A SCINTILLATOR-PHOTODIODE UNIT
AS A PARTICLE DETECTOR

by

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A scintillator-photodiode unit is proposed as a particle detector. Configurations employing NaI(Tl) and CsI(Tl) as scintillators, and photodiodes manufactured by RCA Victor and Simtec are tested using a monochromatic beam of 100 MeV protons from the McGill Synchrocyclotron. The tests are conducted with the diodes at room temperature and cooled to dry ice temperature (-56.2°C). The best combination is found to be the cooled Simtec with a CsI(Tl) crystal, having a resolution of 1%. All results are discussed in the light of predictions made in the text and are compared to those for the standard scintillator-photomultiplier unit. Possible applications of the unit are outlined, and improved configurations are suggested.
ACKNOWLEDGEMENTS

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The author acknowledges his indebtedness to Mr. P.M. Portner of the J.S. Foster Radiation Laboratory for help in adapting his system of obtaining a monochromatic beam of 100 MeV protons from the McGill Synchrocyclotron to the author's needs. Also acknowledged are the many pieces of equipment borrowed from Mr. Portner to achieve this end.

Thanks are also due to Dr. R.W. Jackson of RCA Victor Co. Ltd., who originally suggested research into the scintillator-photodiode unit to Professor Martin and through whom the author was initiated into many of the aspects of photodiodes.

Thanks are especially due to Mr. S. Doig, foreman of the J.S. Foster Radiation Laboratory machine shop, and his staff, whose helpful advice on certain aspects of the design of the system and whose co-operation especially when the author felt pressed for time, were surely beyond the call of duty.

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INTRODUCTION

1. General

The phenomenon of certain materials scintillating when irradiated has long been known and dates back at least to the time of Rutherford when zinc sulphide was used as an \( \text{\textsuperscript{-}} \)-particle detector and light flashes were counted visually. This aspect changed drastically with the advent of the modern phototube, with which much lower light intensities could be detected and actually different levels of light intensity distinguished. Thus was born the highly successful scintillator-photomultiplier unit, which has served many years now as a detector of particles and \( \text{\textsuperscript{-}} \)-rays. However, of late, i.e. within the last ten years, the development of the semiconductor particle detector has reached such a stage that in certain areas it far surpasses the scintillator-photomultiplier unit as a detector. Appendix A gives a more complete discussion of this, and as well defines the common nuclear spectroscopic terms to be used throughout this work. Suffice it to be said here that these detectors have exhibited a resolution far better than any scintillator-photomultiplier unit \(^{(1)}\), second only to magnetic spectrometers. Their principal limitation at present is that they cannot fully absorb charged particles of even moderately high energy. For example, a lithium-drifted silicon detector 1 cm. thick has a proton range of 45 MeV. On the other hand, scintillators which have a much greater energy capability are readily available.

During the normal investigation of the properties of
these semiconductor detectors, it was found they were light-sensitive\(^{(2,3)}\). It was an easy extension to postulate a configuration of a scintillator on a photodiode (a semiconductor detector used for its light-sensitive properties) to be used like a scintillator-photo-multiplier unit. This was the way the problem was presented by Dr. R.W. Jackson of RCA Victor to Prof. W.M. Martin of the Foster Radiation Laboratory who suggested it to the author. Subsequent to this, some work has been published. Tuzzolino et al.\(^{(3)}\) investigated the light response of photodiodes, and tried the configuration suggested here without great success. Fan\(^{(4)}\) investigated the problem of coupling the scintillator to the photodiode, with an aim of using the configuration as a cosmic particle detector in satellites. To date, however, the author knows of no other work than the one to be presented which considers the scintillator-photodiode unit as a particle spectrometer for the case of various scintillators and photodiodes.

2. The Scintillation Spectrometer

To enlarge on what was said above, the scintillation spectrometer consists basically of a scintillator and some means of detecting and perhaps amplifying the light output of the scintillator and then analysing it. The mechanism is this: some radiation incident on a special crystal or plastic causes it to scintillate. The light output is proportional to the energy deposited within the crystal. So if some means can be found to detect and distinguish between the various intensities of light emitted, an energy spectrum could be obtained. This can be accomplished through either the photomultiplier
or the photodiode.

The photomultiplier will not be explained here since very good and detailed information can be obtained from almost any standard text (e.g. Ref. 12). However, a few of its features, as well as some of those of the scintillator-photomultiplier unit, will be noted. The photomultiplier essentially has the incident photon liberate electrons from a photocathode and then causes these electrons to multiply in number by approximately $10^6$, whence they are collected at the last dynode with a suitable RC to achieve complete collection. The pulse obtained has a component of its resolution arising in the photomultiplier due to statistical fluctuations in $N$, the number of electrons collected at the last dynode. Thus, this part of the resolution is of the type $100 \left( \frac{N}{N} \right)^{\frac{1}{2}}$, i.e. the resolution varies inversely as the square root of $N$ and hence inversely as the square root of the incident particle energy. Other components of the total resolution observed are due to properties of the crystal and will not be discussed here because the crystal is common to both the scintillator-photomultiplier unit and the proposed scintillator-photodiode unit.

The technique of coupling the crystal to the photomultiplier is a very exacting one, as can be seen by reading any of the literature put out by the larger companies in this field (e.g. Ref. 7). This has come about mainly because scintillation light has a definite spectral distribution. Typical curves for NaI(Tl) and CsI(Tl) are shown in Fig. 1. Photomultiplier photo–cathodes have been constructed with this in mind and actually they fit the emission spectra
remarkably well (see Fig. 1a.). In addition, much has been done to maximize the light collection efficiency by very judiciously encapsulating the scintillator and mounting it carefully on the photomultiplier. A normal $1\frac{1}{2}'' \times 1''$ NaI(Tl) matched exhibits a resolution of $\sim 7\%$ at $662$ keV $^{(6)}$ and $\sim 0.8\%$ at $100$ MeV $^{(6)}$, although theoretically at this latter energy a resolution of $0.4\%$ $^{(6)}$ could be achieved.

The electronics required for a typical experiment employing a scintillator-photomultiplier unit are shown in block diagram form in Fig. 2a.

