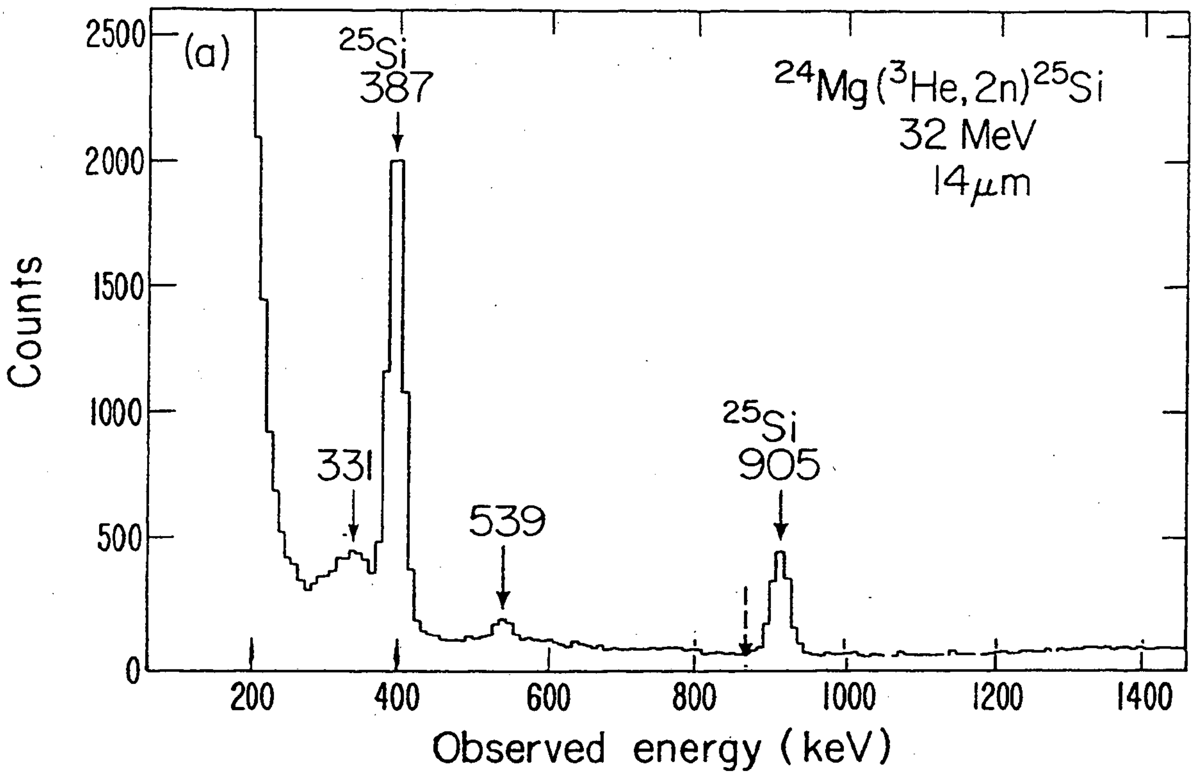
Fig 7. Beta-delayed proton energy spectrum from $^{25}$Si. See text.

Fig 8. Cross section of a gas ΔE-gas ΔE-Si E three element telescope.

