size and distribution in sulfur sols by both the counter and HOTS. The most probable diameters by HOTS were significantly lower than that found by the counter, practically in the ratio 0.94/1.17. One is thus forced to conclude that HOTS was giving low results for the mean diameter of the polystyrene latex, as well as for the sulfur sols.

With respect to the unexpectedly broad size distributions found by us with the counter for "monodisperse" polystyrene latex and by Petro[3] for sulfur sols, we are unable to say finally, at this time, that these results are indeed real. It is conceivable that a truly monodisperse suspension would give in the Coulter counter a slightly polydisperse distribution of pulse heights because not all particles traverse the sensing region in the same way. If this were the case, one would expect to find a different degree of polydispersity when orifices of different sizes were used to measure the same nearly monodisperse suspension. Essentially, the same apparent distribution of particle diameters was found, however, for one sample of Dow latex No. LS-067-A with the 30-μ orifice as with the 70-μ orifice. In addition, two samples of latex LS-067-A obtained at different times and counted with a 30-μ orifice gave essentially the same median particle diameter but different populations of large and small particles. The results taken from smooth curves through the experimental points are summarized in Table III; they show that at least part of the apparent polydispersity of these "monodisperse" lattices is real; it may be caused in part by the presence of stable aggregates.[1]

The resolving power of the Coulter counter has been tested in another way by Petro with mixtures of two sulfur sols of slightly different diameter.[3] We have obtained similarly a fairly satisfactory resolution of a mixture made up to contain 35% wt of Dow latex LS-067-A, with a nominal diameter of 1.171 μ, and 65% wt of Dow latex LS-066A, with a nominal diameter of 0.814 μ. The latter showed in the Coulter counter a standard deviation of 0.05 μ rather than the 0.01 given by Dow. Analysis of the Coulter counter curve for the mixture led to an apparent concentration of 38–40% wt of LS-067-A rather than the nominal 35% present. This result, obtained with a mixture of particles differing by 0.3 μ in median diameter, suggests that the populations of large particles seen by the Coulter counter in dilutions of the "monodisperse" lattices are real.

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Solid-State Detectors for High Resolution Nuclear Spectroscopy

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Use of an array of solid-state detectors in conjunction with a magnetic analyzer as a replacement for nuclear emulsions in nuclear spectroscopy is described. Arrays of both Au-Ge and gold-doped silicon have been used. The arrays consist of twenty detectors each and cover two inches along the image plane of the magnetic spectrograph. Particles of the same magnetic rigidity, but different mass, are easily identified as their energies are in the ratio Z^2/m. The silicon detectors, which operate essentially as parallel plate ionization chambers, suffer the disadvantage of becoming polarized. The use of such arrays reduces by a factor of the order of twenty the time required to extract precision data from a nuclear reaction.

I. INTRODUCTION

RECENT advances in the physics of the solid state have revived interest in the application of solid-state devices to the detection of nuclear radiation. As a result, a variety of detectors have been developed and are reported in the literature.[1] The purpose of this note is to describe the properties of gold-doped silicon as a parallel plate ionization chamber and to describe the use of an array of twenty such detectors at the image plane of a high-resolution magnetic analyzer as a substitute for the nuclear emulsion. Since the inherent resolution of solid-state detectors is an order of magnitude less than can be obtained with magnetic analysis, it seems unlikely that they will replace the magnetic spectrograph for high precision work. Their use in conjunction with a magnetic analyzer, however, has certain obvious advantages. The long time required for

[1] An extensive bibliography on semiconductor nuclear radiation detectors has been given by J. L. Blankenship in Oak Ridge National Laboratory Report No. 2583, dated October 3, 1958. More recent references are given by G. Dearnaly and A. B. Whitehead in AERE-R3437, Harwell (1960).

developing, drying, and reading of the emulsions is eliminated so that the data are immediately available to assess properly the progress of the experiment. When nuclear emulsions are used for recording high resolution data, the total processing and read-out time is of the order of 15 to 30 times longer than the exposure time, hence, to balance accumulation time and read-out time requires the services of the order of 20 human scanners. Further, their use removes the requirement that high resolution be obtained from the detectors themselves since they need only discriminate between particles of the same momentum, but different mass. Particles of the same magnetic rigidity $B\rho q$ arriving at the image plane of an analyzer have energies in the ratio $E_p=2E_d=3E_t=E_\alpha=\frac{3}{4}E_{He_3}$ for protons, deuterons, tritons, alphas, and He_3 respectively, thus particle indentification is more easily done than by means of track density in the nuclear emulsion.