With the photodiode, the situation is somewhat different. A photon should produce a hole-electron pair if: a) it is not reflected at the surface of the photodiode, b) it is of such a wavelength as to penetrate the diffused layer (typically $0.2\mu$ to $2\mu$ thick), and c) if it has such an energy as to raise an electron from the valence band to the conduction band. For silicon, the band gap is $1.09$ eV, and thus using $E=hc/\lambda$, a maximum wavelength of $1.14\mu$ is possible. On the other hand, light will begin to be absorbed in the diffusion layer as its wavelength approaches the diffusion depth and this will set a practical lower limit on the response. In the principal spectral region, each photon absorbed in the detector produces one hole-electron pair. If this production occurs within the depletion layer, an electronic charge is collected in the external circuit. For generation outside the depletion layer, the charge is collected only if it can diffuse to the depleted region before recombination. The short- and long-wavelength ends of the spectral response curve are determined by such diffusion processes, while the central region is essentially independent of recombination. Because
of this, the expected quantum efficiency is nearly 100% in the middle spectral response region, and the overall efficiency in this region is determined primarily by reflection losses. A typical response\(^{(2)}\) exhibits this and is shown in Fig. 3 along with the reflection losses. Williams\(^{(2)}\) also found that increasing the bias, i.e. the depletion depth, did not affect the response at all, indicating that all photons are absorbed in a very narrow region of the depletion layer closest to the diffused layer. Thus, in this case, bias is selected to give minimum noise and no attention is paid to the corresponding depletion layer thickness, although to avoid recombination losses a thin depletion layer unit is preferable.

Thus it would seem a surface barrier diode with its 50 Å of gold as the front surface would be more suitable. However, Tuzzolino et al\(^{(3)}\) and Fan\(^{(4)}\) have reported great difficulty in achieving good optical coupling between crystal and diode without the front surface deteriorating. The diffusion-type photodiode has an advantage in this respect. With this type, one need not take special care about coupling since the front surface is so rugged (Coupling details will be given below.). However because of the nature of the emission spectra of the crystals used, it was necessary to use the minimum diffusion depths available, i.e. 0.1 to 0.3\(\mu\). A typical response curve is shown in Fig. 3, where it is seen light down to 0.3\(\mu\) is still being detected.

With the photodiode, thermal noise, not statistical fluctuations in \(N\), the total number of hole-electron pairs produced, is the main factor affecting resolution. This is because \(N\) is so large. A practical case illustrates this: Consider a 100 MeV proton
completely stopped in a NaI(Tl) crystal. Of this energy, about 10% is converted. Assuming an average photon energy of 3 eV (blue light), this gives approximately $3 \times 10^6$ quanta produced in the crystal. Now assuming that $2/3$ of these are lost either through not getting out of the crystal or through reflection at the interfaces between the crystal, light pipe and diode, this still leaves $10^6$ quanta entering the photodiode and thus $10^6$ hole-electron pairs generated. The $\%$ statistical fluctuation in $N$ is thus 0.1%. Thermal noise in the diode contributes much more and is constant for any one case. Thus the $\%$ resolution is $\frac{100k}{N}$ where $k$ is some equivalent noise figure. This situation with the resolution inversely proportional to $N$ and hence inversely proportional to the energy is to be contrasted with the situation pertaining to the photomultiplier where the resolution is proportional to the inverse square root of the energy.

The matching of photodiode response with the emission spectrum of various scintillators is not at all the same as say between NaI(Tl) and the S-11 photo-cathode. Whereas most scintillators emit in the region 0.3$\mu$ to 0.4$\mu$, the photodiode is much more efficient for photon detection in the wavelength region 0.5$\mu$ to 1.0$\mu$. From a table from Harshaw(?) which has maximum emission wavelengths and relative pulse heights listed, it was decided that the only two crystals which looked promising were NaI(Tl) because it has the largest relative pulse height, even though it emits at 0.41$\mu$, and CsI(Tl) with 1/4 the pulse height of NaI(Tl) using an S-11 photo-cathode, but having a maximum emission at 0.57$\mu$. Calculations were made to see which would be better and these are recorded in Appendix B. The final results
indicated CsI (Tl) would be slightly better, but it was decided to try both. The entire configuration is drawn in Fig. 2b, and is discussed in much more practical detail in the next section.
1. The Apparatus
   a) The Source

   It was estimated that $N$, the total number of hole-electron pairs produced, would be sufficiently small and $k$, the equivalent noise figure, sufficiently large that most low energy work would be out of the question, and in reality this area is not of too great interest since the semiconductor detector operates very well here and, as already stated, is far superior to the scintillator-photodiode unit. It was decided to explore a region where the semiconductor detector cannot be used: 100 MeV protons from the McGill Synchrocyclotron, which puts out 400 bursts per second, averaging a current of $\sim 15$ nA when the beam is fully focussed. This is evidently far too high an intensity for a direct counting of the beam. With NaI(Tl) and CsI(Tl) having decay times of 0.25 $\mu$sec. and 1.1 $\mu$sec. respectively, all that can be tolerated is one count for each 10 $\mu$sec. burst. Instead of scattering off some target to reduce the intensity, it was decided to employ a configuration used by P.M. Portner\(^{(10)}\) in his work on finding the actual energy of the beam by the floating wire method. In essence, the system works like this: protons extracted from the cyclotron are bent through $73^\circ$, and thus having considerable dispersion are passed without any focussing through two vertical slits and a horizontal slit. (See Fig. 4), the first of which is mechanically inserted into alignment with the other two and the beam at the proper time. Selecting only 0.015" of the disperse beam ensures an almost monochromatic full energy beam.
Portner (10) quotes a FWHM of < 0.1 MeV for 100 MeV. It is evident the slits are thick enough only to degrade the beam slightly and for 100 MeV, 1/16" is equivalent to ~7 MeV, and 1/8" to ~14 MeV. This is done to minimize slit scattering. These components are easily removed by employing the beam switching magnet as an analyzing magnet, bending the protons through 12° so that only 100 MeV protons are incident on the detector. Detuning the cyclotron by raising the Dee bias and lowering the oscillator plate volts can give on the average an incident intensity of only one full energy proton or less per burst on the detector.

b) The Detector

The scintillation crystals chosen were NaI(Tl) and CsI(Tl) each 1 1/2" long X 1 1/2" diam., encapsulated by Harshaw Chemical Co. to be sure of maximum light output. In both cases, the 1 1/2" length was sufficient to stop completely 100 MeV protons. These are shown in Figs. 5a, 5b respectively. The photodiodes employed were one RCA Victor Type 200-4-25-0.3 and one Simtec Type LC-100-2.0-85. These are shown in Figs. 6a, 6b respectively. Most of the initial work was done with the RCA diode and as an initial configuration the crystal was coupled to the diode through a thin (~1/16") piece of lucite using silicone jelly as the coupling medium. Initial pressure was exerted to insure good coupling and a ring structure served both as a holding and centering device and as a light shield. This proved unsatisfactory because it was found very easy to exert excessive initial pressure and separate the silicon wafer from its can. A configuration like Fig. 7 was then tried and proved successful. The
springs and hood cause the crystal-light pipe and light pipe-detector interfaces to be under slight but constant pressure. This ensures good coupling and also forces any air bubbles which might form in the coupling medium to the outer edges and eventually out.