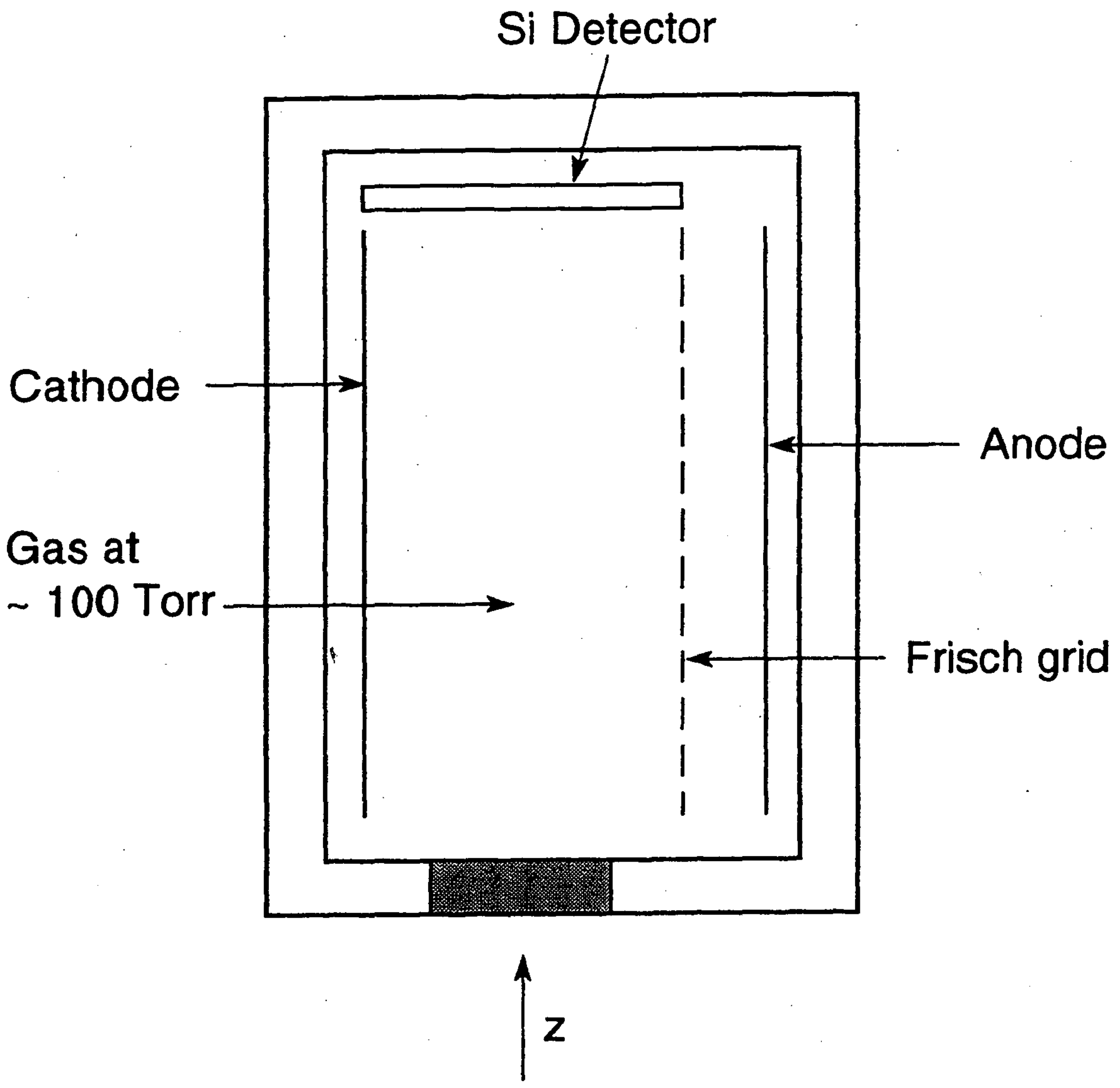
Fig 9. Delayed proton spectra from $^{25}$Si decay. a) Two-dimensional (trigger gas vs. silicon energy) spectrum showing the alpha, proton and beta bands. b) One-dimensional Si energy projection of the proton gate in a). c) Two-dimensional (filter gas vs. silicon energy) spectrum showing the same particle bands. c) is necessarily a subset of a). d) Spectrum b) with the addition of the proton gate in c). Energies are in keV.



