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THE SEMICONDUCTOR REVOLUTION IN NUCLEAR RADIATION COUNTING

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Introduction

There is no more basic aspect of science than the structure of matter and, for those concerned with this subject, there is no more pervasive experimental pursuit than the measurement of electromagnetic radiation. Radiations of specific wavelengths are absorbed to change a structural configuration to one of higher energy and emitted in the reverse process. Between the different domains of structure (molecules, atoms, nuclei) the wavelengths of radiations differ tremendously and it is not even possible to discuss the experimental aspects as a single subject. Nevertheless all correctly bear the title spectroscopy and share some common objectives: to measure the radiations with highest possible discrimination of wavelength, and to obtain the greatest sensitivity in determining the intensities of these photon lines.

Once the "spectroscopy" of a system has been determined, important dividends accrue which are unrelated to considerations of structure per se. The distinctive features of spectra make them ideal analytical tools and indeed permit determinations which often can be made in no other way. It is our purpose here to review some applications of nuclear gamma-ray spectroscopy which became possible when it was found that certain semiconductor materials could help fill an existing void in techniques of broad applicability. We shall also say something of what these new techniques have meant when addressed to their primary objective: the elucidation of nuclear structure.

The nuclear spectroscopist, almost uniquely, is concerned with the measurement of charged particles (such as high-energy electrons, alpha particles, protons, and a multitude of others) in addition to photons. Here magnetic spectrometers have long served as instruments of high resolving power and general applicability; but important applications of semiconductor counters have taken root in this domain also. This subject too will be touched upon.

I. Goals and Tools of Gamma-Ray Spectroscopy

The demands upon γ -ray spectroscopy are severe even in light of the new developments to be discussed here. Typically, spectra are complex and the experimenter needs to resolve all of the γ -ray lines present and measure their intensities if he is to make a full analysis of the energy level structure. Actually he must do a good deal more in the form of auxiliary measurements which in themselves may be major pieces of research.

The paramount objectives for proper instrumentation are (a) high-energy resolution and (b) high efficiency. Unhappily, methods which excel in one are deficient in the other. A brief statement of some of the problems encountered may be in order to show that the best possible instrument for most general usefulness is one which excels in neither.

The typical γ -spectrum, as already stated, is complex. The γ rays may cover an energy range from a few kilovolts (keV) to several million electron volts (MeV).¹ The relative intensities of the γ -lines may vary over a range of thousands, and some substances of great interest cannot be made in large amounts. An instrument which is inefficient will not measure the very weak lines, but the problem of resolution also enters here. If peaks are sharp, the weak transitions have a better chance of standing out above the tailing from the intense transitions² and the background from extraneous sources. Finally, it should be mentioned that economy of time in taking data is often an important consideration. Many radioactive species have half-lives too short for prolonged measurements and, more generally, the volume of information needed for a thorough study is discouraging if the experimental methods are slow.

Two methods have been employed which meet the criterion for high resolution quite well. One of these, diffraction by a crystal, gives absolute energies and has been responsible for a number of γ -ray energy standards. Despite the appearance of a considerable number of excellent studies by this technique, it is not of general applicability because an intense source is required and the time for measurement is long. Both the resolution and the efficiency decrease fairly rapidly with increasing photon energy so that it is not only tedious to measure γ rays as high as 500 keV but the resolution is actually poorer at this point than that obtained with some methods of higher efficiency.

An indirect method for measuring γ -spectra is to analyze, with a β -ray spectrometer, the photoelectrons produced in a thin "radiator" upon which the γ rays impinge.³ An instrument of high resolution has a low transmission and in a thin foil the production of photoelectrons is small. As a rough guide, the number of photoelectrons at the detector is $\sim 10^{-7}$ of the γ rays at the source. Such systems have given excellent results but cannot be used for weak lines. For best resolution, data accumulation is slow because the spectrum must be scanned one point at a time. The resolution obtainable is about 0.3% at 1 MeV, a figure considerably better than that for a crystal diffraction spectrometer at this energy.⁴

