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DETECTION OF HIGH ENERGY PROTONS
BY THIN-WINDOW LITHIUM-DRIFTED GERMANIUM COUNTERS

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Lawrence Radiation Laboratory
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Summary

Recent developments in producing thin-window Li-drifted germanium detectors have enabled us to investigate their response to 29- and 40-MeV protons. The window is of negligible thickness for long-range particles, probably about 0.5 μ, although a precise measurement has not been made. Resolutions of 28 and 44 keV (FWHM) were obtained on 29- and 40-MeV protons, respectively. After subtracting nondetector contributions, mainly the energy spread in the cyclotron beam, the resolutions obtained approach the theoretical limit for a Ge detector.

A brief discussion of the response of a 0.5 cm thick, high-voltage Li-drifted silicon detector is also presented. Although extensive measurements have yet to be performed, these devices appear to be capable of a resolution approximately equal to that for Ge detectors for 29-MeV protons.

Introduction

Until very recently the use of Li-drifted silicon counters for the high-resolution measurement of charged particles having a range greater than ~3 mm was severely hampered by the inability to collect all the charge within a reasonable period of time. Although we have successfully used 0.5 cm silicon detectors, these thicker devices can stop only 29-MeV protons, and even a 1 cm silicon detector is good only to 44-MeV protons. Since the distance required to stop a particle of a given energy is nearly twice as great in Si than it is in Ge, detectors made of the latter have a considerable inherent advantage for detecting long-range particles. Consequently there has been considerable interest in evaluating the usefulness of Li-drifted germanium counters for detecting long-range charged particles.

Manufacture of Detector

The technique employed[1] is similar to that used for thin-window Li-drifted silicon detectors. This consists of drifting from a Li-diffused face until the drifted region reaches the lapped back face. When punch-through occurs the detector leakage current tends to increase markedly, and since the drift controller adjusts the temperature to maintain the leakage current constant, a sudden fall in temperature results. After etching the back face, gold is evaporated onto this face to form a p+ contact.

When this process was applied to devices whose entire volume was lithium compensated, very high leakage currents and noise were observed. This may be attributed to the presence of an n-type surface channel providing a conducting path between the Li-drifted face and the gold back. To avoid such a conducting path the detector structure was modified to provide a periphery of the original p-type germanium surrounding the gold back. Several possible structures meet these requirements, but that shown in Fig. 1 was found to be the most convenient to manufacture. Such a shape is also advantageous in applications near an accelerator because there is relatively little "excess" volume of lithium compensated germanium to absorb gammas. For the detectors used here the area ABCD (see Fig. 1) was 1 × 1 cm and the total thickness was 0.6 cm. AE is about 0.4 cm with a 45 degree flare-out 0.2 cm from the back face. By appropriate lapping one obtains an intrinsic region on the back face whose area is approximately equal to the area of the Li-diffused face.

Precise measurement of the effective window thickness on the back face is very difficult. A typical x-ray spectrum obtained on Am^{241} exhibited relative line intensities[2] which agree well with previously measured values, indicating an efficiency close to 100% in the energy range 10 to 60 keV. This implies that the dead layer must be very small. A more critical test of the window thickness is to use the detector for natural α-particles. Although the output pulse-height from 5.48-MeV α-particles from Am^{241} was very close to the calculated value, this is difficult to interpret in terms of window thickness since charge produced in a dead layer may diffuse into the intrinsic region. However, the behaviour of signal amplitude as a function of amplifier time-constant indicated that the window thickness could be only a very small fraction of the α-particle range—0.5 μ would be a good estimate.

Most of our proton data were obtained from a detector that was capable of giving a resolution of 1.4 keV on the 122 keV gamma from Co^{57} and 6.0 keV on the 1173 keV gamma from Co^{60}, when used with 700 V bias and a field-effect transistor preamplifier.