Realizing the temperature dependence of noise, it was decided to cool both diodes and so cooling arrangements whereby both diodes could be cooled by means of dry ice were constructed in the Foster Radiation Laboratory machine shop. (See Figs. 8a, 8b). The design was such that the detector could be placed inside the external beam pipe of the cyclotron to prevent ice formation on all surfaces. The end plate was made of plexiglass to prevent heat conduction. Initially the ring structure and hood were made of aluminum, but graphs (11) of the temperature dependence of the light output of CsI(Tl) showed that at -56.2°C (dry ice temperature) the light output is only 85% that at room temperature (See also Fig. 9). An attempt was made to prevent the CsI(Tl) from cooling while cooling the photodiode by using plexiglass instead of aluminum for the ring structure and hood. This proved unsuccessful in that pulse height drifting was observed up to ½ hour after cooling had commenced. However, the use of the plastic was retained to ensure extra slow cooling of the crystal and thus minimize any chance of the crystal cracking due to the difference in thermal expansion between itself and its aluminum can. This slow cooling idea was also applied to the NaI(Tl), although from graphs in Ref. 12 it was calculated that the pulse height would increase by 11% when NaI(Tl) is cooled.
c) The Detecting Apparatus

An elementary consideration of the photodiode shows that it only changes the incident photon pulse into an electrical pulse and, unlike the photomultiplier, does not perform any internal amplification. As a result, the output of the photodiode is somewhat under 1 mV and so requires much amplification. One of the better amplifiers specifically designed for this is made by Ortec. The Ortec 101 preamplifier was used after the Ortec 100A had been rejected because of excessive noise and the 101XL had been rejected because of excessive pickup. The Ortec 101 is a very low noise charge sensitive preamp employing capacitative feedback and having a pulse height gain of approximately 1000. Its output is fed through a cathode follower so that the pulse may be transmitted over long cable distances (up to 500 ft. of 93 ohm cable according to the manufacturer). The preamp was connected to the detector using only about 6" of cable, thus keeping detector noise to a minimum by having essentially no contribution of cable capacitance to the total input capacitance and having minimized a region very susceptible to pickup pulses. The preamp was also well grounded. The signal was fed through ~100 ft. of 93 ohm cable to the Ortec 201 amplifier after which it was kicksorted and analysed by a method to be outlined below. The Ortec 201 is an essentially noise-free amplifier of variable gain 10 to 160 with a discriminator and post amplifier of variable gain 2 to 16 in the output. Two kicksorters, a Victoreen 400 channel and a TMC 256 channel, were available for use.

A further note may be added about the Ortec 101 preamp. Its output pulse shape (~2 μsec. rise, ~10 μsec. fall) is determined
by three 1 \( \mu \)sec. clipping time constants in three successive stages. Since the decay time of CsI(Tl) is 1.1 \( \mu \)sec., it was thought that these might be a little short for collecting all the light emitted. Contemplation of extending each of these to 2 \( \mu \)sec. to give a total rise time of 3.5 \( \mu \)sec. was abandoned because then the pulse rise time would be far too long for the kicksorter to be able to handle the pulses properly.

2. The Experiment

Before an actual test was carried out, the system first had to be aligned by monitoring the beam to be used with a plastic scintillator-photomultiplier unit borrowed from P.M. Portner\(^{(10)}\). The process on occasion took several hours because of the critical nature of the adjustments to be made to the bending and switching magnets and to the aligning of Slit No.1 (See Fig. 4) with the other slits and the beam, so that a "clean" peak, i.e. one without high- or low-energy straggler components, could be employed for the test. Secondly, various aluminum absorbers were inserted into the beam by means of the Analyser Box (See Fig. 10) which consists of three wheels of ten absorbers each, any combination of which could be electrically inserted into the beam. The resulting pulse heights were noted and this, coupled with a knowledge of the zero-pulse-height channel of the kicksorter (obtained from a calibration using a precision mercury pulser), gave the energy of the beam under study. Invariably, it was found to be the full energy beam, not one 7 MeV or 14 MeV less (See Fig. 12). Thirdly, a beam profile picture was taken (See Fig. 11).

Then and only then was the detector under test inserted
into the beam. Two kicksorters were employed, one to watch the total spectrum including pileup pulses, and one to analyse the main proton peak. These were employed not only for the full energy peak, but also for the peaks corresponding to three different thicknesses of the aluminum absorbers. It was hoped that once noise and straggle contributions were quadratically subtracted from the peaks there would remain an "intrinsic" detector resolution, the same for all cases.

The peak analysis was performed as follows: The post amplifier and discriminator of the Ortec 201 Amplifier were employed to spread the proton pulse over approximately 30 kicksorter channels. Then, after sufficient data had been collected, and with the cyclotron on but no protons incident on the detector, two pulser lines were introduced at the input of the preamplifier, i.e. at the same place as the detector signal goes in, before any amplification stage, and were arranged so as to appear in the kicksorter spectrum on either side of the proton peak. Knowing their respective dial settings on the pulser, and assuming the kicksorter to be linear in between them (a very reasonable assumption), the kicksorter channels were calibrated in terms of the pulser dial. The peak location and width were expressed in terms of the pulser dial and the resolution was calculated. The resolution of the pulser lines was also calculated to give the contribution of the total noise to the peak. Where necessary, Gaussian paper (14) was employed. All results are tabulated in the next section.

The straggle widths were calculated using a formula due to W.T. Link (13):

$$\Delta E_f (\text{STR}) = 0.0246 \frac{3.34}{E_f} \left( E_i - E_f \right)^{\frac{1}{2}} \text{ MeV}$$

$$\frac{0.78}{E_f}$$
where $\Delta E_f$ (STR) is the straggle width of the protons of final energy $E_f$ in MeV expressed as a full width at half maximum, and where $E_i$ is the initial energy in MeV. These widths are tabulated below in Table I. The absorber thickness listed for Analyser Box Absorber 000 in place is due to the aluminum encapsulation about the crystal, as quoted by the manufacturer. $E_f$ was calculated from data published by Rich and Madey (15). The primary beam of course is not completely monokinetic, but has a spread in energy $\Delta E_i$. After degradation to energy $E_f$, this spread is magnified to

$$\Delta E_f = \left( \frac{E_i}{E_f} \right)^{0.78} \Delta E_i \text{ MeV}$$

and should be added quadratically to the spread due to straggle. However, since $\Delta E_i < 0.1$ MeV, the corresponding $\Delta E_f < 0.15$ MeV at $E_f = 61$ MeV and $(\Delta E_f)^2 < 0.022 \text{ MeV}^2$. At any $E_f$ used, this $(\Delta E_f)^2$ is negligible in comparison to the $\Delta E_f$ (STR) $^2$ calculated.

