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The Elastic Scattering of 1.33 MeV Gamma Rays from Tin

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THE ELASTIC SCATTERING OF
1.33 MEV GAMMA RAYS
FROM TIN

by

J. Edward Terdal

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INTRODUCTION

An interesting effect predicted by quantum electrodynamics is the scattering of light by light.[1] This effect is non-linear[2] and is in contradiction to the classical Maxwell equations, since they are linear.[3]

Experimental verification of this effect has proven impossible in a crossed beam experiment, because of its extremely small cross section.[1] However another scattering process which is closely related to the scattering of light by light is that in which light is scattered by the static electric field surrounding a nucleus.[3] The scattering of light by a Coulomb field is referred to as Delbrück scattering or nuclear potential scattering.

The problem of Delbrück scattering is difficult both experimentally and theoretically. First of all, it is coherent with Rayleigh scattering and nuclear Thomson scattering. So to detect Delbrück scattering the contributions of these others to the total elastic scattering must be known. But since the L-shell contribution to the Rayleigh scattering amplitudes is not accurately known, it is difficult to tell conclusively whether a part of the total elastic cross section should be ascribed to Delbrück scattering or to incomplete Rayleigh scattering calculations. Secondly, the Delbrück[4] and Rayleigh cross sections are strongly peaked in the forward direction where photons from the compton process have energies close to that of the incident photons, therefore also to elastically scattered photons. A number of workers[3-7] have dealt with this problem, but taken together, their work gives no conclusive evidence for Delbrück scattering.

This thesis will discuss the theory of the scattering processes which occur in the energy range of a few MeV, and also some of the previous experiments in this area, and will report on the desirability of using a newly developed semi-conductor detector for this type of experiment.

THEORY

The interaction of gamma radiation with matter is characterized by the fact that each photon is removed from the incident beam in a single event. The scattering is either coherent or non-coherent. For coherent scattering the cross section is obtained by summing the amplitudes for the various processes in this category and then squaring this sum. On the other hand the total incoherent scattering cross section is found only by adding the cross sections of each individual inelastic process.

Because the internal state of the atom is unchanged in a coherent process the gamma ray recoil must be taken up by the atom as a whole, so the scattering is approximately elastic. This provides a means of distinquishing the coherent scattering from the much more probable incoherent Compton scattering, and from other inelastic effects. Experimentally this separation is the chief problem.[5]

This thesis discusses inelastic or non-coherent scattering briefly, and then elastic scattering in more detail.

Inelastic Scattering

The predominant inelastic scattering process around 1 MeV is the well known Compton effect[8] in which the gamma ray is scattered by an atomic electron, where the photon energies (E_o) are so large compared with the electron binding energies that the electrons can be considered as free. The interaction produces a photon deflected from the original direction at a scattering angle θ and at lower energy (E'), plus a recoiling electron. Conservation of energy and momentum give the following well known expression for the energy of the scattered quantum:

$$E' = \frac{E_0}{1+\alpha(1-\cos\theta)} \qquad \text{where} \qquad \alpha = \frac{E_0}{m_0 c^2} \quad ,$$

m_0c^2 being the rest energy of the electron.

It is evident that as the scattering angle approaches zero, the energy of the new photon approaches the energy of the incident photon.

Of special interest is the cross section of Compton scattering. Klein and Nishina [9] performed a quantum mechanical calculation and obtained the expression:

$$\left(\frac{d\sigma}{d\Omega}\right)_\theta = \frac{1}{2} r_0^2 \left\{ \frac{1}{[1+\alpha(1-\cos\theta)]^2} \left[1+\cos\theta + \frac{\alpha^2(1+\cos\theta)^2}{[1+\alpha(1-\cos\theta)]} \right] \right\} ,$$

r_0 representing the classical electron radius $\frac{e^2}{m_0c^2}$, and $(\frac{d\sigma}{d\Omega})_\theta$ representing the differential scattering cross section at an angle θ, being measured in units of cm^2/steradian/scattering center.

The relationship of Compton scattering of a 1.33 MeV gamma ray vs. angle is shown in figure I. [10]

Above incident photon energies of 1.02 MeV, a second type of inelastic interaction becomes possible. This is Pair Production, [11] in which a photon, in the field of a nucleus disappears with the creation of a positron-electron pair whose total kinetic energy is equal to the photon energy minus the mass-energies of the two particles which have been created.

As energy increases (at about 3 MeV) pair production becomes the predominant type of interaction between photons and matter.