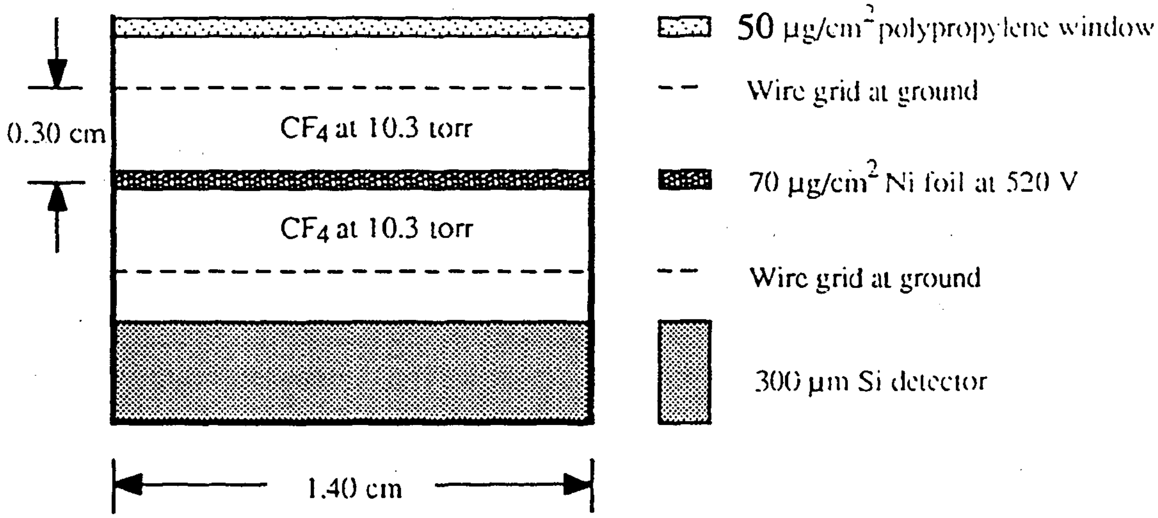
XBL 7311-6804


(a)
$^{25}$Si
387
331
539
$^{25}$Si
905
$^{24}$Mg($^3$He,2n)$^{25}$Si
32 MeV
14μm
Counts
0
500
1000
1500
2000
2500
200
400
600
800
1000
1200
1400
Observed energy (keV)