In constructing the arrays, two types of semiconductor detectors have been used; the gold-germanium surface barrier detector, the properties of which have been described in detail in the literature, and gold-doped silicon made from phosphorous-doped silicon, counter-doped with gold which behaves essentially as a parallel plate ionization chamber. While the properties of gold-doped silicon have been described,[2] little use has been made of them.[3]

II. PROPERTIES OF THE PARALLEL PLATE DETECTOR

The process fundamental to the detection of nuclear radiation is the ionization produced in a medium by the passage of a charged particle. In silicon, the average energy necessary to produce one electron-hole pair is 3.60 ev. Just as in the gas counter, the operation of the detector depends on the separation of the positive and negative members of the pair and this separation is caused by the presence of an electric field. In the rectifying barrier junction and the diffused P-N junction the electric field is not uniform, but more nearly resembles that of a spherical ionization chamber. In gold-doped silicon the electric field is essentially constant, and therefore resembles that of a parallel plate ionization chamber. The distance over which charge can be collected is determined primarily by the cross section for capture or trapping. When the members of the pair, formed in the interior of the silicon, have separated a distance x due to the influence of the applied electric field, the charge induced on the electrodes is $q=ex/d$, where e is the electronic charge and d the separation of the electrodes. For the counter to operate effectively, the mean free path of the electrons for trapping must be large compared to the distance between the electrodes. A second necessary condition for effective operation is that the dark current be small compared to the signal current. Both conditions can be realized in gold-doped silicon[2] provided the concentration of the gold is approximately 3 times the concentration of the impurity. Silicon doped with 2×10^{14} atoms/cm^3 of phosphorus and counter-doped with 5×10^{14} atoms/cm^3 of gold behaves very much like intrinsic silicon. At temperatures near 180°K, the resistivity is of the order of 10^{10} ohm-cm and an applied electric field of 1000 v/cm results in a mean free path of the conduction electrons of approximately one centimeter. The mean free path for the positive holes is much less and as a result less charge is induced on the electrodes than if both members of the pair were collected. The trapped positive charges establish an internal electric field which results in polarization of the detector. This has the effect of degrading the pulse height distribution and reducing the resolution. The polarization can be removed by warming the crystal, but we have had little success in finding an operating temperature where the trapped charges are neutralized by the conduction current while maintaining a good signal-to-noise ratio. This difficulty will limit the use of gold-doped silicon as a charged particle detector.

As an example of the pulse formation, consider the pulse produced by an alpha particle which enters the crystal through one electrode. The range is extremely short and therefore the electron-hole pairs are produced in a region close to the surface. If the electrons are collected at the opposite electrode, the charge induced on the electrodes corresponds to the separation of essentially all of the electron-hole pairs by the thickness of the crystal ($x=d$). When the direction of the applied electric field is reversed, the induced charge is essentially zero. A proton, however, has a significantly larger range (the range of a 10-Mev proton in silicon is approximately 0.6 mm) and since the positive holes do not move appreciably, only the electrons are collected from the interior region of the crystal and the total charge induced on the electrodes will be somewhat less than that for an alpha particle of exactly the same energy. In this situation, when the applied field is reversed the total charge is again collected from the interior and a pulse of opposite polarity is obtained, the amplitude of which depends on the range of the proton in the crystal. The fact that a lower pulse height is obtained for protons than alpha particles is useful in identifying and separating alpha particles and protons which arrive at the image plane of the magnetic analyzer for the same setting of the magnetic field.

[2] C. B. Collins, R. O. Carlson, and C. J. Gallagher, Phys. Rev. **105**, 1169(1957); W. D. Davis, Phys. Rev. **114**, 1006 (1959).