### Table I

<table>
<thead>
<tr>
<th>Absorber</th>
<th>Absorber Thickness</th>
<th>$E_f$, MeV</th>
<th>$\Delta E_f$(STR), MeV</th>
<th>$\Delta E_f$(STR)$^2$, MeV$^2$</th>
</tr>
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<tr>
<td>000</td>
<td>0.29 $\text{gm/cm}^2$</td>
<td>98</td>
<td>0.384</td>
<td>0.15</td>
</tr>
<tr>
<td>220</td>
<td>&quot;</td>
<td>87</td>
<td>1.01</td>
<td>1.02</td>
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<tr>
<td>440</td>
<td>&quot;</td>
<td>75</td>
<td>1.46</td>
<td>2.13</td>
</tr>
<tr>
<td>660</td>
<td>&quot;</td>
<td>61</td>
<td>1.96</td>
<td>3.84</td>
</tr>
</tbody>
</table>
RESULTS

Typical total spectra are shown in Fig. 13. Of note is the fact that the insertion of the absorber causes the beam to become more diffuse and thus add proportionately to the low energy background observed, as may be seen by comparing the first sixty channels of the two spectra. Also of note is the lack of pileup pulses: a precaution taken lest too much pileup contribute to the observed peak width. A typical analysis spectrum is shown in Fig. 14, with the peaks plotted using Gaussian paper in Fig. 15. The calculated proton energies were also plotted against the peak height in pulser divisions to make sure no malfunction of the Analyser Box had occurred (See Fig. 16). For Fig. 16, it is to be noted that the origin should be a point on the correct straight line since zero pulse height should correspond to zero energy. The sensitivity of this is fully appreciated when it is realized the peak locations are accurate to at least 10 pulser divisions, i.e. the points have virtually no horizontal error bars.

The data obtained are tabulated below in Table II. The following terms are defined:

ABS is the absorber inserted into the beam,

$E_f$ is the calculated mean proton energy after passing through the absorber,

P.P.H. is the proton pulse height expressed in pulser dial divisions, as explained in the previous section,

TLW is the total line width expressed as $\%$ FWHM,
\[(NLW)^2 \quad \text{is (Noiseless Width)}^2 = (TLW)^2 - \text{(Noise width FWHM from the pulser line)}^2,\]
\[S^2 \quad \text{is (Straggle)}^2 = \Delta E_f \text{ (STR)}^2 \quad \text{obtained from Table I,}\]
\[I^2 \quad \text{is (Intrinsic Width)}^2 = (NLW)^2 - S^2.\]

Data for NaI(Tl) and CsI(Tl) on the Simtec detector at room temperature are not included because the resolution obtained was far worse than for any of the other cases (13% as compared to 1% to 5%), due to an excessively high noise level in the Simtec at room temperature.
### Table II

**Final Results**

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Detector</th>
<th>ABS</th>
<th>$E_r$, MeV</th>
<th>P.P.H.</th>
<th>TLW</th>
<th>NLW</th>
<th>$NLW^2$, MeV²</th>
<th>$S^2$, MeV²</th>
<th>$I^2$, MeV²</th>
<th>I, MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI(Tl) (cooled)</td>
<td>Simtec</td>
<td>000</td>
<td>98</td>
<td>1474</td>
<td>1.22%</td>
<td>1.19%</td>
<td>1.36</td>
<td>0.15</td>
<td>1.21</td>
<td>1.10</td>
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<td></td>
<td></td>
<td>220</td>
<td>87</td>
<td>1313</td>
<td>1.67%</td>
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<td>2.04</td>
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<td>440</td>
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<td>1139</td>
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<td>3.10</td>
<td>2.13</td>
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<td>660</td>
<td>61</td>
<td>934</td>
<td>3.75%</td>
<td>3.72%</td>
<td>5.15</td>
<td>3.84</td>
<td>1.31</td>
<td>1.14</td>
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<tr>
<td>RCA (Room T) (cooled)</td>
<td>Simtec</td>
<td>000</td>
<td>98</td>
<td>2197</td>
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<td>1.64%</td>
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<td>2.32</td>
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<td>1682</td>
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<td>2.45%</td>
<td>3.38</td>
<td>2.13</td>
<td>1.25</td>
<td>1.12</td>
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<td>6.70</td>
<td>3.84</td>
<td>2.86</td>
<td>1.69</td>
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<td></td>
<td></td>
<td>000</td>
<td>98</td>
<td>1691</td>
<td>1.54%</td>
<td>1.40%</td>
<td>1.76</td>
<td>0.15</td>
<td>1.61</td>
<td>1.27</td>
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<tr>
<td>NaI(Tl) (cooled)</td>
<td>Simtec</td>
<td>000</td>
<td>98</td>
<td>802</td>
<td>2.27%</td>
<td>2.22%</td>
<td>4.75</td>
<td>0.15</td>
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<td></td>
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<td>782</td>
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<td>1.47%</td>
<td>2.07</td>
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<td>98</td>
<td>799</td>
<td>2.55%</td>
<td>2.20%</td>
<td>4.66</td>
<td>0.15</td>
<td>4.51</td>
<td>2.12</td>
</tr>
</tbody>
</table>
DISCUSSION AND CONCLUSIONS

1. Discussion of Results

The results are analysed with regard to proton pulse height, overall resolution and intrinsic line width.

a) Comparative Proton Pulse Heights

Relevant information is given in Table III. Significant ratios are listed in Table IV and are discussed below.

Table III

<table>
<thead>
<tr>
<th>Relevant Information For Proton Pulse Height Comparison</th>
<th>Simtec</th>
<th>RCA</th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area, mm$^2$</td>
<td>100</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Diffusion Depth</td>
<td>0.2</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\lambda_M$, Å</td>
<td>-</td>
<td>-</td>
<td>4100</td>
<td>5700</td>
</tr>
</tbody>
</table>

$\lambda_M$ = the wavelength of maximum emission

Table IV

<table>
<thead>
<tr>
<th>Comparison of Proton Pulse Heights at 98 MeV</th>
<th>CsI(Tl)</th>
<th>NaI(Tl)</th>
<th>Simtec</th>
<th>RCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\left(\frac{\text{CsI(Tl)}}{\text{NaI(Tl)}}\right)$ cold</td>
<td>-</td>
<td>-</td>
<td>1.84</td>
<td>2.12</td>
</tr>
<tr>
<td>$\left(\frac{\text{cold}}{\text{room T}}\right)$ RCA</td>
<td>0.77</td>
<td>1.02</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\left(\frac{\text{Simtec}}{\text{RCA}}\right)$ cold</td>
<td>0.87</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\left(\frac{\text{Simtec}}{\text{RCA}}\right)$ x A.F.</td>
<td>1.7</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