It is small wonder that the scintillation counter spectrometer (sodium iodide) became so important when it came into general use some 15 years ago. The resolution is relatively poor (6% peak width at 1 MeV; 18% at 100 keV) but the efficiency approaches 100% and it is a "multichannel device," that is, the entire spectrum can be recorded simultaneously. It became possible to measure γ rays quickly, the instruments were produced commercially, and there

was an explosive growth in applications. Despite the tremendous impact which this device has had upon nuclear physics and its applications, the lack of resolution was clearly causing experimenters to miss important information. This deficiency is brought into sharper focus when results obtainable from semiconductor counters are viewed. An illustrative comparison will be given before discussing more broadly these recently-developed γ -ray spectrometers. At the start it should be pointed out that semiconductor materials so far employed (principally germanium) have inherently poorer detection efficiency than sodium iodide.

Neptunium-239 is a β -emitter whose decay populates various excited states of Pu^{239} giving rise to γ rays from these levels. A published spectrum of γ rays taken with a scintillation spectrometer is shown in Fig. 1. For a particular aspect of the structure of Pu^{239} the weak groups labelled 0.44 and 0.49 MeV were of interest. (Note the logarithmic scale of intensities.) When this energy region was examined with a germanium counter spectrometer in the summer of 1964, the data shown in Fig. 2 were obtained. As seen, 12 lines showed up; their positions and intensities permitted a detailed analysis and interpretation which would be utterly impossible from the data of Fig. 1. In this illustration the relative importance of resolution over efficiency is readily seen. The efficiency of the germanium counter was still good enough to see these gamma rays which have about 1/1000 of the intensity of the most prominent line at about 280 keV. To measure these weak lines with a crystal diffraction spectrometer would require a source of Np^{239} of some 1000 curies and perhaps take several hundred times as long. The two factors, resolution and efficiency, as they come into the use of several types of spectrometers are displayed in Figs. 3 and 4. It is characteristic of the rapid developments in semiconductor counter technology that the curve shown for germanium in Fig. 3 and for the resolution shown in Fig. 2 are already

out of date. The value for the line width of 300 keV photons is shown as 3 keV and this resolution has now been bettered by about a factor of two.

II. Properties of Semiconductor Spectrometers

It is by no means possible to discuss satisfactorily in an article such as this how a semiconductor counter works and what sets it apart from others. Briefly, it is a device for converting ionization produced in the crystal into an electric pulse. This is amplified and registered according to energy by a pulse-height analyzer. As compared with gaseous ionization chamber the pulse of electrons collected is greater, the pulse sizes are more discrete (better resolution) and the collection time of ions is more rapid. All of these factors are of great importance. Since we are interested in events caused by the photons which mirror accurately their energies, we are concerned primarily with the photoelectric effect. The cross section for producing photoelectrons by particular photons increases with atomic number and it is here that the semiconductor counters fall short of the efficiency inherent in sodium iodide scintillators. The only materials used successfully so far are silicon and germanium, both elements of rather low atomic number. Emphasis will surely be directed toward heavier elements just as it is already being successfully placed on constructing larger and larger counters to overcome partially the intrinsic qualities of the material. Both the science and art involved are by no means trivial, so rapid development in these directions is not assured.

A primitive view of a counter may be taken as a block or wafer of material with an electrode attached to opposite faces and a certain voltage maintained across the block. Ionization within the block results in a

movement of charge carriers in the direction of the potential gradient. It is already obvious that a metal will not serve as a counter because of the large current which flows without induced ionization. Similarly it is important that the semiconductor has very few free carriers since the ionization pulse is not very great from a single photon.

The huge advantage that the semiconductor counter has over other devices is the small amount of energy required to create an ion pair. In germanium, the photoelectron from a 300 keV γ ray produces about 100,000 ion pairs. If these can be collected before they are trapped the statistical dispersion would produce a peak width from this source alone of about 1 keV. Actually the problem cannot be treated so simply and there is reason to believe that the limiting width would be even smaller than this. Until very recently the amplifier noise and leakage currents have been clearly limiting but it will be recalled that in conjunction with the discussion of Fig. 2 a peak width of 1.5 keV has been attained. In detector materials which produce fewer ion pairs or those which depend upon light collection (sodium iodide) the statistical factors are in principle limiting. A scintillation counter-photomultiplier spectrometer gives a peak width of 25 keV for a 300 keV photon. The reasons for this large spread are rather complex but can be brought into perspective by the statement that about 300 electron volts of energy absorbed in the crystal are required to produce one electron at the cathode of the photomultiplier tube.