Below energies of about 0.1 MeV the predominant mode of gamma

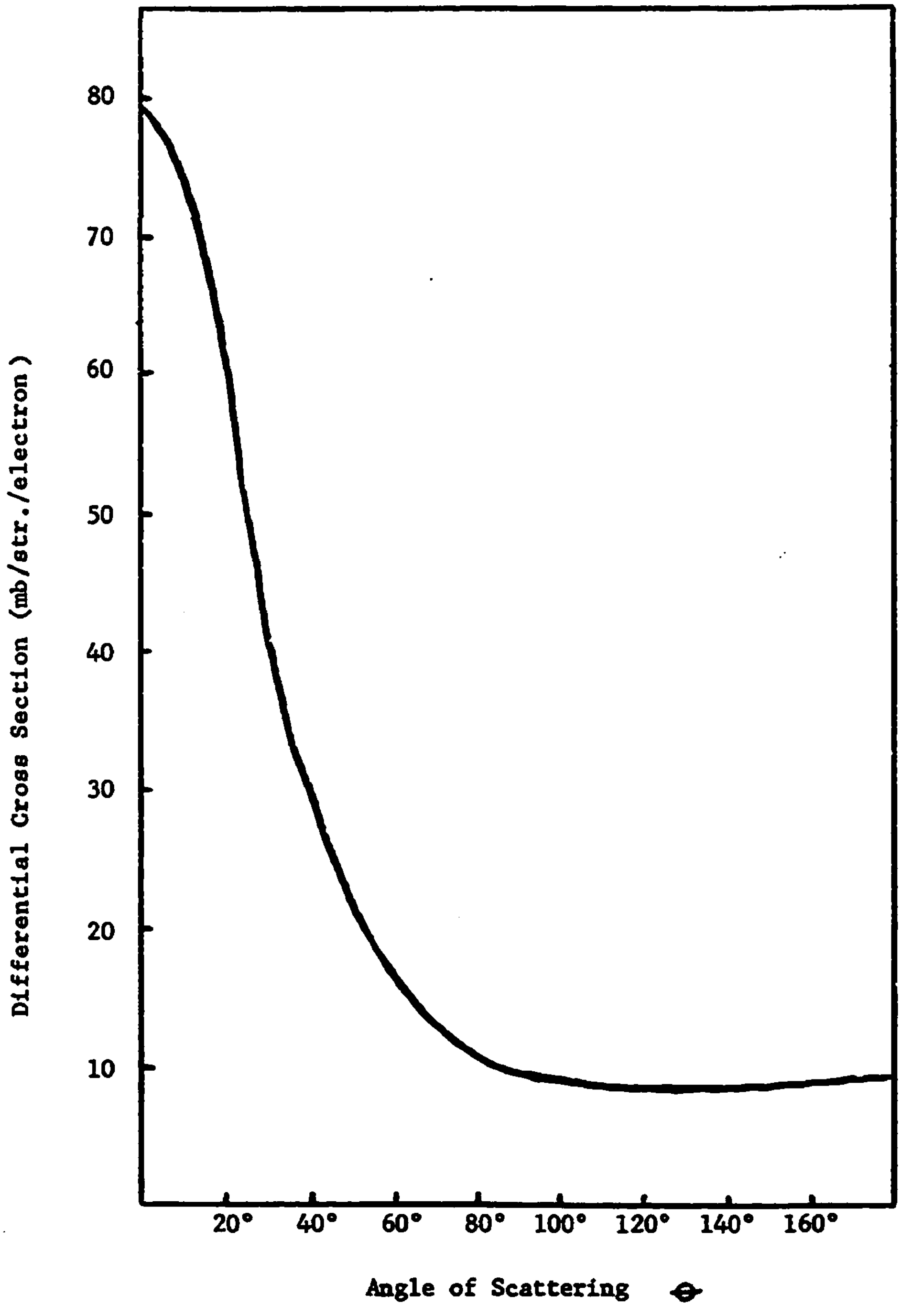

Figure I. Compton Cross Section vs. Angle ray interaction is the photoelectric effect.[12] This process is the total absorption of a photon by an electron which is initially bound in an atom. It is found that absorption increases rapidly with the tightness of the electron binding and that at energies greater than the K-electron binding energy about 80 per cent of the photoelectric absorption processes take place in the K-shell.

The energy of the photoelectron is equal to the energy of the incident photon minus the binding energy of the electron.

The relative strengths of the photoelectric, Compton, and pair production effects are shown in figure II.[13]

Elastic Scattering

The Klein-Nishina formula reduces to the classical Thomson equation in the non-relativistic case,[14]

$$\left(\frac{d\sigma}{d\Omega}\right)_{\theta} = \left(\frac{e^2}{m_0c^2}\right)^2 \frac{1}{2}\left(1+\cos\theta\right) \quad ,$$

where the energy of the incident photon is much smaller than the rest mass of the scattering center, i.e. for $\alpha \ll 1$.

Nuclear Thomson scattering is analagous to Thomson scattering from a free electron, and is a non-relativistic case since the rest mass of the nucleus is much greater than a few MeV. Therefore the classical Thomson equation can be applied. In the Thomson formula the classical electron radius (i.e., $r_0 = \frac{e^2}{m_0c^2}$), the electron charge (e) must be replaced by the nuclear charge (Ze), and the electron mass (m) by the nuclear mass (M). This gives then the nuclear Thomson cross section per unit solid angle. The greater mass of the nucleus allows only a negligible transfer of energy to itself, and