[3] This work was described in Bull. Am. Phys. Soc. **5**, 245, H2 (1960). Similar detectors have been used by J. D. Van Putten and J. C. VanderVelde, Bull. Am. Phys. Soc. **5**, 197, H10 (1960), for dE/dx measurements of high energy particles. A more complete report of their work has appeared in IRE Trans. on Nuclear Sci. **NS8**, 124 (January 1961).

III. PREPARATION OF COUNTERS

Each silicon crystal was a rectangular parallelepiped of dimensions 2 cm×2 mm×1 mm.[4] After etching in CP-4 solution and washing in acetone the 2 mm×2 cm faces were coated with a thin layer of gold by evaporation. A mask 0.010 in. smaller on a side than the crystal surface, allowed accurate control of the location of the gold electrodes. Contacts were made to the gold with indium coated phosphorus-bronze fingers as illustrated in Fig. 1 which shows an array of 20 mounted ready for use at the image plane of the analyzer.

A similar array of 20 detectors was prepared using N-type germanium[5] of resistivity 50 ohm-cm. The technique for fabricating the gold-germanium surface barrier detector has been described previously.[1] Perhaps the only additional point of interest is that the crystals were soldered to Kovar mounting strips before etching. A fine copper wire was attached to the gold electrode using indium solder and zinc chloride flux. The Au-Ge array is shown on the right in Fig. 1.

IV. OPERATION OF THE DETECTORS

To obtain a good signal-to-noise ratio, both types of detectors must be operated in the neighborhood of 80°K. The arrays were mounted on a cold trap maintained at liquid nitrogen temperature. Each crystal in the array was connected to a three stage transistor amplifier followed by a two stage discriminator circuit, and the assembly, shown at the top of Fig. 1, was constructed so as to operate in the vacuum in close proximity to the detectors to minimize the input capacitance. The twenty discriminator outputs, connected by cable to the control room, fed the individual scaling units of a model 520 Atomic Instrument Company twenty-channel pulse-height analyzer. (More recently the amplifier-discriminator unit has been moved to the control room to make the individual discriminators more readily accessible. Cathode followers are used to drive the long cables.) This scheme was particularly easy to construct because of the availability of the 20-channel unit; a system which uses a delay line to sort the pulses has been described elsewhere.[6]

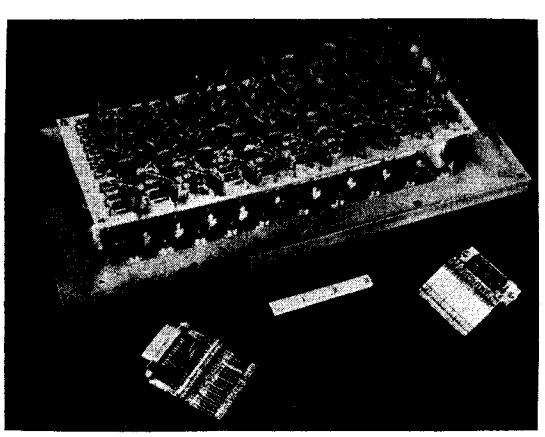

FIG. 1. The arrays of solid-state detectors and the transistor amplifier-discriminator circuits for use at the image plane of the magnetic spectrometer. The array at the lower left consists of 20 crystals of gold-doped silicon. The array at the lower right consists of 20 gold-germanium surface barrier detectors.