The difficulty in obtaining good semiconductor counters lies in the problems which arise in collecting all of the electrons produced and in the elimination of currents not connected with the photon-induced ionization. Without belaboring the technical difficulties it will suffice to say that high purity germanium must be further treated to reduce free carriers and the

counters must be operated at reduced temperatures (usually liquid nitrogen) in order to reduce thermal noise. Figure 5 is a photograph of a counter assembly.

III. Studies in Nuclear Spectroscopy

Since this article aims to introduce the semiconductor counter to a wide readership, the emphasis in discussing nuclear spectroscopy will be to contrast results with those from other techniques rather than to shed enlightenment on the subject itself.

The partial γ -ray spectrum of Np^{239} showing weak transitions unobservable by other techniques has already been mentioned in conjunction with Fig. 2. Ten of these twelve photon lines established four new energy levels simply by matching energy differences with those of known lower states. For example, the photons of 492.3, 484.3 and 434.7 keV fit well for transitions between a level at 492.3 keV and the ground state, 7.9 keV, and 57.3 keV states, respectively. The latter group of states are well-known from other studies. Indication of what kinds of states these might be was of course the focal point of the investigation. The spacings of the four states gave a clue that they might be members of a nuclear rotational band whose base state has total angular momentum $1/2$. Theory also predicts what the relative intensities of the γ rays should be for that assignment and the experimental evidence gave further support. Using published data on the electron spectrum from the same nucleus, it was possible to set certain limits on the internal conversion coefficients (for definition, see next section) for the γ -transitions and this further limited the type of rotational band involved. Finally, the absolute intensities of the lines gave information

on the β -decay population to these states which in turn gave further detailed information on the nature of these states.

The point of the above example goes beyond the conclusion that γ -ray spectroscopy can be done well with semiconductor counters. It shows that a nuclear system which had been investigated almost exhaustively by other techniques quickly yielded new information. Even though these counters have been in use only for a very short time a most impressive list of other examples could be cited. It is also tempting to think that this type of device is in the stage of developmental infancy that its chronological age would indicate.

Just one other study involving a radioactive nucleus will be mentioned. Alexander, Boehm and Kankaleit⁵ made an elegant and exhaustive study of the energy levels of Lu^{177} in which crystal diffraction spectrometry played a central role. They used a source of 100 millicuries and the measurements required six months. (Fortunately, in this case, such a large amount of radioactivity could be prepared.) The spectrum was quite complex, consisting of more than 40 γ rays, and was interpreted neatly in terms of a few highly-revealed rotational bands. The same spectrum was later measured by Blok and Shirley⁶ with a germanium spectrometer; they employed a source of less than 1 millicurie and the measurement took 8 hours. Their measurement confirmed the earlier work in great detail but in addition they looked for a "missing" line presumably too weak to have been seen by other methods. This was found without special search and in addition its position in the energy level sequence was tied down unequivocally. Using two germanium counters they were able to show that this line was in coincidence⁷ with particular other γ rays which should lie below it in the decay sequence. This type of experiment is mandatory for many decay scheme studies and puts added strain

on efficiency requirements; in this case it involved a transition too weak to be seen even in direct measurement by other methods.

More recently still, this spectrum has been measured under similar conditions by with a germanium spectrometer of improved resolution.⁸ A part of the spectrum is shown in Fig. 6. This spectrum revealed four new lines not seen in either of the other studies and which fitted perfectly into the level scheme of Alexander, et al. In addition there were found ten new lines, still weaker, which have not yet been definitely interpreted. The peak widths shown here are about 1.5 keV; this is at least three-fold better than has been done by crystal diffraction at this energy. More important than the resolution in seeing the very weak lines was the vastly improved peak-to-background ratio. In the diffraction spectrometer study this ratio was about 1:1 for one of the weakest lines seen; in Fig. 6 it is 40:1 for the same peak! Not only does this favorable peak-to-background ratio make it easier to observe weak groups but the measurement of their intensities can be determined more accurately. This is of great importance in the theoretical interpretation of the level structure.