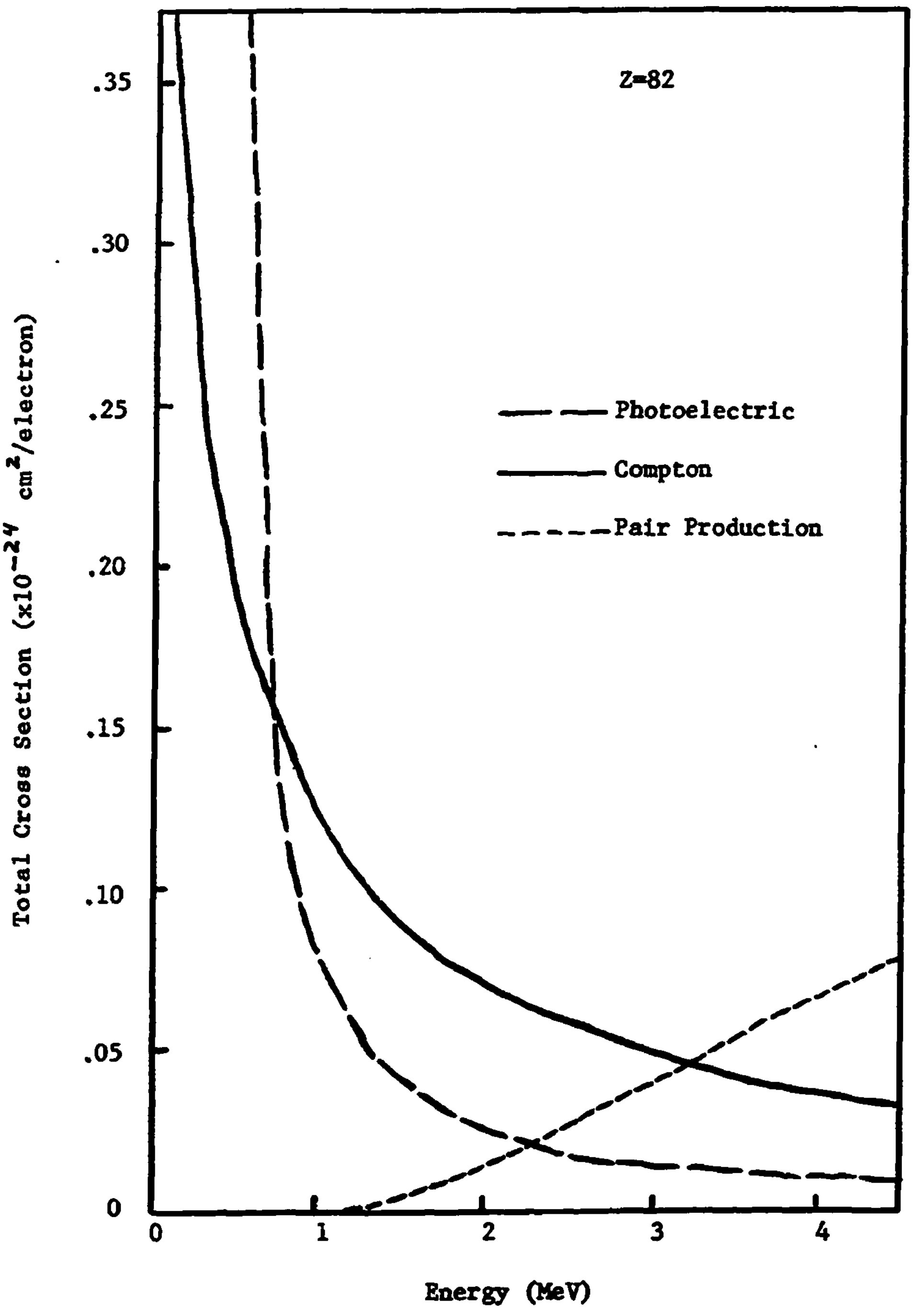

Figure II. Inelastic Cross Sections

the photon is therefore scattered elastically.

Rayleih scattering is the process whereby the tightly bound electrons of a high Z nucleus scatters the photon with the atom recoiling as a whole. It is well known in the x-ray region, where it accounts for x-ray diffraction. In this energy region the differential cross section is given by the cross section for Thomson scattering from an electron multiplied by the square of a form factor to take into account the atomic charge distribution.[3] The cross section is given as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\theta} = \frac{r_0^2}{2}(1+\cos^2\theta)\,|F(Q)|^2$$

where Q is the change of momentum of the photon.

The form factor as calculated by Bethe using the large components of the Dirac wave function[15] is

$$F(Q) = \sin(2\gamma \tan^{-1} Q)/\gamma Q(1+Q^2)^{\gamma} \qquad \text{where } \gamma = \sqrt{1-(\alpha Z)^2}$$

and α is the fine structure constant.

Form factor calculations are not exact because they consider only K-electrons, neglect relativistic effects, and consider only dispersive (virtual) scattering.[3]

Whereas early calculations neglected the effect of the nuclear Coulomb field in the intermediate states of the electron, Brown and Mayers[16,17] carried out calculations in the form of scattering amplitudes as functions of angle which took this into account. They calculated the Rayleigh scattering from the Mercury K-electrons of 1.28 and 2.56 mc^2 gamma rays.

The real parts of the scattering amplitudes of Brown and Mayers, extrapolated upwards about 10% from mercury to lead, assuming a rough

Z^5 dependence, are shown in figure III. The imaginary amplitudes may be neglected as they are negligible at this energy.

Delbrück scattering, or elastic "nuclear potential" scattering is due to pair formation in the static electric field of the nucleus, followed by pair annihilation and is intimately related to the scattering of light by light.[6] As suggested in the introduction, observance of this effect would show that quantum electrodynamics is superior to classical electrodynamics in its ability to describe processes in the atomic domain.

The Delbrück scattering amplitude consists of two parts,[18] an "absorptive" (imaginary) part, which is directly related to ordinary pair production, and a "dispersive" (real) part, which is the part arising from virtual pair production and annihilation. Below the pair production threshold the "absorptive" part is zero, but at higher energies it increases more rapidly at 0° than the "dispersive" part and predominates above about 10 MeV. For this reason it seems most valuable to look at energies of a few MeV or less, where the "dispersive" (real) part is expected to predominate.

The Delbrück scattering amplitude is quite difficult to obtain; however Ehlotzky, et al.,[4] have recently made numerical calculations of the real and imaginary parts for energies between 1 and 20 MeV at scattering angles from 0 to 120° with an accuracy of 5-10%. Figure IV shows the Delbrück amplitudes at 1.33 MeV for a lead scatterer.