A.F. = Area Factor = 2
The ratio \( \frac{\text{CsI}(\text{Tl})}{\text{NaI}(\text{Tl})} \) \( \sim 2 \) reflects the better optical match with the photodiode which is possible with the longer wavelength of CsI(Tl) light. The somewhat higher value of this ratio obtained with the RCA photodiode probably results from the fact that the diffusion layer is thicker and hence the longer wavelength of CsI(Tl) is more important. The ratio \( \frac{\text{cold}}{\text{room T}} \) RCA for CsI(Tl) and 1.02 for NaI(Tl). These correspond to the temperature dependence of conversion efficiency in the two scintillators and agree tolerably with the values 0.85 and 1.11 obtained by Homma and Takemoto(11) and Mott and Sutton(12) respectively. The ratio \( \frac{\text{Simtec}}{\text{RCA}} \) cold is 0.87 for CsI(Tl) and 1.0 for NaI(Tl). It must be remembered, however, that the area of the Simtec photodiode is only 100 mm\(^2\) and had it been 200 mm\(^2\) (equal in area to the scintillator and the RCA diode), almost double the pulse height might be expected.

b) Overall Resolution

In this section, the overall resolution obtained with the full energy beam is considered. The best resolution was obtained with the cooled Simtec-CsI(Tl) combination, viz. 1.22\%, and the worst was obtained with the Simtec at room temperature, viz. 13\% (not shown). Had a larger area photodiode been used, the resolution for the cooled Simtec-CsI(Tl) unit might have been considerably less than 1\%. Thus it is seen that the Simtec detector though not usable at room temperature, is very promising at dry ice temperature. On the other hand, if one wishes to avoid the considerable inconvenience of cooling the detector, the RCA-CsI(Tl) combination is available. In either case,
with the preamplifier used, electronic system noise makes no significant contribution to the overall resolution and total noise is of small importance when the detector is cooled.

With a surface barrier diode and CsI(Tl), Fan\(^{(4)}\) obtained a resolution of 15% for 40 MeV \(\alpha\)'s from the Heavy Ion Accelerator at the University of California. If the peak was due to monokinetic \(\alpha\)'s, the cooled Simtec-CsI(Tl) unit would have exhibited a resolution of 3.4% (calculated using the fact that, for the unit, resolution varies inversely as the energy, and assuming that the particles produce only 80\%(16) of the light protons do at 40 MeV, and assuming that there is no straggle width introduced in going through the entrance window of the detector). It would thus seem that the cooled Simtec-CsI(Tl) unit is the most promising scintillator-photodiode unit available.

c) Intrinsic Line Width

When the total noise and the straggle introduced by absorbers are quadratically subtracted from the total width of the proton line, the remainder, here called the intrinsic width, should be characteristic of the particular detector combination used, and should be independent of the particle energy. Intrinsic widths are listed in Table II for four different energies for the cooled Simtec-CsI(Tl) and for the RCA-CsI(Tl) at room temperature. These widths are seen to be closely grouped in the first case, and three out of four are closely grouped in the second case. The intrinsic width in the first case would have been substantially reduced if the photodiode area had been equal to the scintillator area. The intrinsic width may be regarded as a figure of merit for the device.
2. **Improvements**

Since the cooled Simtec-CsI(Tl) appears to be the most promising arrangement, possible improvements in it are now considered. First, as previously mentioned, the area of the photodiode should be increased to match that of the scintillator. Second, the thinnest possible diffusion depth should be sought. Third, the depletion layer should be no thicker than necessary to absorb all the light from the scintillator. Finally, the optical coupling could no doubt be improved. Possibly the scintillator and photodiode could be encapsulated together. In any case it is worthwhile to keep the entry window for the particles as thin as possible.

Thus it is seen that for the cooled Simtec-CsI(Tl) unit, with the improvements suggested, a total resolution of considerably less than 1% at 100 MeV might be expected. This would make the unit comparable with a NaI(Tl)-photomultiplier unit which has a resolution of 0.8%\(^6\) at this energy. Because of the difference of the variation of resolution with energy for the scintillator-photodiode and the scintillator-photomultiplier, the scintillator-photodiode might find numerous applications at higher energies where its slightly better resolution, smaller size and non-susceptibility to magnetic fields could be used to advantage.
The Semiconductor Particle Detector

The semiconductor particle detector is basically a solid state ionization chamber, i.e. an insulator between two electrodes. A nuclear particle in passing through creates ionization by collision, which ionization is swept out by the electric field, the pulse of current thus obtained being amplified and measured. For the current pulse to be an accurate measure of the particle energy, the particle must be stopped entirely in the volume, all charge or some calibrated fraction of it must be collected in a time compatible with experimental requirements, the energy lost by the particle going through the window or dead layer must be minimal, and a maximum amount of ionization must be produced to give good statistics and a large signal above amplifier and current noise.

Such a solid state ionization chamber has several advantages, among which are, firstly: a solid's greater density and stopping power make it feasible to achieve complete absorption of long range particles. At the same time, the solid can also be made very thin to give a dE/dx measurement, which, coupled with an E measurement, leads to particle identification. Also, as will be seen shortly, of the three, i.e. the solid state ionization chamber, the gas ionization chamber, and the scintillator-photomultiplier unit, the first gives the signal with the least % fluctuation, i.e. the best resolution.

The properties a solid must have to be used as an
ionization chamber are: 1) a very low density of free electrons or holes to minimize the standing current produced when bias is applied so that noise is well below signal and charge collection is not interfered with; 2) long carrier drift lengths so that the charge liberated by the incident radiation can and does reach the electrodes and is not held up or lost at traps or recombination centers; 3) a high Z for greater stopping power; 4) availability in single crystals (not essential but desirable) so that the detector behaves in an ideal way. Needless to say, such a solid does not exist and the idea of a single block of solid between two electrodes being used as an ionization chamber must be abandoned. However, there is one configuration which produces essentially the same effect: the reverse-biased n-p junction, the so-called rectifying junction counter, and it is this which has proved so successful in certain areas of nuclear spectroscopy.