By no means do all measurements of nuclear spectroscopy employ radioactive decay. Increasingly, valuable information is being obtained from the analysis of radiation and particles produced in nuclear reactions, usually involving accelerators to induce the reactions. Most of such experiments are done while the beam is turned on, a situation which can involve considerable extraneous background radiations. To discriminate against this, instruments of high resolution have a distinct and obvious advantage. As might be expected semiconductor counters have been used to good advantage here also. Although the general technique of in-beam experiments and the use of semiconductor counters as spectrometers are both quite new, important results have already appeared in abundance and the prospects for the future are most exciting.

IV. Auxiliary Aspects of Nuclear Spectroscopy

It would be tedious to list the many types of experiments involving high-energy photons which shed light on nuclear and atomic structure and for which a spectrometer of moderate efficiency and high resolution is an asset. A few examples will be given to illustrate the diversity of applications.

Low temperature nuclear orientation. The magnetic moment of a nucleus interacts weakly with that of the atomic electrons. At sufficiently low temperatures in a magnetic field the nucleus becomes oriented through this interaction and γ rays which are emitted have angular anisotropy patterns which depend upon the angular momentum of the initial and final nuclear states. The effects often are not large and if there are gamma rays which cannot be resolved, the observed angular anisotropies are likely to be washed out or otherwise be made impossible to interpret.

Nuclear orientation studies have given valuable information with scintillation spectrometers in cases where the γ -spectrum is extremely simple. In the more general situation better resolution is required. Now with the availability of germanium spectrometers some highly successful experiments have been reported and the potentially broad usefulness of this type of experiment seems on the way to realization.

The above cited experimental form is only one of a number in which the directional emission of radiation is used to probe the currents of electric charge and the mechanical moments of nuclear systems. Some of these are exotic as they are ingenious; all benefit by high resolution spectrometry.

Mössbauer effect. The cross section for the absorption of a photon by a nucleus depends with extreme sensitivity upon the matching of its energy with the energy of excitation between two nuclear states. The exploration of

this effect has enjoyed great popularity particularly as it was recognized that the resonances obtained reflect the finest distinctions of chemical environment in which the atom sits. In practice, the proper γ -ray energy is obtained by using the same nuclear species for the absorber and for the source of the γ rays and eliminating the largest source of mismatch, the small recoil energy of the emitting and absorbing systems. This is the "Mössbauer effect." The resonances are then observed by shifting the photon energy ever-so-slightly through the Doppler effect. Although the technique is in first principle broadly applicable, it is limited on two scores. The natural width of the photon line is important and this is related to the lifetime of the state giving rise to the gamma ray. Therefore, in practice, one must be lucky enough to find the right γ -ray emission half-life in the substance of interest. Further limitation arises (again) from the problem of γ -ray resolution by the detector which measures the degree of absorption as one sweeps through the resonances. A number of otherwise suitable "Mössbauer nuclei" had other γ rays or x rays of energy sufficiently close to that of the particular usable transition that they were thought useless or at least limited in use. The advent of germanium and silicon counters will surely broaden substantially the scope of this fantastically sensitive technique as has already been demonstrated in a few specific cases.

Internal conversion coefficients. As already alluded to, the ratio of the emission rate of an orbital electron (nonradiative transition) to that of a photon for the same transition is an extremely valuable index of the type of transition involved. The index number is called the internal conversion coefficient and it can be calculated with satisfying reliability. The detail of information which one can obtain from such measurements is strongly dependent upon the accuracy with which conversion coefficients can be measured. High

accuracy is by no means easy because the electrons and photons require two different types of instrumentation each with its own resolution and intensity-calibration problems. Up until recently the electron lines could only be measured with sufficient resolution and accuracy using point by point scanning with a magnetic spectrometer.