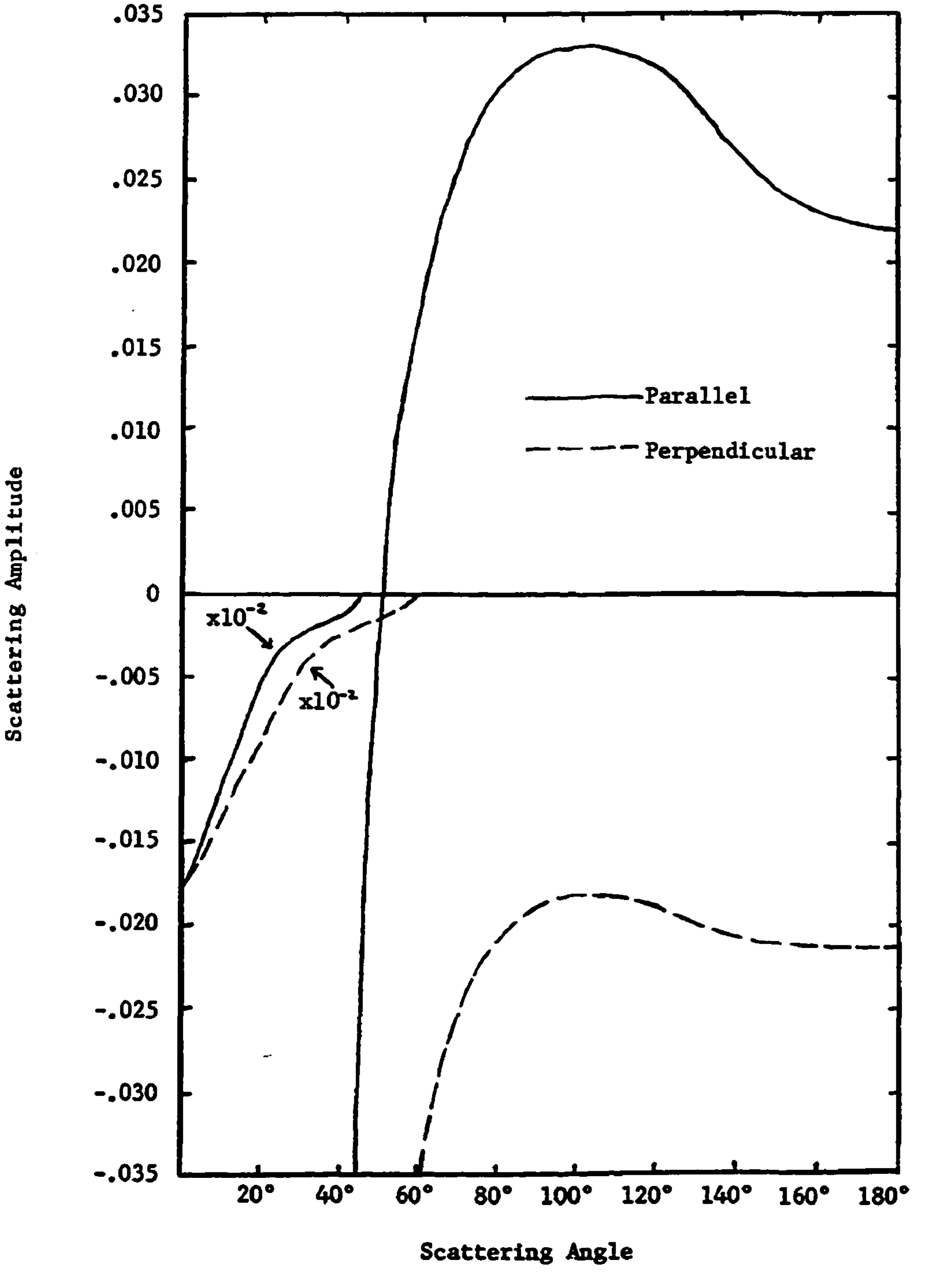

Figure III. Real Rayleigh Scattering Amplitudes

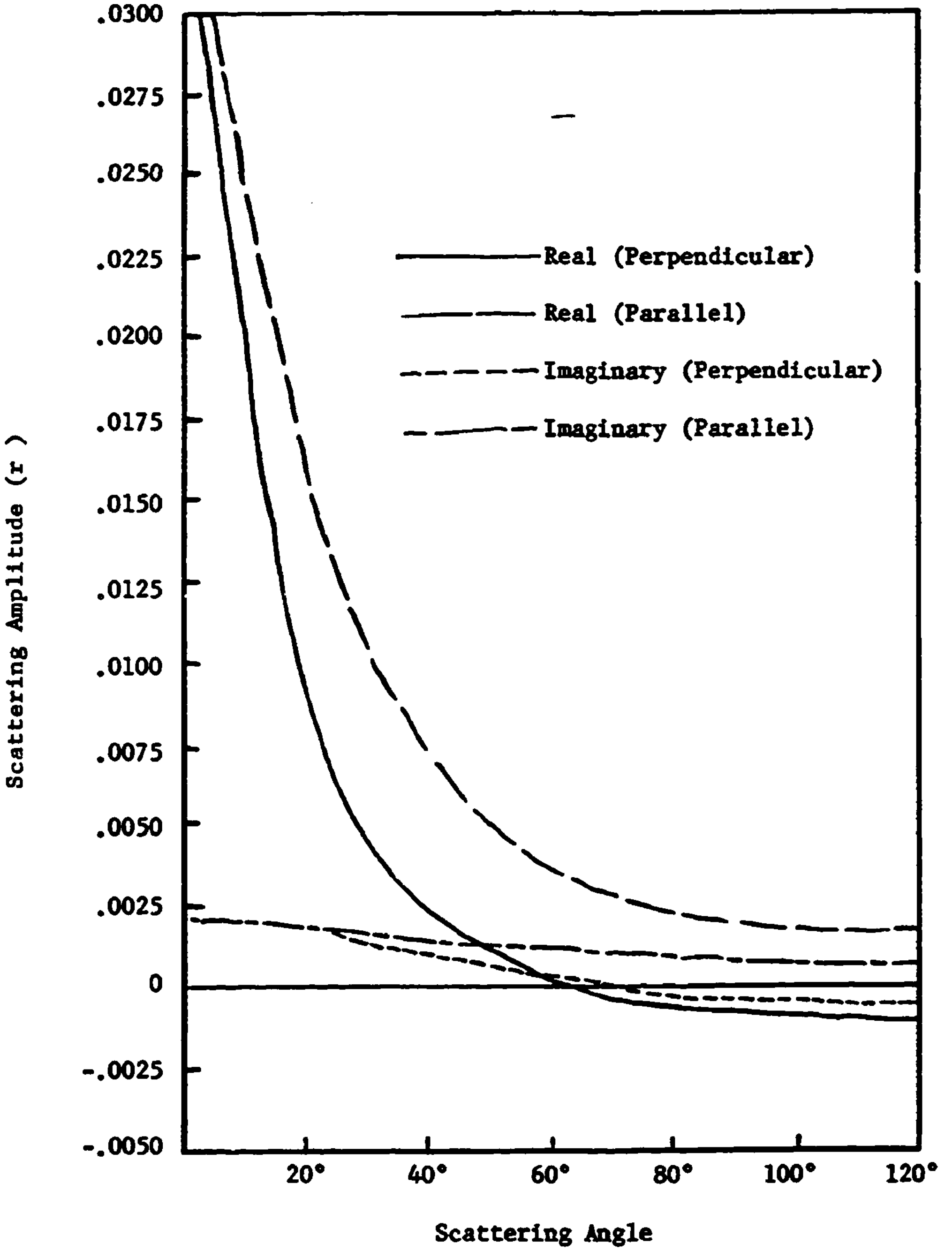

Figure IV. Delbrück Scattering Amplitudes

PREVIOUS EXPERIMENTAL WORK ON DELBRÜCK SCATTERING

The main difficulty in experimentally establishing the existence of Delbrück scattering is its small scattering amplitude. Therefore it is obscured by the more probable processes which occur when gamma rays interact with matter. This has resulted in different groups obtaining results which differ from each other far outside their quoted uncertainties.

The first experiments to indicate the possible presence of Delbrück scattering were those of Wilson, who measured the scattering of 1.33 MeV gamma rays from lead. His measured cross sections were considerably lower,[7] at angles less than 90°, than the Bethe calculations for Rayleigh-Thomson scattering. His conclusion was that Delbrück potential scattering probably accounts for the difference and therefore it must interfere destructively with the nuclear Thomson and Rayleigh contributions. This was not surprising since through theoretical considerations it is known that the interference will be destructive, at least for a 0° scattering angle.

Results of Hara, et al.,[5] and Bernstein and Mann[3] published since then have shown similar experimental cross sections; however the accurate calculations of Rayleigh scattering by Brown and Mayers[17] have completely changed the interpretation of the experimental results. These results now lie above the values predicted by nuclear Thomson and Rayleigh scattering, rather than below them.

But values with experimental errors of $\sim$ 20% which disagree from one another by factors of $\sim$ 2, raise the question as to whether the difference is caused by Delbrück scattering by L-shell corrections, or simply by systematic experimental errors.

Conventional Methods

All of these early experiments made use of a scintillation spectrometer, which consists of a Na I scintillator and photo-multiplier. The pulses from the photomultiplier are amplified and analyzed with either a single or multichannel pulse-height analyzer. To reduce pile-up from the low energy part of the scattered spectrum, the scintillator is shielded with lead of thickness equal to a half-thickness for the source gamma rays.

Still one of the major experimental problems is to distinguish elastic scattering in the presence of the large inelastic (Compton) scattering; the resolution of a scintillation spectrometer is not sufficient to separate the elastic and inelastic components of the scattered radiation at angles less than about 60 degrees.[6]