Experimental Method

The Berkeley 88-inch variable-energy cyclotron was used for these experiments.+ After energy analysis, the protons were scattered either from a gold or carbon foil—both of which were

+The fact that this machine can accelerate protons to nearly 60 MeV, which is beyond the range for total energy absorption in normal silicon detectors, has stimulated research interest in the work described in this paper.

about 200 $\mu g/cm^2$ thick. Typical beam intensities of 200 nA were used. To reduce the background radiation the beam was stopped about 4.5 m behind the target, and the counter was shielded by lead from the Faradey cup and beam pipe. All measurements were made at a fixed scattering angle of 19.7^o, and with the detector, preceded by a 2.5-mm diameter collimator, approximately 65 cm from the target. To protect the germanium detector from the relatively dirty scattering-chamber vacuum system, a 2.5 μ Havar window separated the counter holder from the system. The counter was operated at 77^oK in a vacuum of 10^{-6} mm Hg obtained by an ion pump. All non-electronic experimental details were the same during the brief test of the 0.5-cm silicon detector except that no window separated the silicon detector from the scattering chamber and it was operated at 173^oK.

A field-effect transistor preamplifier having a feedback capacitor of 3.3 pF and a feedback resistor of 100 MΩ was used for 29-MeV protons; for 40-MeV protons the feedback capacitor was increased to 6.8 pF to reduce the gain, and the feedback resistor was decreased to 30 MΩ to reduce the decay time-constant. A standard linear amplifier system[3] was used for all measurements. Electronic resolution, measured by feeding a pulser signal to the preamplifier to simulate a detector signal, was 9 and 14 keV when the system was adjusted for 29- and 40-MeV, respectively, with an amplifier shaping network that gave optinum counter resolution. Main amplifier noise limited the electronic resolution, but this could have been lowered if the electronic resolution had been an important component of the observed particle resolution. It should also be remembered that the energy resolution range of interest here corresponds to about 0.05 to 0.1% of the particle energy. This small percentage places very stringent requirements on amplifier gain stability.

Figure 2 shows a typical energy spectrum of 29-MeV protons scattered off Au; similar spectra were obtained when the 40-MeV proton beam was incident on Au. Pulser signals were fed in simultaneously with signals from the scattered protons. Calibration of the system in terms of keV per channel was done in two different ways, both of which gave the same result.

1. By feeding in three pulser signals of known dial settings the pulser equivalent of the peak corresponding to elastically scattered protons off Au can be obtained. Since the cyclotron beam energy is known, and zero on the pulser dial corresponds to zero voltage the desired calibration is accomplished.

2. Peaks corresponding to protons scattered off C^{12} and O^{16} were also observed (see Fig. 2) when the Au target was bombarded; these probably arose from contamination by pump oil. The difference in energy between protons scattered from Au and from C^{12} (and O^{16}) can be accurately calculated if the scattering angle is known, and the difference in channel number is obtained directly from the energy spectrum.

For 29-MeV protons we typically used 1.46 keV per channel, while the value for 40-MeV protons was 2.6 keV per channel.

Experimental Results and Discussion

The experimental program consisted of varying the bias, amplifier shaping network, and scanning the particle beam across the detector by changing the collimator position. Although this detector was typically operated at 700 V bias, a decrease to 500 V had very little effect, at least when a shaping network of 1.6 μsec delay line differentiator and 0.5 μsec R.C. integrator was used. (Insufficient time has been available to make an extremely extensive cross check of the three parameters mentioned above.) With neither 29- nor 40-MeV protons did this bias change make a discernible difference in the resolution. The apparent pulse height was 14 and 39 keV greater for 29- and 40-MeV protons, respectively, when the higher bias was used. This negligible difference (<0.1%) indicates that essentially all the charge was being collected; such a conclusion is substantiated by the fact that the apparent pulse height, compared with the pulser, did not vary by more than 0.5% over a wide range of shaping networks.

The "standard" amplifier shaping circuit consisted of a 1.6μsec delay line differentiator and a 0.5 μsec R.C. integrator. These settings provided nearly optimum resolution; use of either a 0.8 μsec delay line differentiator and a 0.5 μsec R.C. integrator, or a 5 μsec R.C. differentiator and integrator produced considerably worse energy resolution on particles. When a 0.2 μsec R.C. integrator was used nearly equal resolution was obtained with either a 1.6 or 0.8 μsec delay line differentiator, and this value was also close to the optimum, although the electronic resolution was slightly worse compared with results based on a 0.5 μsec R.C. integrator. The behavior of the electronic resolution as the networks were varied, compared with that of the particles, indicated that fluctuations in the charge collection time in the detector contributed to the resolution in the case of the 0.8 μsec delay line differentiator and 0.5 μsec R.C. integrator.