As part of the development of semiconductor counters it has been found that a silicon counter coupled with pulse height discriminator serves as an electron spectrometer of high efficiency (weak sources may be employed) and of sufficiently great resolution to encourage wide application. The electron peak widths so far obtained range from about 1.5 keV at 100 keV to approximately 3.5 keV at 1 MeV. Although these values are considerably poorer than the corresponding values obtained with a good magnetic spectrometer, the resolution is sufficiently good to separate a good majority of spectral lines. A simple conversion coefficient instrument has been built in which the electrons are measured with a silicon detector and the γ rays with a germanium detector simultaneously.⁹ Each part of the system must be calibrated, of course, and has other problems which make the accuracy of determinations somewhat short of that which has been achieved in special cases by laborious methods. Nevertheless, data may be taken so rapidly compared with other methods and can be used with such weak sources, that some modification of this instrument is bound to come into general use. We should bear in mind that conversion coefficients are among the most valuable indices of nuclear structure in use.

V. Activation Analysis

The conversion of atoms to others which are radioactive has become established in the repertory of analytical methods. The detection of the radioactivity with high sensitivity and discrimination is the goal of successful

activation analysis. Despite the wide diversity of successful applications of this technique it is not difficult to generalize on what is required to give it added scope and usefulness. In general the induced spectrum is complex and with the resolution obtainable from the sodium iodide scintillation spectrometer the specimen is usually subjected to chemical fractionation in order to simplify the spectrum and to accentuate those signals coming from weak components. This procedure not only destroys the sample (often undesirable) but obviously adds to the time and expense associated with a determination. Since, in principle, each radioactive substance has a unique spectrum, any instrument which helps resolve the individual signature from others cuts down on the amount of auxiliary manipulations necessary.

Figure 7 shows the results of measurement with a scintillation spectrometer and with a germanium spectrometer on a specimen of a sulfide ore which had been subjected to neutron activation.¹⁰ From Spectrum I it would be difficult to obtain useful information without some prior knowledge of what was in the sample. Chemical fractionation would of course simplify matters considerably. Analysis of the two spectra taken with the germanium spectrometer permitted assignment of the peaks from the raw spectrum. The analytical results are given in Table I. It should be noted that all of the γ rays here are of rather high energy, for which the small germanium counter used is quite inefficient. When larger counters become available this shortcoming will be proportionately alleviated. It should be noted that at present if the spectrum is simple and a peak of interest is set far apart from all others, the high efficiency of the sodium iodide counter give it an advantage in pressing the limits of sensitivity.

Of the many items that could be discussed about these spectra one should note in Spectrum I that the 819 keV peak from indium was not resolved

at all from the 845 keV peak from manganese. Its presence could not be detected easily by repeating the measurement at intervals because the half-lives of the two radioactivities are not grossly different. In Spectrum II, the indium peak is not only resolved but the signature is complete through the detection of two other peaks belonging to the same isotope.

Nothing has been said about the precision of analytical results obtainable with germanium counters because these add little in this respect. Activation analysis in general does not give high precision for major components of a sample but finds its great usefulness in measuring minor components which cannot be detected easily or at all by other methods.

VI. Radiochemical Tracing and Analysis

The multitude of uses to which radioactive tracers are put are, broadly speaking, not faced with problems such as have been discussed here. Generally a single tracer is added to the system and any detection method is adequate. However it is not difficult to concoct situations involving multiple tracers in which high resolution would be an advantage. No doubt, such situations will arise.

A particular complex mixture of radioactivities does appear in a particular industry—that of the separation of the fission products from irradiated fuel elements from nuclear reactors. Considerable laboratory effort is expended in following the progress of the separation process and in the development of improved processes. Quite obviously any analytical procedure which shows up the troublesome fission products without tedious chemical fractionation would have distinct usefulness. One such case may be cited. An isotope of zirconium and of niobium are among the most prominent fission

products and these two elements happen to be somewhat unpredictable in aqueous-organic systems because of their many complex ions and proclivity to hydrolyze. The analysis of the two radioactive substances is difficult because their γ -ray energies lie close to each other and chemical separation is not easy. The germanium spectrometer alleviates the necessity of time consuming manipulations by resolving completely the γ rays.