This Compton scattering should be eliminated however by using scatterers of high and low Z, which have been made to have the same number of electrons, and by then taking the difference in their counting rates.[3] This difference is expected to exhibit a gamma ray line of the same spectral shape as the unscattered gamma ray plus a continuous spectrum due to bremsstrahling from electrons produced in the scatterer, and Compton scattering from the K-shell in lead. A photon scattering from the bound electrons of the atom, an effect well known for x-rays,[9] may give some of its momentum either to an electron which remains in an excited state or to an ionized atom which it leaves behind. Consequently the momentum and energy of the scattered photon may differ from scattering from a free electron. The energy of the scattered photon may have any value up to its original energy less the energy needed to excite or release the electron.

The resolution of the scintillation detector being only ~8% along with the fact that the high energy end of the inelastic continuum is likely to be included in the measured elastic scattering, suggested the need for new experimenting using a somewhat different method of detection.

Two-photomultiplier Method

Preliminary work by Hardie,[19] and Standing and Jovanovich[5] indicate that much greater experimental accuracy might be expected from use of two-photomultipliers facing a single scintillator, where the "gated" pulse from one photomultiplier is counted only when it corresponds to a larger pulse from the other. This method greatly reduces the inelastic continuum, but at the expense of efficiency.

The cross sections obtained by Standing, et al.,[20] using this method agree with the calculated cross sections for Rayleigh and Thomson scattering within the possible errors, therefore still giving no evidence for the presence of Delbrück scattering.

Problems now to be dealt with are to improve the energy resolution over the ~10% for the two multiplier system and to reduce the shifts in pulse height and peak position, which are likely to be interpreted as a change in counting rate.

EXPERIMENTAL SET-UP

Figure V shows the experimental apparatus used to collect data with the Li-Ge detector. A 1-curie Co^{60} gamma ray source is enclosed in ~3000 lbs. of lead housing which has an eight inch long mercury filled stainless steel cylindrical shutter. When the mercury is blown out of the shutter, the Co^{60} gamma rays strike the target.

The target is placed at an angle (ϕ=15°) so that the angle of scattering (θ=30°) from all points on its surface would be the same to the first order. It is easily shown that this requires $\sin\phi/\sin(\theta-\phi)=r/R$, where r (in this case 75 cm.) is the source-target distance and R (also 75 cm.) is the counter-target distance.