If an n-p junction is reverse biased, a depletion layer containing almost no free electrons and holes is formed between the n and p regions. Under these conditions, current flow through the device is severely limited since neither the n nor the p region can supply carriers of the appropriate sign. In addition, the field in the crystal distributes itself automatically almost entirely across the depletion layer, suiting the purpose of using this region as the "chamber" remarkably well. Thus so long as the solid is available in uniform single crystals and has a long carrier drift length, it can be used in this manner, even though it has a high density of free electrons and holes. The price paid is that there is a limit to the counter volume, since an applied field can reduce carrier concentration
by just so much and the field can be increased just so far before breakdown. Thus the use of these detectors is limited to the lower energy particles (Typical upper values are 18 MeV protons, 1.2 MeV $\beta$'s, 72 MeV $\alpha$'s.), whereas scintillators can stop particles of much higher energy, as noted earlier.

As stated above, the depletion layer forms at the n-p junction, and extends into both the p-type and the n-type regions. In the p-type region, $N_D = 0$ and in the n-type region, $N_A = 0$, where $N_D$ and $N_A$ are the donor and acceptor impurity concentrations respectively. Thus Poisson's equation for a depleted p-type region is:

$$\frac{d^2 V}{dx^2} = \frac{4 \pi e}{K} (N_A^+ + n - p)$$

where $N_A^+$ is the ionized acceptor impurity concentration, 

$n$ and $p$ are respectively the local electron and hole densities,

$K$ is the dielectric constant of the crystal.

At room temperature, one may assume that the impurities are fully ionized so that $N_A^+ = N_A$. Within the depletion layer, $n$ and $p$ are very small and so it can be assumed that $N_A^+ \gg n, p$, i.e.

$$\frac{d^2 V}{dx^2} = \frac{4 \pi e N_A}{K}.$$ Integrating this equation and applying boundary conditions leads to $V = 2 \pi e N_A w_p^2$ or $w_p = \left( \frac{KV}{2 \pi e N_A} \right)^{1/2}$, where $w_p$ is the width of the depletion layer in the p-region and $V$ is the corresponding potential difference. A similar expression holds for the n-region. Normally the impurity concentrations are very different in the two regions so that the depletion layer extends only in the high resistivity region, say the p-region. Then it can be said that the total width $w$ of the depletion layer is given by $w \approx \left( \frac{KV}{2 \pi e N_A} \right)^{1/2}$. 
If all acceptors are ionized, the resistivity of the material is
\[ \rho = \frac{1}{N_A e \mu_p} \], where \( \mu_p \) is the hole mobility. Then \( w = \left( \frac{K \mu_p \rho V}{2 \pi} \right)^{\frac{1}{2}} \).

If \( \rho \) is in ohm-centimeters and \( V \) is in volts then
\[ w = 3.2 \times 10^{-5} \left( \rho V \right)^{\frac{1}{2}} \text{ cm. for p-type silicon} \]
and \[ w = 5.3 \times 10^{-5} \left( \rho V \right)^{\frac{1}{2}} \text{ cm. for n-type silicon.} \]

Typical values of \( w \) are in the neighborhood of hundreds of microns, but may run as high as one or two millimeters.

To the same order of approximation, the capacity of the junction will be that of a parallel plate condenser of thickness \( w \) with a silicon dielectric, i.e. \( C = \frac{KA}{4 \pi w} = \frac{A}{2 \pi \mu_p \rho V} \) for p-type silicon. \( w \) and \( C \) can be obtained through nomographs such as the one by Williams and Webb (5).

In considering the actual construction of these devices, it seems most logical to have a configuration as in Fig. 17a, i.e. the particle incident directly on the depletion layer. However, for the purposes of construction and detection, it has been found easier and better to have a configuration like Fig. 17b, with the particle incident through the front face with, naturally, the front face layer very thin. This layer can be either n-type or p-type material and is constructed on the remainder of the block which is p-type or n-type material respectively. There are two methods to do this and detectors made by these methods are called diffusion type counters and surface barrier type counters respectively.

For the diffusion type, an appropriate substance is diffused to a depth of 0.1 to 2 microns into a block of high resistivity silicon or germanium. Common materials are phosphorus for p-type
and gallium or boron for n-type silicon. The phosphorus and p-type are the preferred configuration because it is easier to obtain high resistivity floating-zone-refined p-type silicon, and because it is found easier to diffuse phosphorus, than boron, and simultaneously diffuse aluminum on the back surface to establish an ohmic contact. Contact with the front surface is simplified by the high conductivity of this surface, and a spring wire or gold leaf fastened with conducting cement usually suffices.

Surface barrier types are made on n-type crystals of silicon or germanium where spontaneous oxidation gives an inversion layer on the front surface having properties very like a diffused p-type layer. Gold is then evaporated over the top to form the top electrode. Contact with the back surface is achieved through a thick layer of evaporated aluminum.

As to materials, silicon is more popular than germanium in spite of its lower Z, because germanium can be used only when cooled whereas silicon behaves very well both when cooled and at room temperature.

In comparing the diffusion and surface barrier types, the surface barrier has the advantage that it can be prepared at or near room temperature, whereas the diffusion type requires heating to approximately $1000^\circ C$, which heating must be done carefully and has the adverse effect of reducing carrier drift lengths. In addition, the gold layer of the surface barrier type is typically 50 Å thick, giving the device effectively windowless operation, whereas Williams and Webb\(^{(5)}\) report a window thickness for diffusion types of approximately half the diffusion depth. However, the diffusion
type has several points in its favor, one of which concerns the ohmic contact at the back surface. A good one is easily established during the diffusion process, but doing this for the surface barrier type takes away two advantages it has, namely no loss of carrier drift length and complete construction at room temperature. Another point is the question of encapsulation and edge protection so that surface films cannot give leakage paths in parallel with the junction and thus increase current noise. Complete edge encapsulation is the answer and the much more rugged surface of the diffusion type is a decided advantage. Photographs of both types are shown in Fig. 18.

These detectors have been said to have properties which make them useful as spectrometers. Their applicability as spectrometers can be seen by considering the factors which affect resolution. These can be divided into four broad classes: statistical limitations, incomplete charge collection, detector noise, and radiation damage. Incomplete charge collection, although important, arises mostly in devices having special configurations and is of no consequence in this work. Radiation damage, also important, is not applicable for this work either.