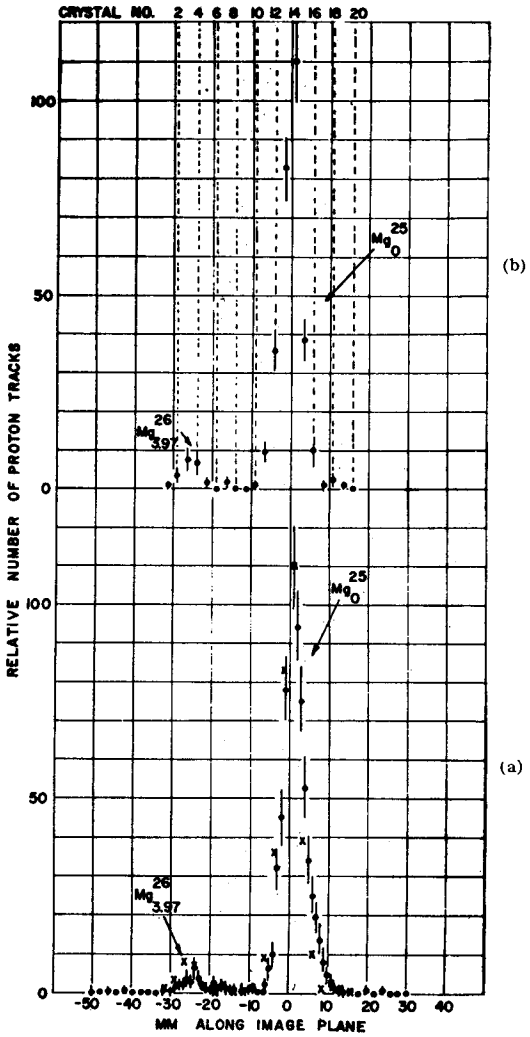

FIG. 2. A comparison of the data obtained using nuclear emulsions with that obtained from the crystal array. The groups correspond to protons from the ground state of Mg^{25} and the 3.97-Mev level of Mg^{26} in the reaction Mg(d,p). The crosses in Fig. 2(a) are the data points of Fig. 2(b).

The germanium detectors were operated without bias. While bias as high as 0.5 v improves the signal level, the signal-to-noise ratio decreases. The silicon detectors were operated with biases between 100 and 250 v corresponding to a collection field of 1000 to 2500 v/cm. The signal at the

[4] The silicon crystals were obtained through the courtesy of D. Hartman of the General Electric Semiconductor Laboratories, Syracuse, New York.

[5] Obtained from Sylvania Electric Products, Towanda, Pennsylvania.

[6] O. M. Bilaniuk, A. K. Hamann, and B. B. Marsh, University of Rochester Report No. NYO-9026 (1960).

output of the amplifiers for both types of detectors was approximately one volt for 5.3-Mev alpha particles. The rise and decay times of the output pulse, determined entirely by the amplifier and its associated circuitry, were approximately 3 μsec. While this is a "slow" system, it is more than adequate for the counting rates involved.

V. APPLICATION OF THE DETECTORS TO NUCLEAR SPECTROSCOPY

The magnetic analysis equipment associated with the Michigan 42-in. cyclotron has been described previously.[7] The reaction products analyzer magnet, with a resolution of $(E/\Delta E)=2\times10^3$ provides at the image plane an image of the target area illuminated by the incoming beam. The useful width of the image plane is 10 in. and covers 7% in momentum. When nuclear emulsions (1×10 in.) are used for recording the data, the read-out procedure consists of plotting for each millimeter of the image plane the number of proton (say) tracks observed in the corresponding swath across the 1-in. dimension of the emulsion. When targets of thickness greater than 15 kev are used, the half-width of the proton group at the image plane is determined by the target thickness and by the dispersion of the analyzer. The proton group of energy 12.70 Mev corresponding to the ground state of Mg^{25} in the reaction $Mg^{24}(d,p)Mg^{25}$, shown in Fig. 2(a), has a half-width of 40 kev or 6 mm. The weak group at the left, of energy 12.54 Mev, corresponds to the 3.97-Mev level of Mg^{26} and is separated from the Mg^{25} group by 160 kev. The length of the line associated with each point is the square root of the number of tracks counted.

The 20-channel array covers a distance across the image plane of 2 in., so that each crystal covers very nearly 2.5 mm. The data obtained with the silicon array for the same proton groups is shown in Fig.2(b). These data are shown transferred to Fig.2(a) by the crosses. The point to point correspondence in Figs. 2(a) and 2(b) is evident. The background counting rate of the detectors is low because first the efficiency for neutrons and gamma rays is small, and second, the pulses due to such background are small and the discriminator can be set above them.