The target is an ellipse, with the major and minor axes such that it appears circular to both the source beam and the detector. The semi-minor axis was calculated from the measured diameter of the beam image taken on a photographic plate at distance r; however, the target determines the effective beam size.

The scattered gamma rays are observed by a Lithium drifted Germanium semi-conductor detector,[21] shielded by ~700 lbs. of lead which eliminates virtually all air scattering from areas in the room other than those in the direction of the target. Without the target, any background in the elastically scattered peaks region is now independent of whether the shutter is open or not. The target scattering measurements were taken with a 1/2 inch

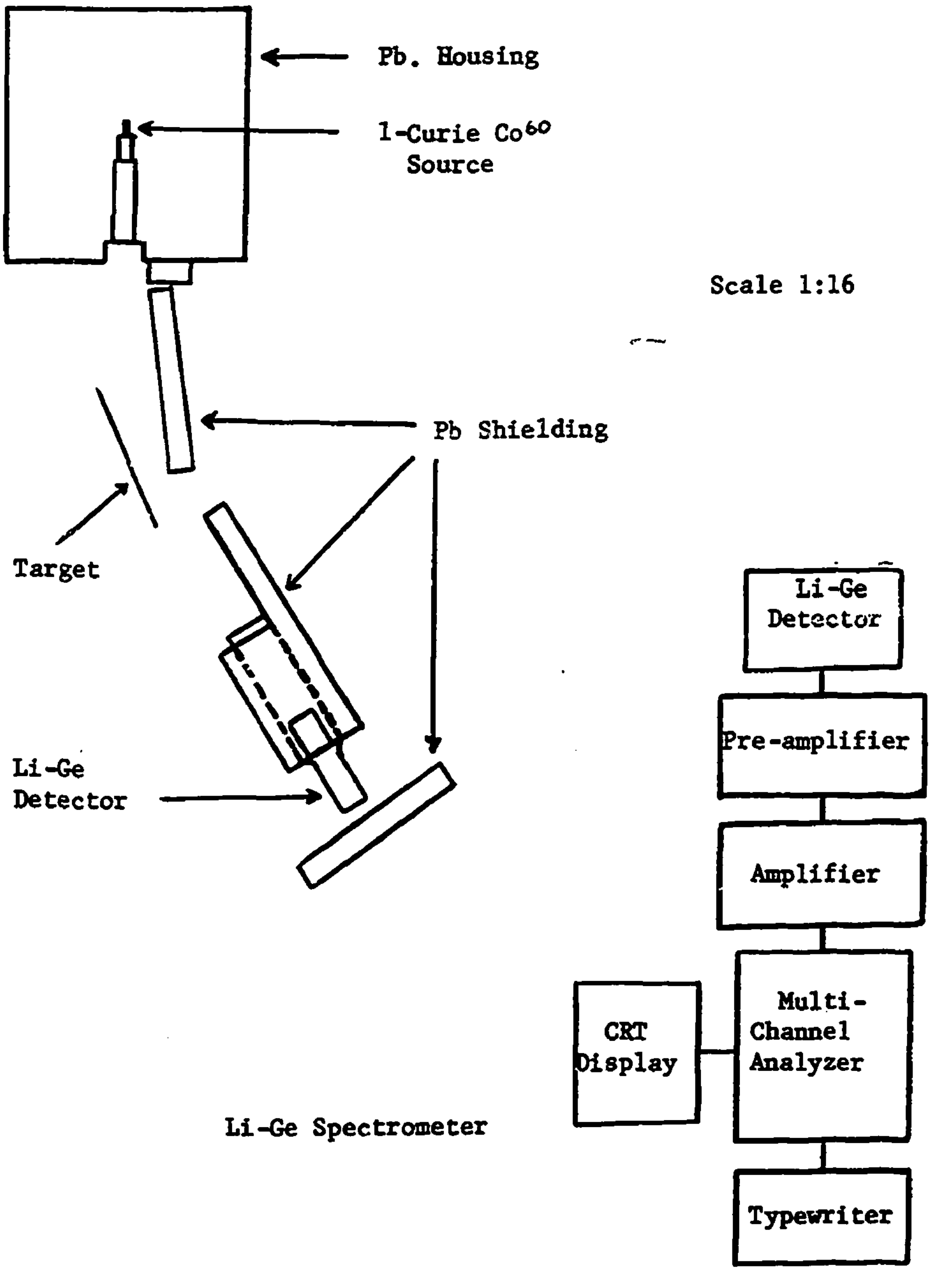

Figure V. Experimental Hardware

lead absorber in front of the detector to reduce background even more, and to significantly attenuate Compton scattering of lower energy compared to the elastic peaks.

The detector pulses are first fed to a preamplifier (Tennelec T C-100), then to a linear amplifier (Tennelec TC-200), and finally to a multichannel analyzer (Nuclear Data series 120). The spectrum is then displayed on a cathode ray tube (CRT), and finally typed out on an I.B.M. typewriter.

Cross Section Measurements

A simplifying feature of gamma ray elastic cross sections is that they can be measured absolutely by two relative measurements.[22] To understand this, consider the counting rate (Na) in the counter from the elastically scattered radiation:

$$n_a = \frac{a}{4\pi r^2} N \left(\frac{d\sigma}{d\Omega}\right)_{el} \omega \epsilon \quad ,$$

where "a" is the number of 1.33 MeV gamma rays per second emerging from the Co^{60} source beam, r is the source-target distance, N is the number of target atoms, ω is the solid angle subtended by the counter at the target, ϵ is the probability of a gamma ray elastically scattered within the solid angle ω being registered by the counter, and $\left(\frac{d\sigma}{d\Omega}\right)_{el}$ is the differential elastic scattering cross section.