The most fundamental contribution to the standard deviation is that due to fluctuations in N, the number of ion pairs produced by an incident particle in the depletion layer. The signal in this case is $\bar{q} = N_{e}$, assuming perfect charge collection. However, since the process of ionization is a cascade one, the final set of events which produce N ion pairs, thereby leaving no electron with more than the threshold energy for impact ionization, are independent of one another. Thus the standard deviation in N is $\sqrt{\frac{N}{}}$, i.e.
\[ \sigma = e(N)^{\frac{1}{2}}, \quad \sigma/\bar{q} = (N)^{-\frac{1}{2}}. \]

But \( N = W/w \) where \( W \) is the particle energy and \( w \) is the mean energy per ion pair, i.e. \( \sigma/\bar{q} = (w/W)^{\frac{1}{2}} \), and in silicon \( w = 3.6 \text{ eV} \). This value, when compared to the 30 eV per ion pair of the gas ionization chamber and the 130 eV per photo-electron of the scintillator-photomultiplier unit, shows the superiority of the semiconductor detector and, in essence, means that for the same energy particle the semiconductor detector has the largest \( N \) and thus the best resolution. Resolution can be expressed in percent using \( \sigma/\bar{q} \), but it can also be indicated by the energy of a particle which would produce a signal equivalent to \( \sigma \), i.e. \( (\sigma w)/e = (w/W)^{\frac{1}{2}} \).

The most familiar way to express it is through the full width at half maximum (FWHM) of the peak, which, if the peak shape is Gaussian, is 2.35 \( \sigma \).

Detector noise can be divided into two broad categories: thermal noise and current noise. By thermal noise is meant Johnson noise with the mean square voltage proportional to the temperature and thus is minimized by cooling. Current noise arises when a field is applied to the detector and the resulting current made up of holes and electrons is interrupted by various processes e.g. introducing and withdrawing carriers at the electrodes, and trapping, recombining and thermally generating carriers within the detector. A complete theoretical picture of these processes has never been presented, and so this phenomenon is considered from the point of view of volume generated noise and surface generated noise. Volume generated noise arises out of the spontaneous formation of hole-electron pairs within the volume of the detector. Normally this is negligible, but with short carrier drift lengths or large depleted volumes, it can be
minimized by cooling the detector. Surface generated noise arises from currents near the junction edge where the high electric field in the depletion layer comes to the surface and creates leakage paths parallel to the junction. This is minimized by special surface and edge treatments, normally carried out by all manufacturers, and then the edge is protected by special encapsulation (See Fig. 18).

The charge released by a 1 MeV particle stopped completely in the depletion layer is about $5 \times 10^{-14}$ Coulomb, i.e. with a detector capacitance of 100 pf, this amounts to a voltage signal of 0.5 mV. This evidently requires amplification and for spectroscopic reasons, this amplification must be constant and stable. To do this a charge sensitive pre-amplifier with capacitive feedback is employed. Such preamplifiers are available commercially and more than satisfy all stringent requirements since, in most cases, amplifier noise is small in comparison to actual detector noise.
APPENDIX B

The Calculation of Relative Pulse Heights for CsI(Tl) and NaI(Tl)
on a Photodiode

In Figs. 1a, 1b respectively, are shown the emission spectra of NaI(Tl) and CsI(Tl) for γ excitation, i.e. I(λ) is plotted against λ for each of the crystals. The subscript 1 refers to NaI(Tl), subscript 2 to CsI(Tl). The values of I₁(λ) and I₂(λ) are arbitrary and are not normalized to one another.

Normalization is carried out by applying to each curve S(λ), the S-ll response (Fig. 1a). This gives a number proportional to the number of electrons per wavelength interval obtained at the output of the photomultiplier as a function of wavelength, i.e.

\[ I(\lambda)S(\lambda) = n_e(\lambda) \]  (See Fig. 19).

Integrating over all λ gives a number proportional to the total number of electrons obtained, i.e. to the pulse height. Thus

\[ n = \int n_e(\lambda)\,d\lambda = \int I(\lambda)S(\lambda)\,d\lambda. \]

Harshaw(7) quotes the ratio \( n_1 / n_2 = 210 / 55 \). The ratio \( n_1 / n_2 \) was calculated from the respective areas under the curves. The ordinates of \( I_2(\lambda) \) vs. λ were then multiplied by a constant to give \( I'_2(\lambda) \) so that \( n'_1 / n'_2 = 210 / 55 \).

Then \( I'_1(\lambda) \) and \( I'_2(\lambda) \) were multiplied by D(λ), an enlarged section of the quantum detectivity of a 0.3μ photodiode (Fig. 20 taken from Fig. 3) to give Figs. 21a, 21b respectively. These are graphs of \( n_p(\lambda) \) vs. λ, where \( n_p(\lambda) \) is proportional to the number of hole-electron pairs produced per unit wavelength.

Integrating each curve gives \( n_{pl} \) and \( n_{p2} \) for NaI(Tl) and CsI(Tl),
respectively, on a photodiode. It was found that \( n_{p1} / n_{p2} = 1.17 \), i.e. for the two crystals on the same photodiode, for the same incident energy and crystal geometry, and for the same efficiency in optical coupling, NaI(Tl) should give a pulse of height 17% greater than that for CsI(Tl).

However, it is to be noted that this applies for \( \gamma \) rays. For protons, the spectrum for NaI(Tl) is essentially the same as for \( \gamma \) rays(12), but Gwin and Murray(9) have noted an extension of the spectrum for CsI(Tl) from 0.6\( \mu \) to beyond 0.7\( \mu \) (See Fig. 1c and compare with Fig. 1b), which, because of the nature of the quantum detectivity of the photodiode (Fig. 3), would lead one to expect a greater pulse height for CsI(Tl) than was calculated above.
REFERENCES