No variation in resolution was observed when different regions of the detector were scanned with 29-MeV protons. However, there may have been some difference when 40-MeV protons were used. Our data were insufficient to conclusively prove this point. In a preliminary experiment using a different germanium detector[4] a relatively broad satellite peak of slightly lower energy than the main peak was observed. This detector was rather poor—it would not operate at more than 400 V bias—and the observation of the satellite peak suggests that charge collection was not uniform through the whole sensitive volume. (This observation is possibly related to the fact that many germanium detectors exhibit low-energy tails on peaks corresponding to relatively high-energy gammas. Such a phenomenon is probably a function of the particular material used in the manufacturing process.) Unfortunately we could not move the collimator easily during this earlier experiment and therefore variations of the satellite peak as a function of different regions of the detector were not studied. However, we did observe that as the time allowed for charge collection was lengthened (0.8 to 5 μsec), the satellite peak moved toward the main peak, and the resolution became worse. The data obtained with a good detector exhibit no signs of a satellite peak. As can be seen in Fig. 3, the peaks in our spectra do exhibit slight low-energy tails, but this may arise from slit scattering since quite thick collimators are required to stop protons of the energies studied. No variations of collimator geometry (baffle collimator, etc.) have yet been made although such an investigation is obviously needed.

Optimum resolutions of 28 and 44 keV (FWHM) were obtained for 29- and 40-MeV protons, respectively. To determine the contribution from the germanium detector itself one must correct for the energy spread introduced by:

1. the spread of the cyclotron beam energy, assumed to be 0.07%, and thus 20 and 28 keV for the two energies used;
2. the thin Havar window, calculated[5] to cause a FWHM of 12.6 and 9.5 keV for 29- and 40-MeV protons, respectively;
3. electronic noise, determined by observation of many pulser peaks to be 9 and 14 keV for the system adjusted for 29 and 40 MeV, respectively.

(No correction for either the target thickness or the angular resolution contribution is necessary because both these contributions are less than 1 keV.) After subtracting these contributions the remaining spread is 12 keV for 29-MeV protons and 29 keV for 40-MeV protons.

Knowledge of the Fano factor F and the average energy-per-hole-electron pair ϵ permits determination of the theoretical limitation of energy resolution. Figure 3 presents this limitation as a function of the energy deposited in a germanium crystal for different nondetector contributions. This calculation was based on the experimental values of $F = 0.30$ and $\epsilon = 2.98$ eV[6]; such a Fano factor is in excellent agreement with theory.[7] For 29 and 40 MeV the theoretical limit is 12 and 14 keV, respectively. Although it is obvious that lack of knowledge about beam-energy spread prevents a precise comparison between our results and the theoretical limit, we are certainly approaching the limit. A beam whose energy spread is very small, and well-known, must be used to make a more precise comparison. Nevertheless, the use of Li-drifted germanium counters for the detection of long-range charged particles appears very promising.

Comparison with Thick Silicon Detectors

In many respects silicon detectors are more convenient to use than germanium detectors in nuclear reaction experiments. Silicon detectors do not require cooling to liquid nitrogen temperature, and can be used at room temperature for many experiments. Furthermore, they can be surface protected to permit handling more easily than germanium detectors, and can be used directly in typical evacuated scattering chambers with no special precautions.

Unfortunately, the mobility of carriers in silicon near room temperature is much smaller than that of carriers in germanium at 77°K. Consequently, a practical maximum thickness limitation of about 3 mm has existed for silicon detectors used in high resolution nuclear reaction studies. To increase the limiting thickness, the detectors can be operated at low temperatures; in our case, for example, it has proven convenient to equip a scattering chamber with a freon refrigerator loop which provides a temperature of -40°C. At this temperature a mobility increase of nearly a factor of two, compared with room temperature, is obtained. However, higher voltage operation, which implies improving the surface properties, is necessary if a substantial increase in silicon detector thickness is to be accomplished.

Recently a technique has been developed[8] for making high-voltage silicon detectors. Several 0.5 cm thick devices that operate up to 3000 V bias have been made but the one chosen for the proton experiment described in the following paragraph was used at 1200 V at a temperature of 173°K. The estimated maximum hole transit time under these circumstances is about 0.12 μsec.

Since a 0.5 cm thick silicon detector is able to stop 29-MeV protons, a direct comparison with the results obtained using a germanium detector can be made at that energy. The measured resolution for the silicon detector operated with optimum amplifier shaping networks was 35 keV. This compares with 28 keV for the germanium detector—a difference which is probably not significant unless confirmed by further experiments.