With the source of the 1.33 MeV gamma rays closed, suppose the target is replaced by a small Co^{60} source spread over the same area as the target. The number of counts (η_b) now registered by the counter is :

$$\eta_b = \left(\frac{b}{4\pi}\right)\omega\epsilon \quad ,$$

where b is the source strength of the auxiliary Co^{60} target model, and the other parameters ω and ϵ will be unchanged if the detector and geometry are also unchanged. From these two equations we see that

$$\left(\frac{d\sigma}{d\Omega}\right)_{el} = \left(\frac{\eta_a}{\eta_b}\right)\left(\frac{b}{a}\right)\left(\frac{r^2}{N}\right) \quad .$$

Therefore besides the number of atoms in the target and the source-target distance, it is necessary to know only the ratios of source strengths and of counting rates to obtain the absolute differential cross section.

Also, the ratio of the absolute differential cross sections would be equal to the ratio of their respective counting rates.

The Experiment

The data needed to determine the counting rate ratio ($\frac{\eta_a}{\eta_b}$) were collected during a long series of 100 minute live-time runs (total of 24,000 live-time-minutes) with targets of lead and aluminum, and with a Co^{60} auxiliary source. Between each set of three runs, a two live-time-minute run was taken with a standard Co^{60} source to detect and correct for drift.

The auxiliary Co^{60} source was made by painting a solution of $Co^{60}Cl_2$ in water onto construction cardboard, which was then mounted on wood and covered with saran wrap. Its source strength was about 3 micro-curies, producing a counting rate similar to that due to the lead target. The readings from the auxiliary Co^{60} source were taken with it in the same position in which the targets had been, but with the shutter closed.

Both targets as well as the auxiliary source are ellipses having the same major and minor axes. The thickness of the aluminum target compared to the lead one is such that they have an equal number of electrons. Therefore they should both contribute an equal number of Compton events while the aluminum target produces less than 1/2% at 1.33 MeV of elastically scattered photons. The result of the lead spectrum minus the aluminum spectrum should then be a spectrum free of the Compton effect, pile-up, and room background. Of course the greater the resolution of the detector, the more significant will be the results of this difference spectrum. If the photo-peak is highly resolved, then only a small energy spread (in number of channels) of background need be subtracted, and therefore ambiguity is reduced.

RESULTS

The resolution of the solid state Lithium drifted Germanium (Li-Ge) detector used in the experiment is better than 1/2% at 1.33 MeV. That is an order of magnitude better than the NaI scintillator device used in previously reported experiments. The difference can very easily be seen on the graphs of counting rate vs. energy, figures VI[23] and VII. The 1.17 and 1.33 MeV photopeaks of the NaI spectrum are barely discernible, whereas the spectrum from the Li-Ge detector is extremely sharp even for the 1.17 MeV peak.

Experiments using the Li-Ge detector have been performed by Larry Learn,[24] William Merrow,[25] and David Schwandt,[26] leading to cross section calculations on scattering between 30 and 135° from lead and also uranium. Their results have been consistent with past experiments by Standing and Bernstein.

More recently data have been collected with the same experimental set-up (i.e.--figure V), except that a rectangular tin target was placed in a beam of 1.33 MeV gamma rays from a 111-curie Co^{60} source. This gives a cross section of 4.95 mb/str. ± 10% for elastic scattering from tin at 30°.

With their experimental data, Bernstein and Mann[27] have calculated the value as being 14 mb/str. ± 4, while Hara, Benaigs, and Mey[28] have calculated the value as being 10 mb/str. ± 4.