The response of a single detector located at the image plane to alpha particles, protons, and deuterons for two values of the bias is shown in Fig. 3. [The amplification was slightly lower for Fig. 3(b).] These particle groups were obtained from a beryllium target bombarded with deu-

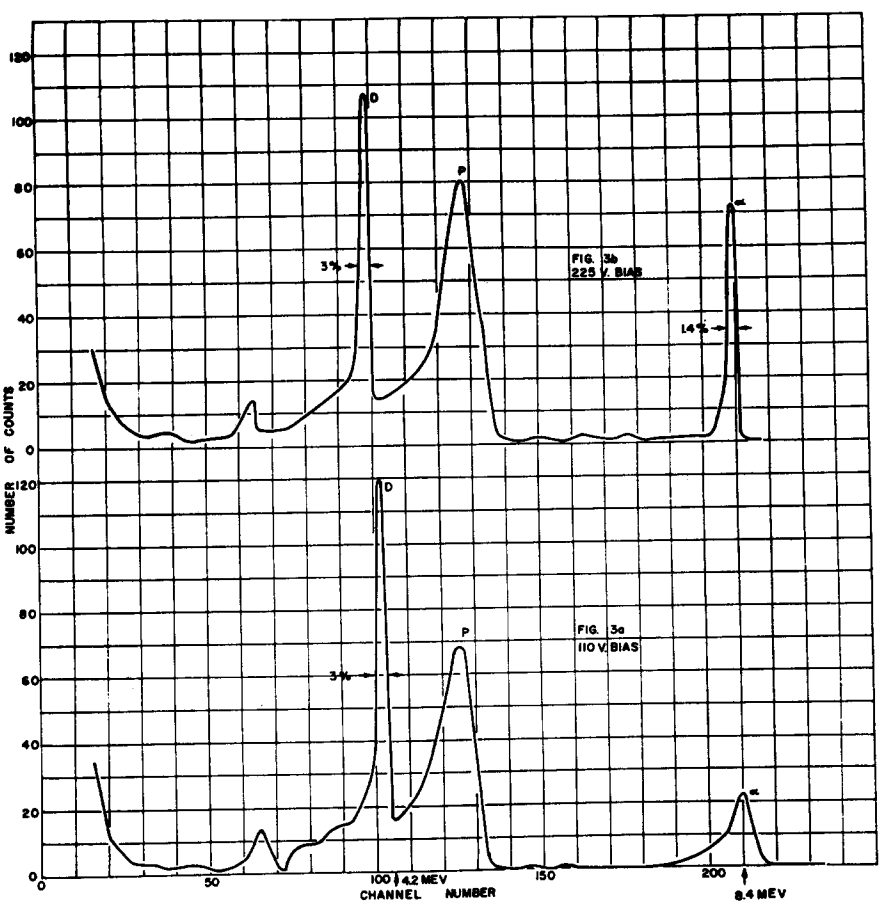

FIG. 3. The pulse height distributions obtained from a single gold-doped silicon crystal (crystal No. 9) located at the image plane of the magnetic spectrograph for two values of the bias voltage. The particle groups obtained from the reaction (Be+d) were identified by observing the change in pulse height as aluminum absorbers were placed directly in front of the crystal.

[7] D. R. Bach, W. J. Childs, R. W. Hockney, P. V. C. Hough, and W. C. Parkinson, Rev. Sci. Instr. 27, 516 (1956).