It appears that, within the range of energies which both can absorb, the performance of silicon and germanium detectors will be nearly equal—at least when the spread in beam energy is not less than 0.05 to 0.1%. However, a practical limit to the drift thickness of thin-window germanium and silicon detectors appears to be about 1 cm, and the greater stopping power of germanium seems likely to extend the range of particle energies which can be measured by a very significant amount. For example, a 1 cm thickness of germanium will stop 60-MeV protons while a similar thickness of silicon will stop only 44-MeV protons. Of course, the possibilities of allowing particles to enter detectors nonparallel to the electric field will probably extend the usefulness of both Si and Ge to considerably higher energies.

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Figure Captions

Fig. 1. Diagram of the thin-window germanium detector.

Fig. 2. Example of energy spectra recorded, showing 29-MeV protons, scattered off Au. The energy calibration is 1.46 keV per channel. Pulser signals were recorded simultaneously with signals from the scattered protons.

Fig. 3. Statistical limitations of the energy resolution as a function of the energy deposited in a germanium detector for different nondetector contributions. This calculation is based on $F = 0.30$ and $\epsilon = 2.98$ eV.

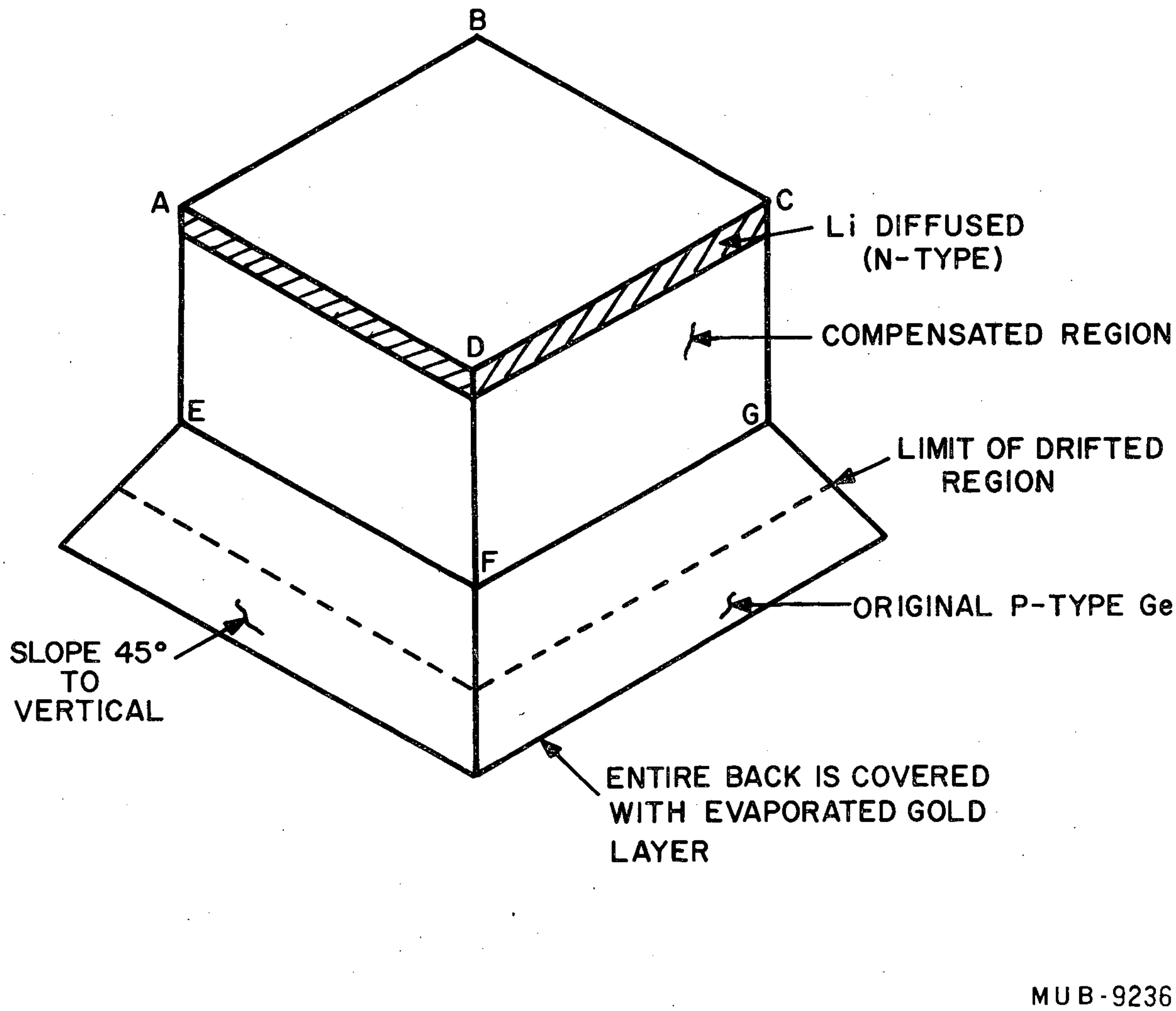
B
A
C
Li DIFFUSED
(N-TYPE)
COMPENSATED REGION
D
E
G
LIMIT OF DRIFTED
REGION
F
ORIGINAL P-TYPE Ge
SLOPE 45°
TO
VERTICAL
ENTIRE BACK IS COVERED
WITH EVAPORATED GOLD
LAYER
MUB-9236