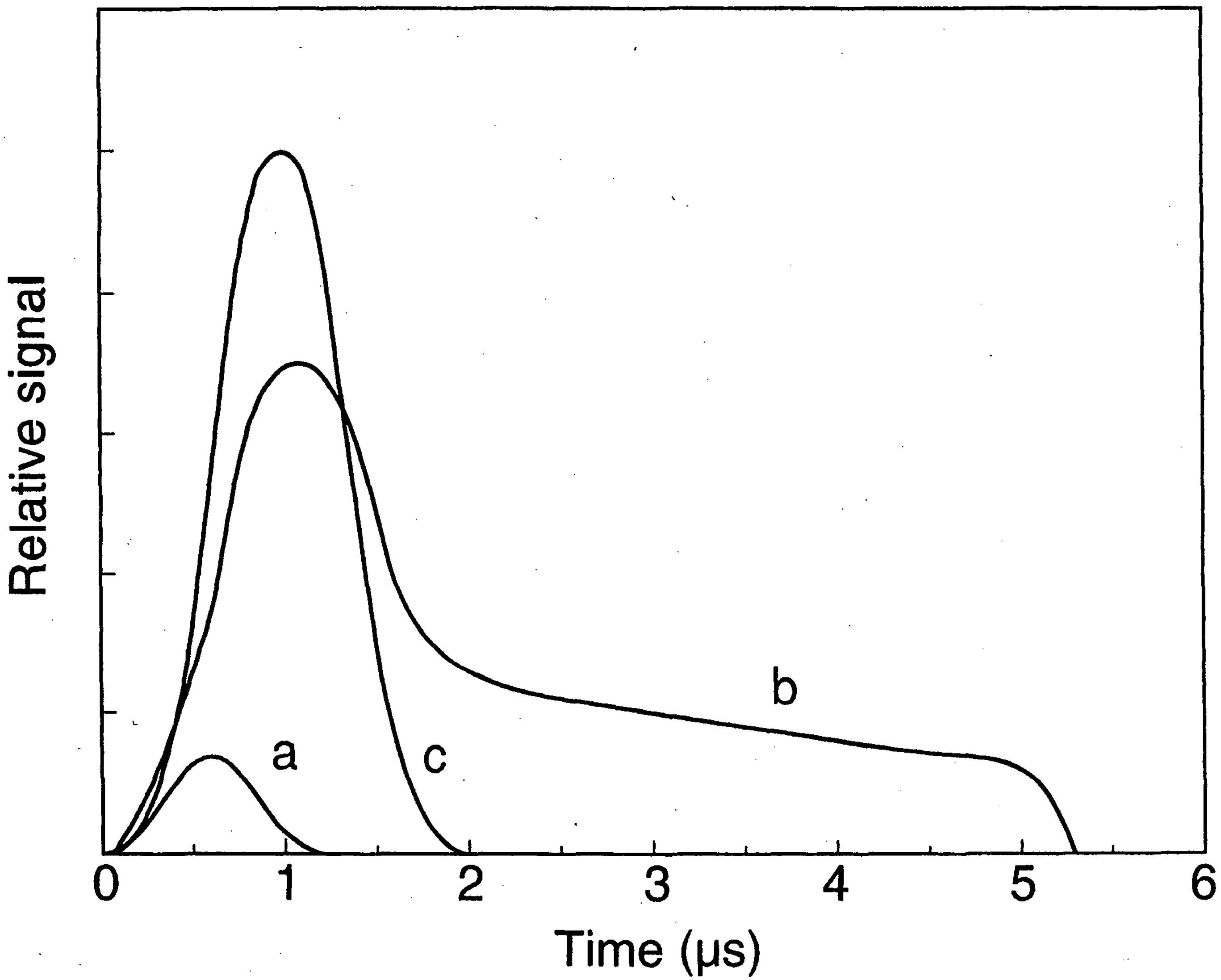
XBL 783-2405



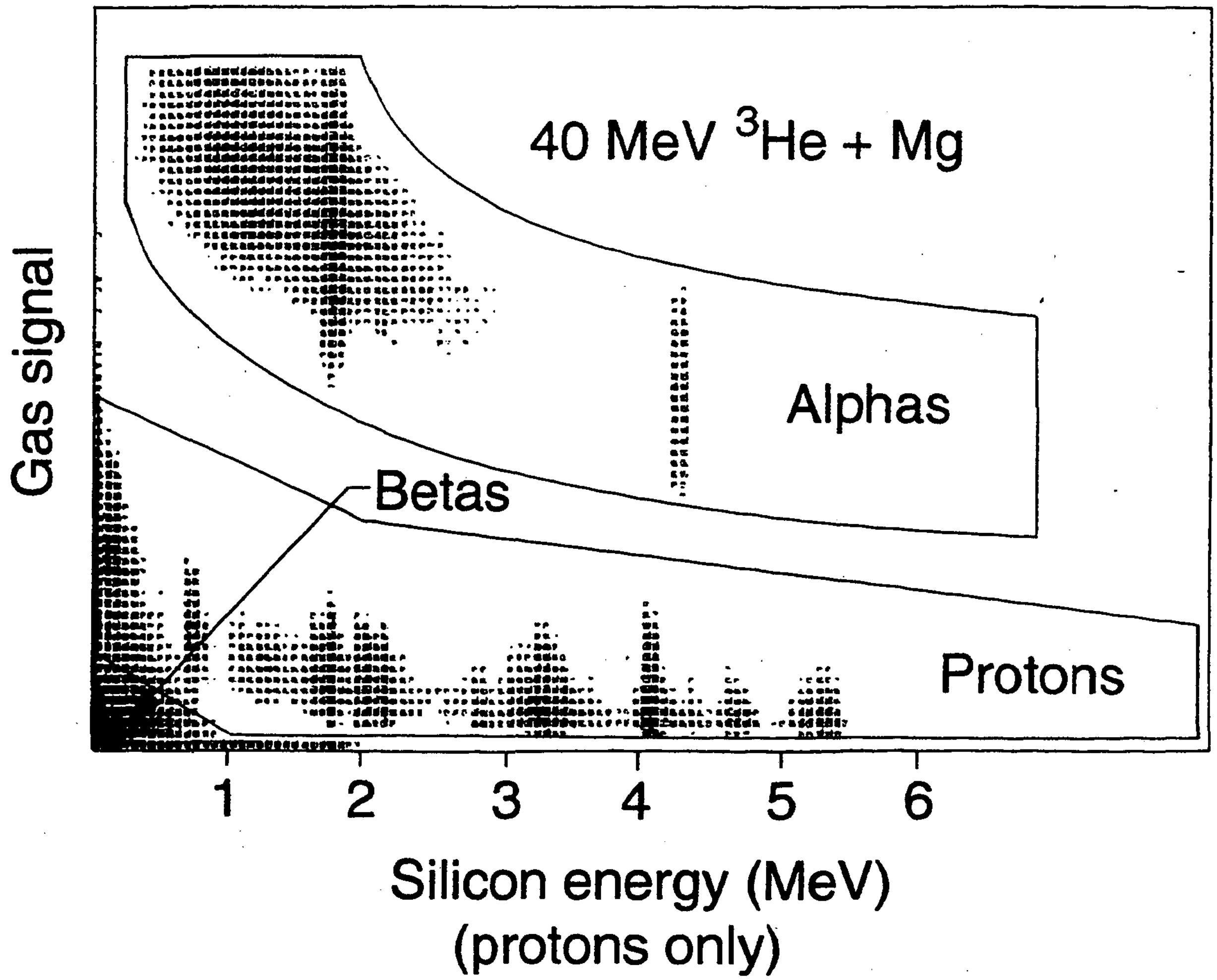
XBL 939-4836


0.30 cm
CF$_4$ at 10.3 torr
CF$_4$ at 10.3 torr
1.40 cm
50 μg/cm$^2$ polypropylene window
Wire grid at ground
70 μg/cm$^2$ Ni foil at 520 V
Wire grid at ground
300 μm Si detector