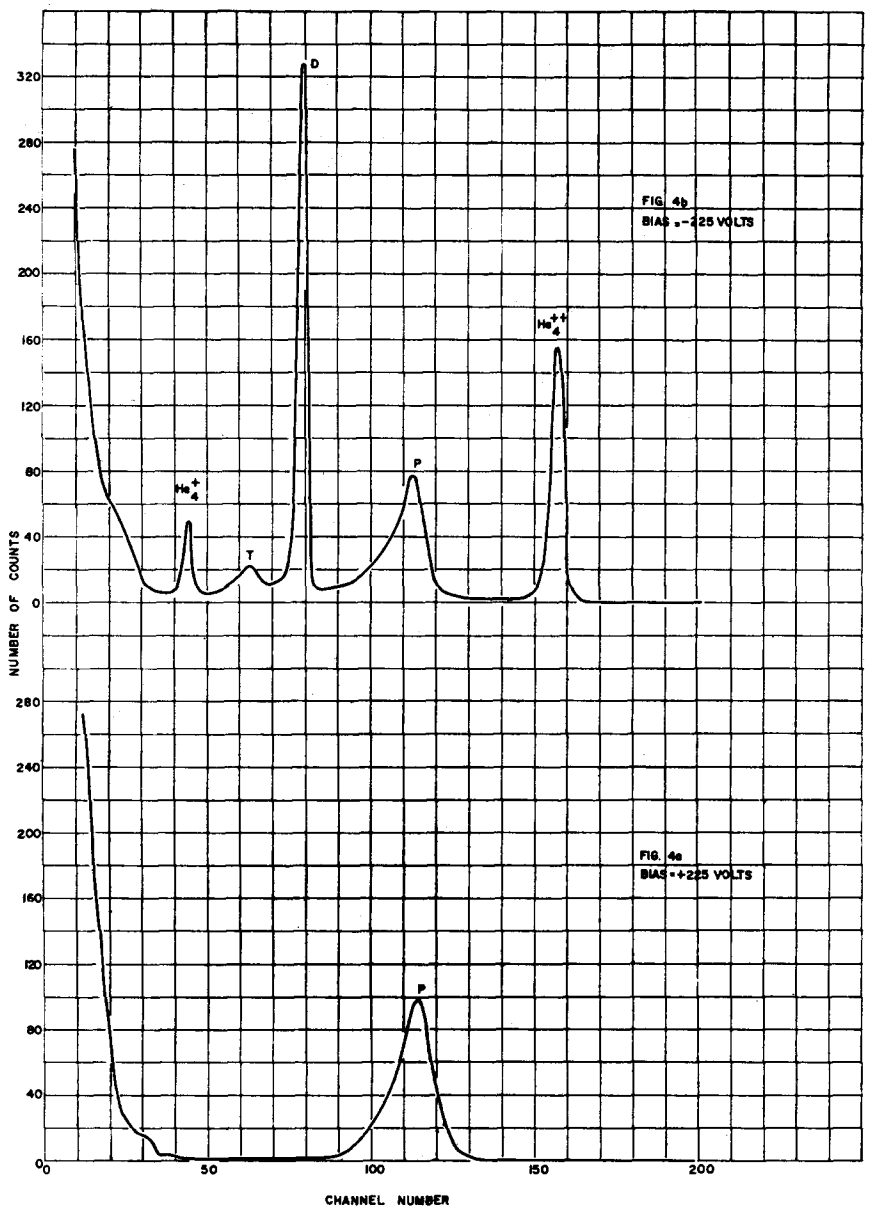

FIG. 4. The pulse height distributions obtained from a single gold-doped silicon crystal (crystal No. 8) for positive and for negative bias.

terons. Since all three particles have the same value of $B\rho q$, and therefore energies in the relation $E_p = E_\alpha = 2E_d$ one might expect the pulse height due to the protons to equal that of the alphas and twice that of deuterons. The ratio of the alpha to deuteron pulse height is very nearly 2:1, but the ratio of the proton to alpha pulse height is considerably less than unity. This is the result of the relatively large range of the proton; the charge induced on the electrodes is considerably less than that corresponding to collection of the electron-hole pair over the full thickness of the crystal. As an aside remark, it is a happenstance of the Q values that Be^9 plus a deuteron yields groups of protons, deuterons, and alpha particles having the same $B\rho q$ value. The particle groups were identified by observing the change in pulse height as thin aluminum absorbers were placed in front of the detector. It is interesting to note that while the half-widths of the proton and deuteron groups are essentially the same for the two values of bias, the half-width of the alpha group is considerably reduced at the larger bias. This is presumably due to a surface region effect. The relatively large width of the proton groups is presumed to be due to range straggling which occurs near the center of the crystal, and hence is magnified by the charge collection mechanism.