(1) Tavendale, A.J. and Ewan, G.T., Nucl. Instr. and Meth. 25, 185 (1963)
<table>
<thead>
<tr>
<th>Fig.</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>la</td>
<td>The Emission Spectrum of NaI(Tl) Due to Excitation, and the S-11 Response</td>
</tr>
<tr>
<td>lb</td>
<td>The Emission Spectrum of CsI(Tl) Due to Excitation</td>
</tr>
<tr>
<td>lc</td>
<td>The Emission Spectrum of CsI(Tl) Due to Proton Excitation</td>
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<tr>
<td>2a</td>
<td>Block Diagram of a Typical Scintillator-Photomultiplier Setup</td>
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<tr>
<td>2b</td>
<td>Block Diagram of a Typical Scintillator-Photodiode Setup</td>
</tr>
<tr>
<td>3</td>
<td>Quantum Detectivity and Reflection Losses for the Photodiode</td>
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<td>4</td>
<td>The Slit System</td>
</tr>
<tr>
<td>5a</td>
<td>The NaI(Tl) Crystal Used</td>
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<tr>
<td>5b</td>
<td>The CsI(Tl) Crystal Used</td>
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<tr>
<td>6a</td>
<td>The RCA Detector Used</td>
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<tr>
<td>6b</td>
<td>The Simtec Detector Used</td>
</tr>
<tr>
<td>7</td>
<td>The Scintillator-Photodiode (RCA) Unit</td>
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<tr>
<td>8a</td>
<td>The Scintillator-Photodiode (RCA) Unit in the Experimental Mount</td>
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<tr>
<td>8b</td>
<td>The Scintillator-Photodiode (Simtec) Unit in the Experimental Mount</td>
</tr>
<tr>
<td>9</td>
<td>Pulse Height vs. Temperature for CsI(Tl)</td>
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<td>10</td>
<td>The Analyser Box</td>
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<tr>
<td>11</td>
<td>The Beam Profile</td>
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<tr>
<td>12</td>
<td>Energy vs. Peak Channel for the Plastic + Photomultiplier</td>
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<tr>
<td>13a</td>
<td>Total Spectrum, RCA - CsI(Tl), Absorber 000</td>
</tr>
<tr>
<td>13b</td>
<td>Total Spectrum, RCA - CsI(Tl), Absorber 220</td>
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<tr>
<td>Fig.</td>
<td>Title</td>
</tr>
<tr>
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<td>14</td>
<td>Analysis Spectrum, RCA - CsI(Tl), Absorber OCO</td>
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<td>15</td>
<td>Analysis Spectrum on Gaussian Paper</td>
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<td>16</td>
<td>Calculated Final Energy vs. Pulse Height</td>
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<tr>
<td>17a</td>
<td>Semiconductor Detector With Edge Incidence</td>
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<tr>
<td>17b</td>
<td>Semiconductor Detector With End Incidence</td>
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<tr>
<td>18a</td>
<td>A Typical Diffusion Semiconductor Detector</td>
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<tr>
<td>18b</td>
<td>A Typical Surface Barrier Semiconductor Detector</td>
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<tr>
<td>19a</td>
<td>The Emission Spectrum of NaI(Tl) Corrected to S-11</td>
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<td>19b</td>
<td>The Emission Spectrum of CsI(Tl) Corrected to S-11</td>
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<td>20</td>
<td>An Enlarged Section of Fig. 3</td>
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<td>21a</td>
<td>The Emission Spectrum of NaI(Tl) Corrected to Fig. 20</td>
</tr>
<tr>
<td>21b</td>
<td>The Emission Spectrum of CsI(Tl) Corrected to Fig. 20</td>
</tr>
</tbody>
</table>
FIG. 1a

\[ I(\lambda) \text{ vs. } \lambda, \gamma \text{ on NaI(Tl)} \]

\[ S(\lambda) \text{ vs. } \lambda, \text{ S-II RESPONSE} \]

\[ I(\lambda), S(\lambda) \text{, arbitrary units} \]

\[ \lambda, \text{microns} \]

FIG. 1b

\[ I(\lambda) \text{ vs. } \lambda, \gamma \text{ on CsI(Tl)} \]

\[ I(\lambda), \text{ arbitrary units} \]

\[ \lambda, \text{microns} \]

FIG. 1c

\[ I(\lambda) \text{ vs. } \lambda, p \text{ on CsI(Tl)} \]

\[ I(\lambda), \text{ arbitrary units} \]

\[ \lambda, \text{microns} \]
FIG. 2a  A SCINTILLATOR-PHOTOMULTIPLIER SETUP

FIG. 2b  A SCINTILLATOR-PHOTODIODE SETUP

FIG. 3  QUANTUM DETECTIVITY & REFLECTION LOSSES FOR A 0.3 μ PHOTODIODE
SLIT NO. 2

SUT NO. 3

12° ANALYSING MAGNET

TO ANALYSER BOX AND DETECTOR

EXTERNAL BEAM

28° MAGNET

45° MAGNET

SLIT NO. 1

SLIT NO. 2

SLIT NO. 3

SYSTEM DIAGRAM - PLAN VIEW (NOT TO SCALE)

BEAM

0.015" 1"

1/16

3" 4"

1"

1/4

SLIT NO. 1 - PLAN VIEW

SLIT NO. 2 - PLAN VIEW

SLIT NO. 3

FIG. 4 THE SLIT SYSTEM
Fig. 5  a) (right) The NaI(Tl) Crystal Used
     b) (left)  The CsI(Tl) Crystal Used

Fig. 6a  The RCA Detector Used

Fig. 6b  The Simtec Detector Used
Fig. 7 The Scintillator-Photodiode (RCA) Unit

Fig. 8a The RCA-NaI(Tl) Configuration

Fig. 8b The Simtec-NaI(Tl) Configuration
FIG. 9 PULSE HEIGHT vs. TEMPERATURE FOR CsI(Tl)

FIG. 10 THE ANALYSER BOX
FIG. 11 THE BEAM PROFILE

FIG. 12 ENERGY vs. CHANNEL FOR PLASTIC + PHOTOMULTIPLIER

(1) CALCULATED $E_f$ ASSUMING $E_i = 100$ MeV
(2) CALCULATED $E_f$ ASSUMING $E_i = 93$ MeV
(3) CALCULATED $E_f$ ASSUMING $E_i = 85.5$ MeV

CALCULATED ENERGY $E_f$, MeV

CHANNEL NUMBER

KNOWN KICKSORTER
ZERO

0 20 40 60 80 100

-40 0 40 80 120 160 200
FIG. 13  a  RCA- CsI(Tl), ABSORBER 000
FIG. 13b  RCA-CsI(Tl), ABSORBER 220
Figure 14: Analysis Spectrum: Cooled RCA - CsI(Tl), Absorber 000

Figure 16: Calculated Energy vs. Pulse Height
FIG. 17a SEMICONDUCTOR DETECTOR WITH EDGE INCIDENCE

FIG. 17b SEMICONDUCTOR DETECTOR WITH END INCIDENCE

FIG. 18  a) (LEFT) DIFFUSION SEMICONDUCTOR DETECTOR
b) (RIGHT) SURFACE BARRIER SEMICONDUCTOR DETECTOR
FIG. 19a

$S(\lambda) \times I(\lambda) \text{ vs. } \lambda \text{ FOR NaI(Tl)}$

FIG. 19b

$S(\lambda) \times I(\lambda) \text{ vs. } \lambda \text{ FOR CsI(Tl)}$
FIG. 20
ENLARGED SECTION OF FIG. 3

\[ D(\lambda) \times 100 \]

\[ \lambda, \text{microns} \]

FIG. 21a
\[ D(\lambda) \times I(\lambda) \text{ vs. } \lambda \text{ FOR NaI(Tl)} \]

\[ D(\lambda) \times I(\lambda), \text{ arbitrary units} \]

\[ \lambda, \text{microns} \]

FIG. 21b
\[ D(\lambda) \times I(\lambda) \text{ vs. } \lambda \text{ FOR CsI(Tl)} \]

\[ D(\lambda) \times I(\lambda), \text{ arbitrary units} \]

\[ \lambda, \text{microns} \]