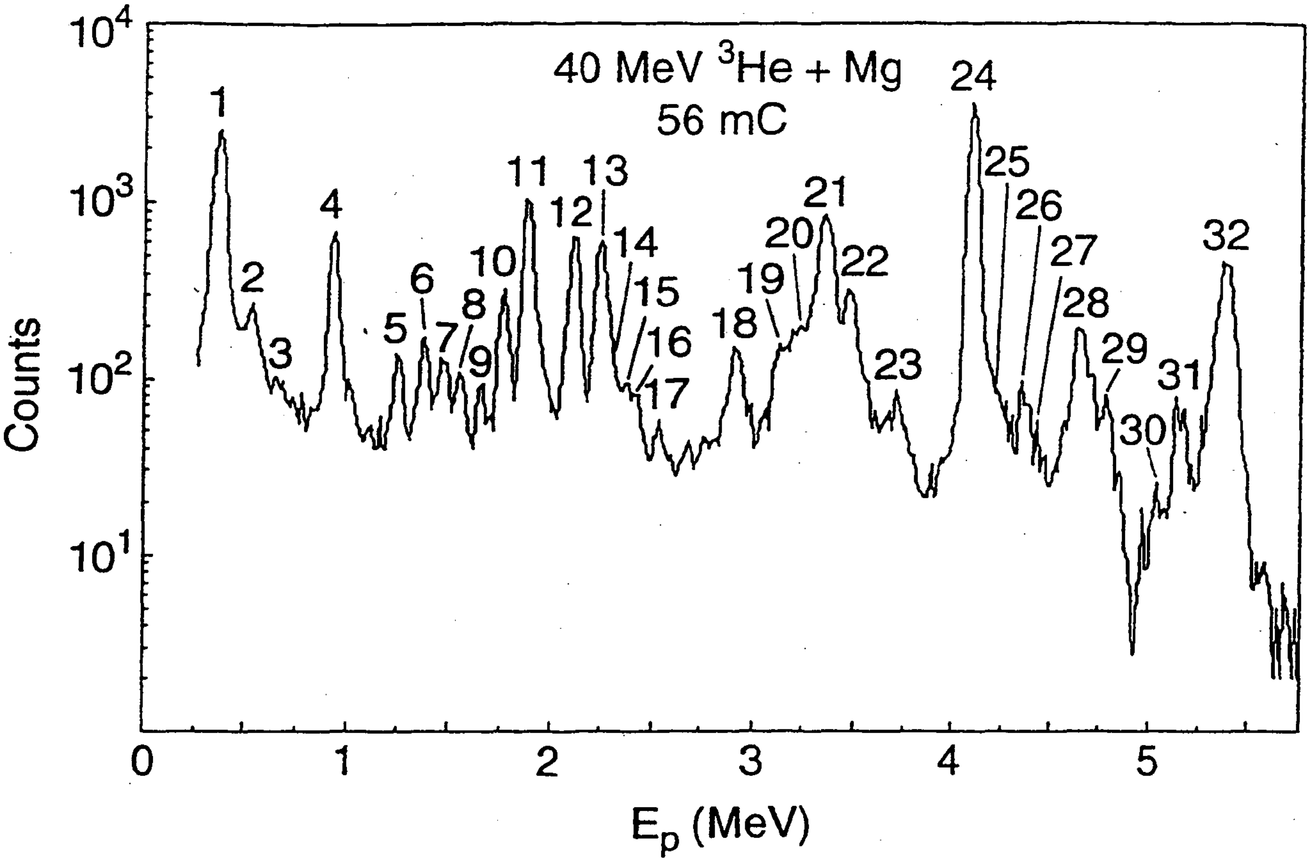
XBL 896-2191



XBL 939-4837


40 MeV $^3$He + Mg
Alphas
Betas
Protons
Gas signal
1
2
3
4
5
6
Silicon energy (MeV)
(protons only)

XBL 927-5751


40 MeV $^3$He + Mg
56 mC
Counts
$E_p$ (MeV)
$10^4$
$10^3$
$10^2$
$10^1$
0
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
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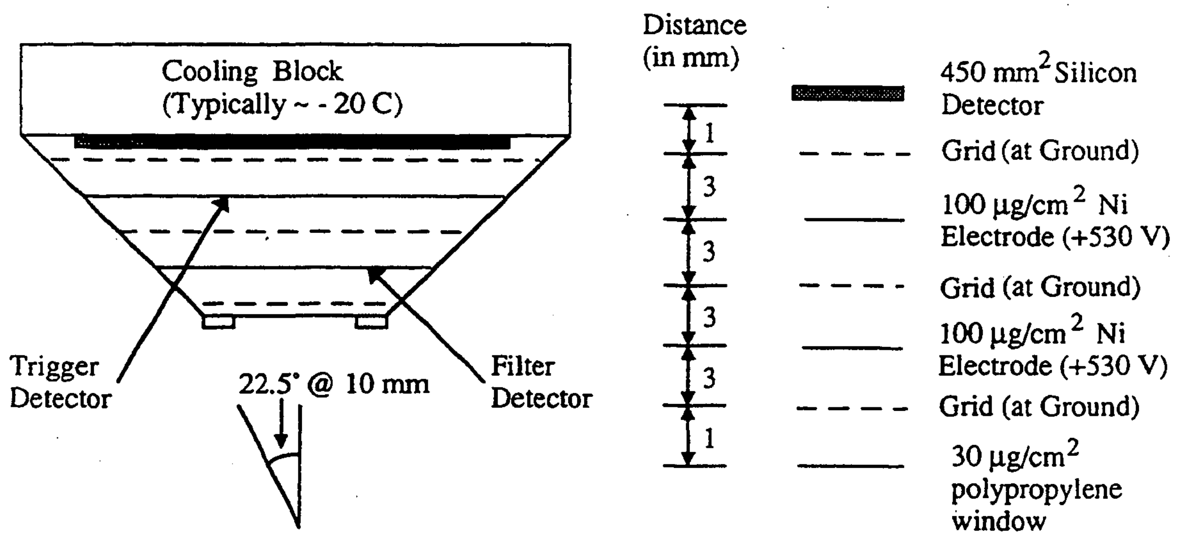