The response of a neighboring crystal in the array is shown in Fig. 4 for positive [Fig. 4(a)] and negative [Fig. 4(b)] bias. The similarity of Fig. 4(b) and Fig. 3 is evident. (The amplification in Fig. 4 is not the same as in Fig. 3.) Peaks believed due to singly ionized He^4 and to tritium are indicated. This assignment is based only on the

relative pulse amplitudes and intensities. In Fig. 4(a), with reverse bias only the proton peak is observed, for the reasons given in Sec. II. The fact that the amplitudes of the proton pulses are nearly the same with positive and negative bias is consistent with the range of the proton being approximately half the thickness of the crystal.

The question has been raised whether the gold-doped silicon detector operates as a parallel-plate ionization chamber or as two P-N junctions back-to-back. While the gold-silicon contacts are nonohmic and therefore introduce potential barriers at the surfaces, the experimental evidence presented above is consistent with an essentially uniform electric field throughout most of the interior. For back-to-back P-N junctions in a material of *low* resistivity the potential distribution would be similar to that shown in Fig. 5(a) for positive and for negative bias. Given such a distribution, with particles incident from the left, the voltage pulse induced on the electrodes can result from electron-hole pairs formed in the shaded region only. In the measurements described above, the range of the deuterons and the alpha particles is small compared to the crystal thickness d while the range of the protons is approximately $d/2$. Therefore, for the potential distribution of Fig. 5(a), no significant pulse should be obtained from alphas, deuterons, *or* protons when the bias is positive. However, if the material has a high resistivity, as is the case here, the potential distribution would approach that shown in Fig. 5(b), corresponding to a more nearly uniform electric field, and therefore more like the field of a parallel plate ionization chamber. To investigate this point further, the pulse height as a function of proton energy was computed assuming a uniform electric field distribution

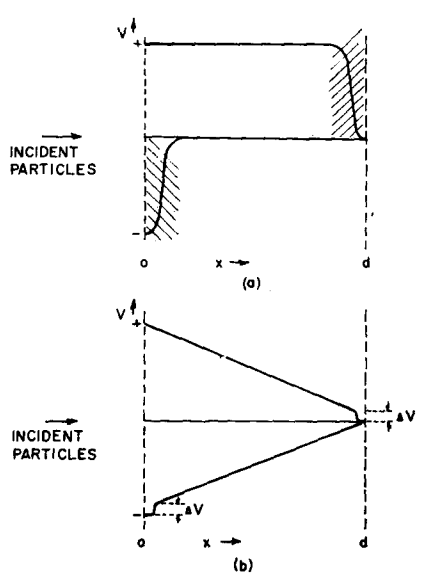

FIG. 5. A schematic representation of the potential distribution within the crystal for (a) back-to-back P-N junctions at the surfaces, and (b) a uniform electric field within the interior of the crystal and nonohmic surface contacts.

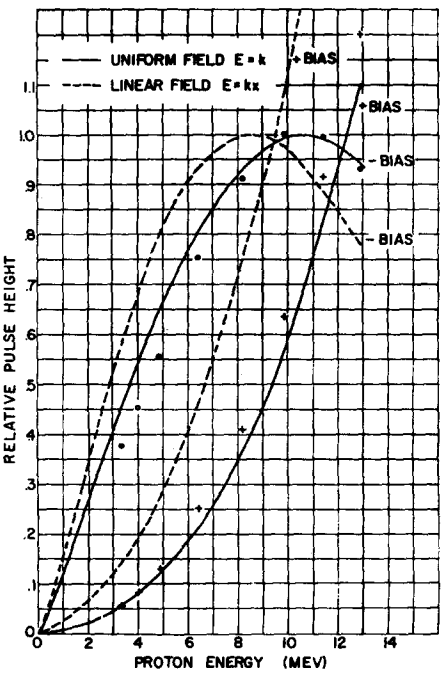

FIG. 6. The calculated relative pulse height as a function of proton energy for positive and for negative bias assuming a uniform electric field (solid lines) and a linear electric field (dashed lines) with $E=0$ at $x=d$, the thickness of the crystal. The measured pulse height distributions for positive and for negative bias are indicated by + and 0, respectively.