VII. X-Ray Emission Spectrometry

The elemental analysis of materials by measuring their characteristic x rays is a much-used albeit tedious technique. The distinctive feature of this form of analysis is that most elements can be determined by a single method. The basic idea is quite simple. The fluorescence spectrum is excited by photons from an x-ray tube and analyzed by crystal diffraction. The equipment is fairly expensive and measurements are not rapid, but in general excellent results are obtained because of the excellent resolution in the x-ray region of photon energies.

Recently the same principles have been employed successfully but with different instrumentation.¹¹ Instead of the x-ray tube, a small radioactive source is used to excite the x rays and in place of the crystal diffraction spectrometer a silicon or germanium counter is employed. There are certain deficiencies as well as great advantages of this new system. The noise level of the counter system precludes at present the measurement of elements with atomic number below about 22. Also the energy range of x rays is that in which the resolution by crystal diffraction is clearly superior. This means that the older technique is better where neighboring elements are present in greatly disparate amounts.

The feasibility of using semiconductor counters for the purpose depended first of all on major improvements in the amplifier system which permitted the resolution of x rays from neighboring elements. The great advantage of the instrument is the speed with which large numbers of analyses can be done. Using a very modest radioactive source a typical sample may be analyzed in a very few minutes. Another feature of the instrument which will undoubtedly be put to use is its portability. The combination of these properties makes it easy to visualize its use for on-line control of industrial process. It could also be used for field work in mineral prospecting and archaeology, where many specimens may demand examination before segregating or discarding them.

Figure 8 shows the peaks obtained from samples of yttrium and illustrates the sensitivity and resolution obtained for x rays of about 15 keV energy. The $K\beta$ peak is separated by 2 keV from the $K\alpha$ peak, an amount which is close to the peak widths. At the atomic number of yttrium adjacent elements have x rays different only by about 1 keV so it would be difficult to resolve these unless the elements were present in comparable quantities. However, since this measurement was made better resolution has been attained by more than a factor of two. For heavier elements the x-ray energies are separated further progressively and analysis becomes progressively easier. Added ease in analysis is obtained when the L x rays enter the energy range where these counters are usable (about 4 keV).

VIII. Particle Spectroscopy

Fewer individuals are engaged in the measurement of particles (such as protons) than γ rays and applications of the techniques beyond the intrinsic nuclear studies are not so widespread for these. Nevertheless, within a more limited scope, the advent of semiconductor counters has produced no less startling changes than in the areas already discussed.

The classical method for measuring charged particles consists of their deflection in a magnetic field. This technique is still much used and will no doubt continue so because of the extremely high resolution attainable. The new semiconductor counters have introduced new dimensions in particle work because they are inexpensive compared with large magnets, they have much higher efficiency and they have made the taking of data more rapid by a large factor. This last attribute can be determinative for experiments in which a reaction must be studied at varying energies of the bombarding particles and at closely spaced angular settings relative to the direction of the beam. As will be explained, the counters can also be used to identify the types of emitted particles, something that simple magnetic deflection cannot by itself accomplish. Since the absorption of charged particles is not sensitive to the atomic number of the detector material, silicon has been favored to now over germanium except for high-energy protons (greater than 30 MeV).

It should be emphasized at the start that small semiconductor counters are thick enough to absorb most of the particles of interest in particle spectrometry. Protons have the longest range for a particular energy and those up to 30 MeV are stopped in a silicon counter 5 mm in thickness and a germanium counter of less than half this thick.