Fig. 1

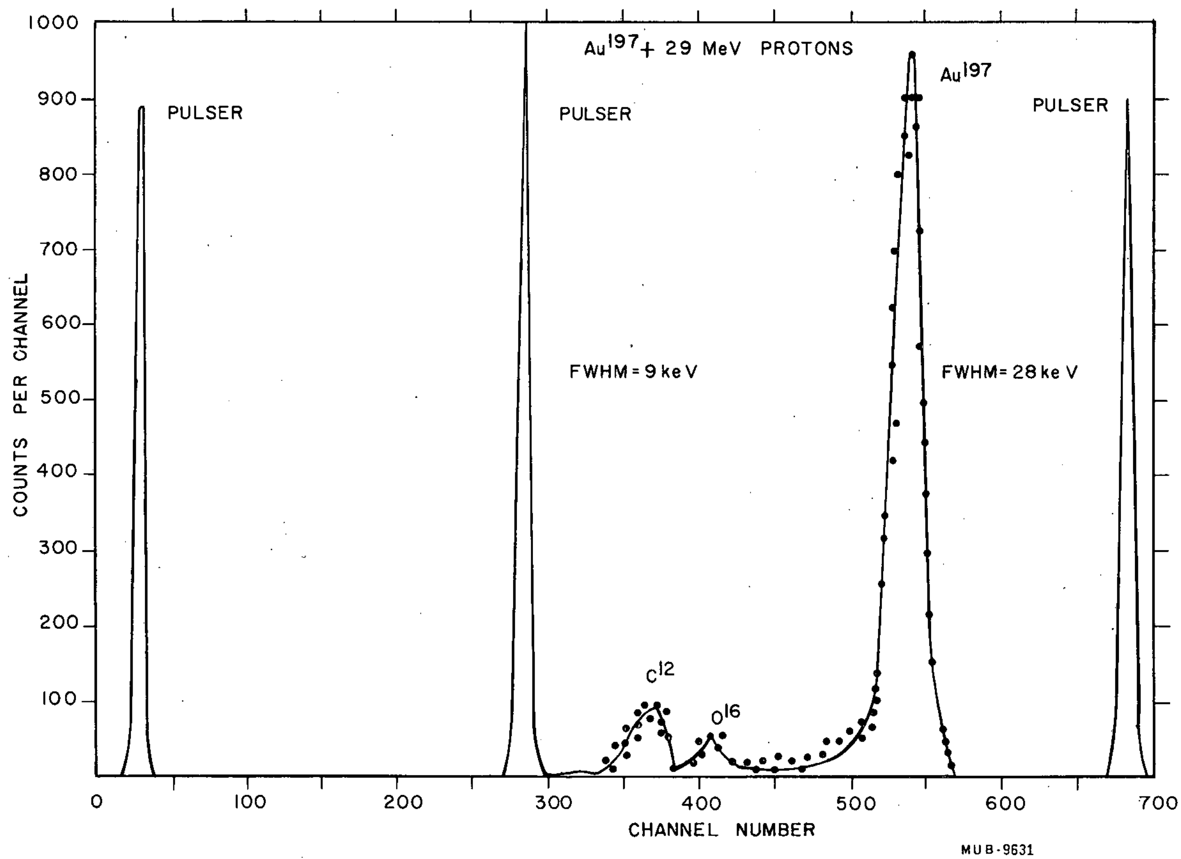
Au197 + 29 MeV PROTONS
PULSER
PULSER
Au197
PULSER
FWHM = 9 keV
FWHM = 28 keV
C12
O16
COUNTS PER CHANNEL
CHANNEL NUMBER
0
100
200
300
400
500
600
700
800
900
1000
MUB-9631