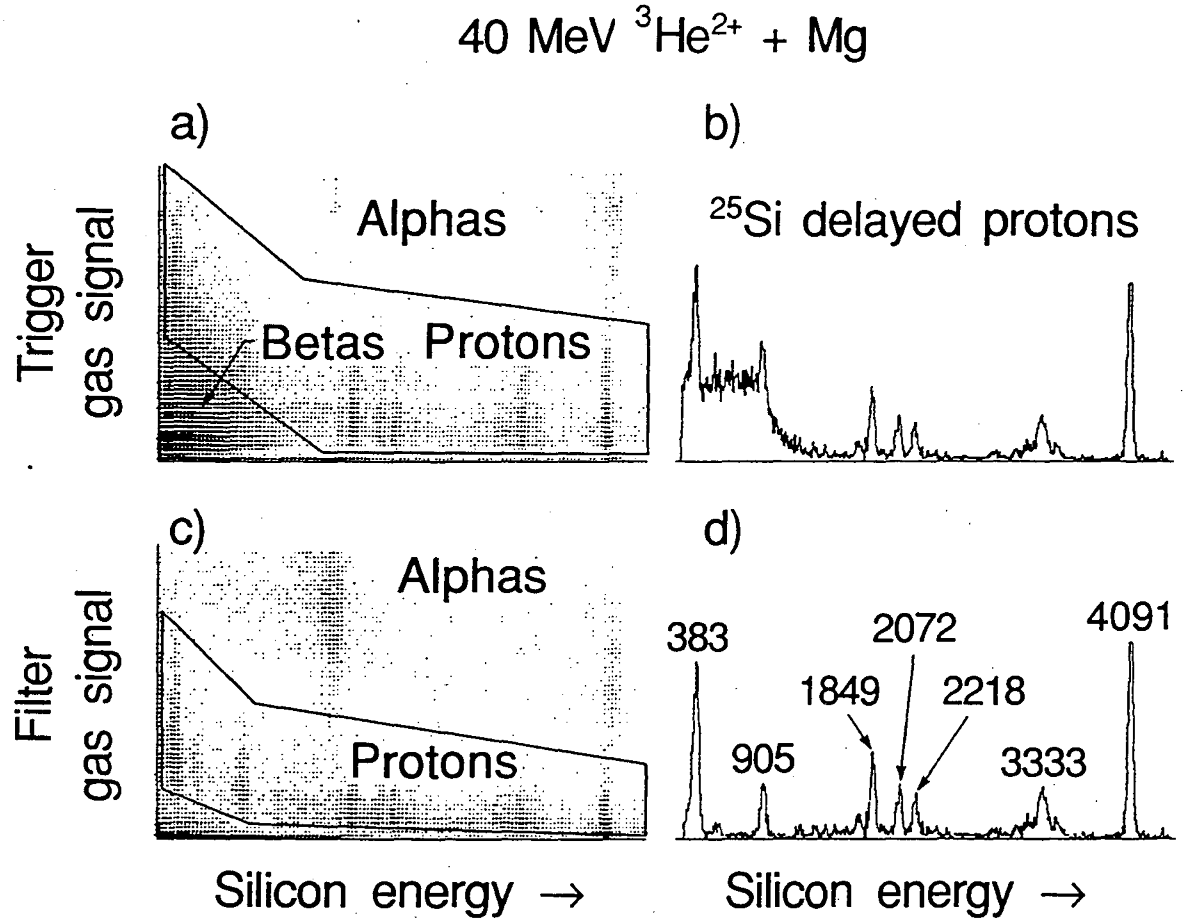
XBL 927-5753


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 $^{3}He^{2+}$ + Mg
a)
b)
Alphas
$^{25}$Si delayed protons
Trigger gas signal
Betas
Protons
c)
d)
Alphas
Filter gas signal
Protons
383
905
1849
2072
2218
3333
4091
Silicon energy →
Silicon energy →

XBL 912-6441

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