Nuclear energy levels. Accelerated charged particles may be scattered elastically by the nuclear forces of the target nuclei leaving the nuclei unexcited. The particles may also excite the nuclei in which case the scattered particles are lower in energy by amount of excitation energy. Thus a series of peaks result; the differences in energy from the elastically scattered peak define nuclear states. This form of spectroscopy differs from direct measurement of γ rays in some important respects. Of fundamental importance is the fact that

states may be reached which are forbidden to radioactive decay processes or of too high energy to be reached. Although we have only mentioned inelastic scattering as the means of exciting nuclear states, they may also be reached by a wide array of other nuclear reactions. For example deuterons may be absorbed and a series of proton groups emitted. Plainly there is a range of nuclear problems open to investigation by such techniques.

The experimental requirements for particle spectrometry are quite severe as an example will illustrate. Suppose that 22 MeV protons are scattered, exciting a state at 4 MeV. The emitted protons will have an energy of 18 MeV. Suppose further that there is another state 50 keV away. If the two proton groups are to be resolved effectively, the resolution of the instrument must be about 0.1% for the 18 MeV particles. Up until quite recently only magnetic analysis could produce such results.

In a recent report¹² energy resolution of 0.1% was achieved for protons of even greater energies than 18 MeV. Actually the resolution of the counter itself was better than this figure because a substantial part of the peak width was due to the spread in energy of the accelerated particles.

Particle identifiers. Considering an array of particles emitted from a target, we must measure at some specific position of the counter relative to the beam axis (a) the energy, (b) the mass number, and (c) the atomic number, in order that the energy data be useable. Simple deflection in a magnetic field gives the momentum per unit charge. Often there is no ambiguity as to the particle involved but as more and more details are sought this is not always the case. A simple ionization detector measures only the energy of the particle so again identification is not complete.

A particle identifier accomplishes two simultaneous measurements
(1) the rate of energy loss (dE/dx) as the particle traverses a very thin counter,

and (2) the total energy which is obtained by adding the increment of energy abstracted by the dE/dx counter to the residual energy determined in a thick counter placed behind the first. It can be shown that the product of E by dE/dx identifies the particle uniquely.

The attainment of satisfactory particle identification where a number of different particles are involved covering a wide range of energies is by no means simple. In addition to good detectors, highly sophisticated electronics circuits are required. In this demanding area of research silicon counters have been used to good effect. The high resolution attainable is of great importance and they have other properties which are advantageous.

The fact that every particle which reaches the detectors is analyzed gives this system a huge advantage in looking for rare events. By employing a somewhat more complicated system than that just described it was found possible to identify and measure the mass of the interesting nucleus He^8 even though it was produced in 10^7 fold lower yield than the prominent particles emitted from the target.¹³

Alpha-particle spectroscopy. Two methods have long been employed to measure the monoenergetic alpha-groups emitted by many radioactive substances in the heavy element region. Magnetic spectrometers can give very good resolution but have inherent limits in sensitivity. Gaseous ionization chambers are highly efficient but the resolution attainable make them poor for looking for weak groups and those which are close together. Typically, an ionization chamber gives peak widths of 30 keV (for a 6 MeV alpha-group) although considerably better resolution has been reported. A good magnetic spectrometer with careful preparation of the source and in favorable cases has given peak widths less than 2 keV, but 6 keV is a more generally attainable value.

Silicon counters are coming into more and more general use as alpha-particle spectrometers. The resolution easily attainable is only about 15 keV, although improvement over this has been attained. Nevertheless, the difference between this value and that from an ionization chamber proves huge indeed when attention is addressed to typical spectra.

Probably the most important feature of silicon counters in this area is that they adapt readily for coincidence measurements between α -particles and gamma rays and electrons. Ionization chambers are not only deficient in resolution but the ion collection time is too slow. The overall low efficiency of magnetic analysis limits its use in coincidence spectrometry to the more prominent events. With silicon detectors for the alpha particles it has been found possible to measure transitions which have less than 10^{-7} the intensity of the main transitions. In working with alpha emitters on nuclear structure problems it is being found that rare transitions are just as important as the more prominent ones.

IX. Final Words

One needs only to scan the foregoing partial list of accomplishments made possible by semiconductor counters for measuring nuclear radiations to assess the impact which these are making in broad areas of research. A number of important fields such as mesic x-ray investigations have not even been mentioned. The features of this new form of instrumentation which are already well established are exciting enough, but it would not be rash to forecast that the next few years will see further important advances.