Fig. 2

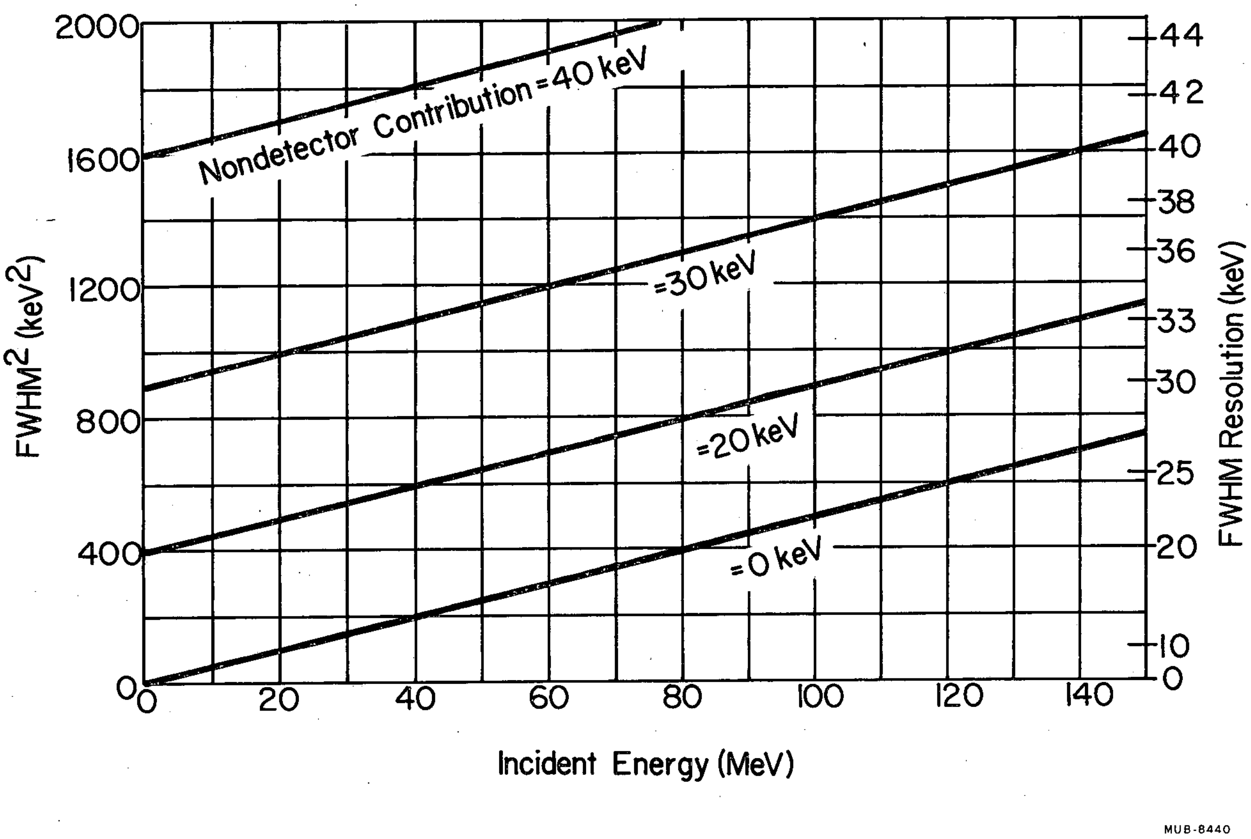
2000
1600
1200
800
400
0
0
20
40
60
80
100
120
140
Nondetector Contribution = 40 keV
= 30 keV
= 20 keV
= 0 keV
44
42
40
38
36
33
30
25
20
10
0
FWHM² (keV²)
FWHM Resolution (keV)
Incident Energy (MeV)
MUB-8440

Fig. 3