($E=k$) and again assuming a linear electric field ($E=kx$ with $E=0$ at $x=1.25$ mm) for both positive and negative bias, using the rate of energy loss (dE/dx) for protons in silicon. The results for a silicon crystal 1.25 mm thick are compared with the measured values in Fig. 6. The calculated curves include the displacement of the holes (approximately 0.1 mm) before trapping, as determined from the trapping cross section given by Davis.[2] The calculated ratios of the pulse height for positive bias to the pulse height for negative bias are compared with the measured values in Fig. 7. These results are consistent with an essentially uniform field. The curves do not change significantly when the hole displacement is neglected. Thus, while the exact nature of the contacts is unknown it seems clear that the principal feature in the operation of the detectors is an essentially uniform electric field in the interior of the crystal. Further evidence for a uniform electric field is obtained from a measurement of the capacitance of the crystal which should be independent of bias. The capacitance was found to be constant over the range of bias from 0 to 250 v within the uncertainty of measurement (5%). Further, the measurements of Davis (Figs. 2 and 3 of reference 2) are consistent with a uniform field distribution.

It is suggested therefore that the actual potential distribution within the silicon is of the form shown in Fig. 5(b) where ΔV is due to the nonohmic nature of the contacts at the surface and is small compared to V. Thus,

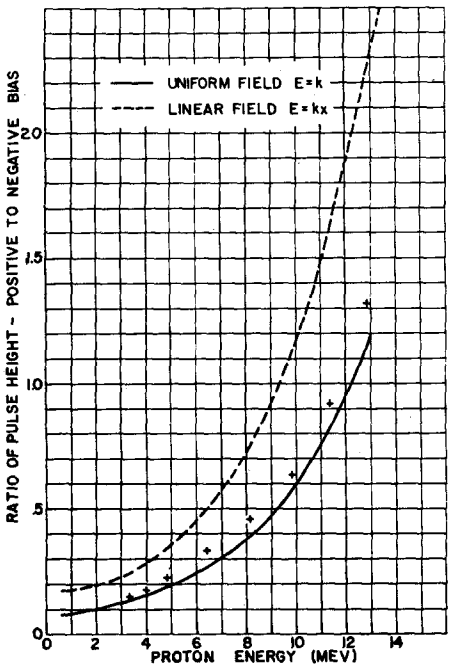

FIG. 7. The calculated ratio of the pulse heights for positive to negative bias for the uniform electric field and the linear field are compared with the measured ratio.

the question of whether the detector acts as two P-N junctions back-to-back or strictly as a parallel plate ionization chamber is academic for this particular application. It has been pointed out, however,[8] that if the contacts are indeed back-to-back P-N junctions, then injection effects would become evident in extremely thin detectors such as might be used for dE/dx counters.

[8] By the referee.

In using the array for nuclear spectroscopy, alpha particles may be selected by adjusting the bias of the amplitude discriminators above the proton group. Protons may be selected by placing thin absorber foils directly in front of the crystals to remove the alpha particles and deuterons. To select tritons or deuterons it is necessary to use a differential discriminator rather than a simple amplitude discriminator.

While both the Au-Ge and gold-doped silicon detectors suffer the disadvantage of operating at liquid nitrogen temperatures and the silicon suffers the further disadvantage of polarization, they nevertheless can be used until such time as diffused junction detectors operating at room temperature become generally available in the size and shape required. The array reduces by a factor of approximately 20 the time required to extract precision data from a nuclear reaction. It is unlikely, however, that semiconductor devices will replace the nuclear emulsion completely. The nuclear emulsion still has the advantage of being an integrating device, it forms a permanent record, permits better discrimination against background, and has inherently better resolution.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the work of W. E. Downer and R. D. Pittman in fabricating the crystal holders and cold trap, and the assistance of J. R. Maxwell and J. A. Koenig in constructing the electronic circuits. T. Holtebekk, on leave from Blindern, Norway, together with J. R. Maxwell have obtained the data shown in Figs. 2(b) and 3, for which we are pleased to express our appreciation.