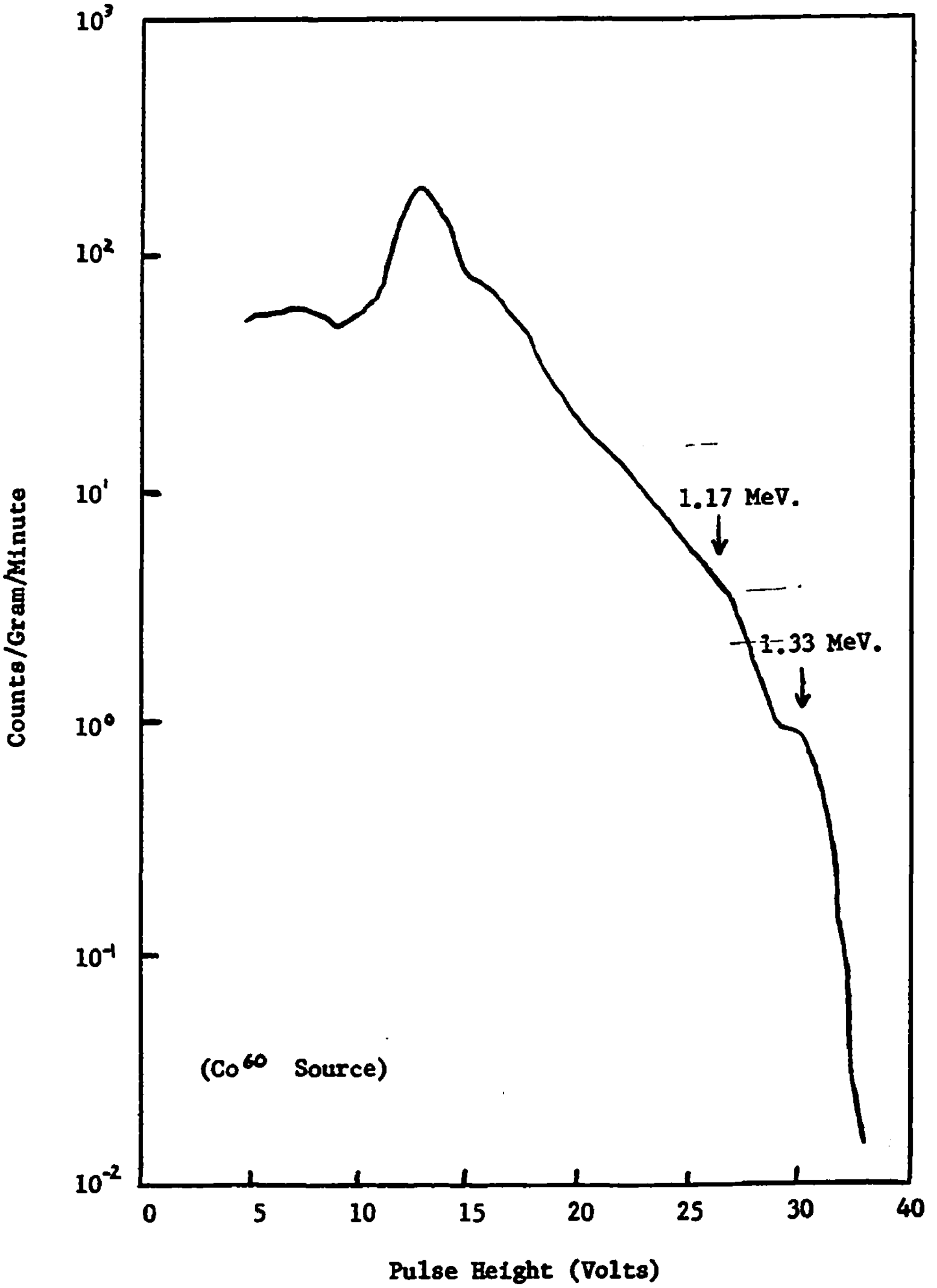

Figure VI. Scintillation Spectrum at 60° From Pb

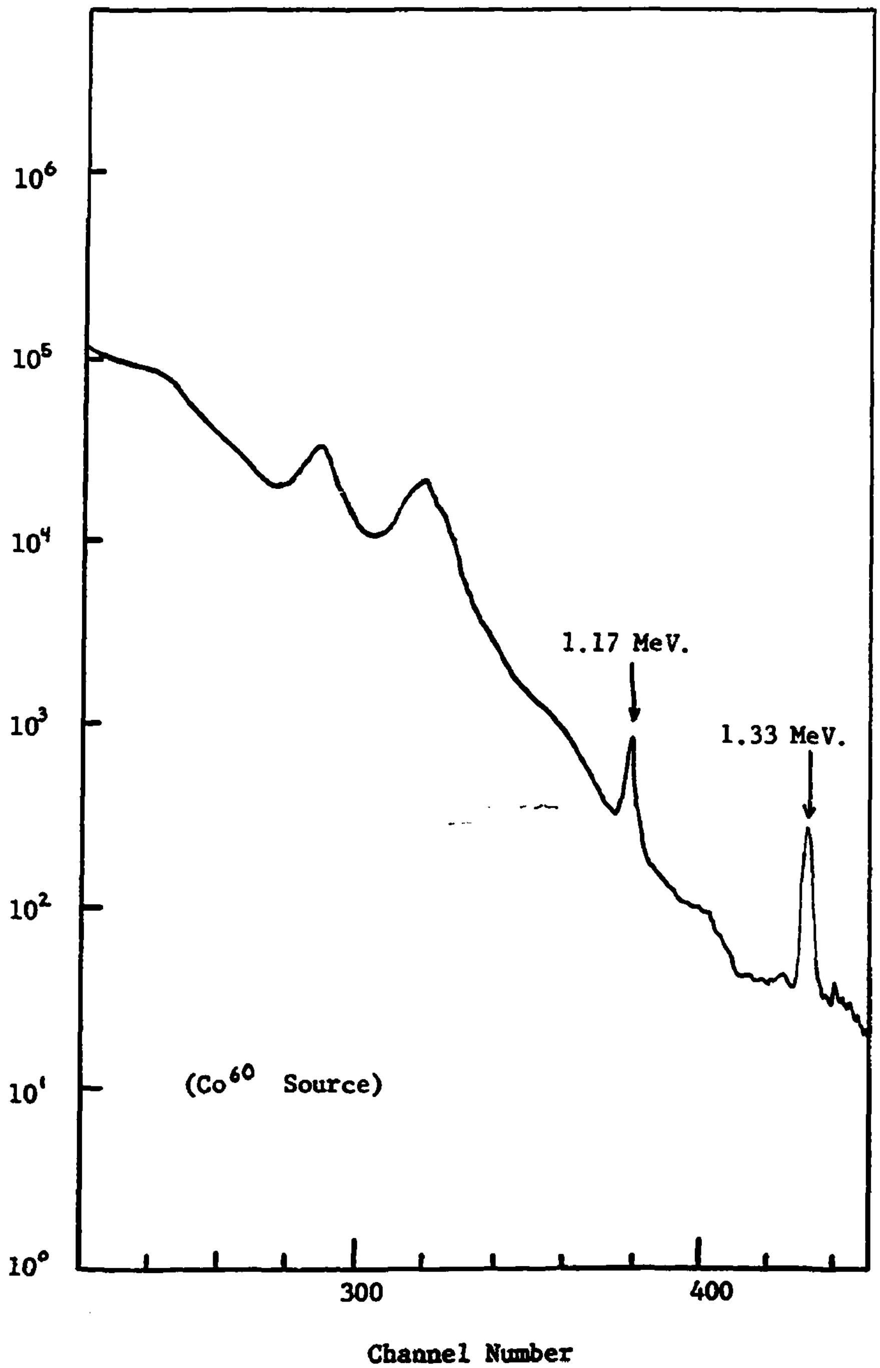

Figure VII. Li-Ge Spectrum At 30° From Pb.

The lower elastic cross section of the present experiment indicates the Li-Ge detector is capable of reducing inelastic events under the elastic peak.

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