Legends of Figures

Fig. 1. Gamma ray spectrum of Np^{239} from a sodium iodide scintillation spectrometer. (Figure taken from Lefevre, Kinderman, and Van Tuyl, Ref.14)

Fig. 2. Portion of the gamma-ray spectrum of Np^{239} . Energies are given in keV. (The peak widths attained in this spectrum have been decreased by about a factor of two in the two years since this measurement was made.) (Figure taken from Davis and Hollander, Ref.15)

Fig. 3. Resolution of various spectrometers. In addition to curves for four photon detectors, curves for electron resolution from three types of β -ray spectrometers employed on conversion electrons are shown with the momentum resolution ($\Delta p/p$) given in parenthesis. Not shown in the figure are performance characteristics of β -ray spectrometers as used with secondary electrons (photoelectrons) as described in the text. Because of problems exterior to the magnet, the line widths attainable are not as good as the curves of this figure. The resolution now attainable with germanium counters is at least a factor of two better than that shown. (Figure is taken from Ref.16)

Fig. 4. Approximate efficiencies of spectrometer systems. The overall detection efficiency shown (ordinate scale) is the product of the intrinsic efficiency and a geometry factor (solid angle subtended from source to detector). The geometry factors commonly encountered are shown in parentheses. (Figure taken from Ref.16)

Fig. 5. Typical basic unit for semiconductor counter.

(a) Assembled unit showing liquid nitrogen reservoir, ion pump on left, detector housing and pre-amplifier on right. Not shown is the pulse-height discriminator.

(b) Major components. Portion immediately above the scale is the cold finger; semiconductor detector is clamped onto disc at left. Not shown are the stand, pre-amplifier, and reservoir.

Fig. 6. Partial gamma-ray spectrum of $^{177}\text{Lu}^m$ taken with an improved germanium spectrometer. Note that the entire section shown covers a range of only 100 keV (Figure from Ref. 8.)

Fig. 7. Gamma-ray spectra of activated sulfide ore. Spectrum 1 represents 60 minute data accumulation using the 3- x 3-inch (diameter) sodium iodide scintillator 5.2 hours after a 2-hour irradiation of 62.9 mg of sulfide ore. Spectrum 2 represents 60 minute data accumulation using the smaller Ge(Li) detector 4 hours after a 2-hour irradiation of 62.9 mg of the ore. Spectrum 3 represents 120 minute data accumulation using the smaller Ge(Li) detector 24 hours after a 49-hour irradiation of 50 mg of the ore.

Fig. 8. K x rays of yttrium excited by radiations of Am^{241} in samples containing 10 mg, 1 mg, and 158 μg , respectively, of yttrium and analyzed with lithium-drifted silicon semiconductor detector. Two-minute runs except for 158 μg sample for which analysis time was 10 minutes. (Figure taken from Ref. 11.)

Table I . Results of Quantitative Analysis of Sulfide Ore

Element	$\mu\text{g.}$ Present	Sample weight mg.	Irradiation time hours	E_{γ} k.e.v.	p.p.m. ^a
Mn	6.0	62.9	2	845(Mn^{56})	95 ± 7
In	7.6	62.9	2	1300($\text{In}^{116\text{m}}$)	120 ± 5
Ga	3.8	62.0	2	835(Ga^{72})	61 ± 16
Zn	3020	24.5	24	438($\text{Zn}^{69\text{m}}$)	$(1.20 \pm 0.01) \times 10^5$
As	60	19.0	72	559(As^{76})	$(3.16 \pm 0.04) \times 10^3$
Sb	8.2	19.0	72	563(Sb^{122})	430 ± 6
Cu	1240	19.0	72	511(Cu^{64}) ^b	$(6.50 \pm 0.01) \times 10^4$
Na	16	19.0	72	1369(Na^{24})	840 ± 25
Fe	3370	19.0	72	1095(Fe^{59})	$(1.78 \pm 0.01) \times 10^5$
Au	0.038	19.0	72	411(Au^{198})	2.0 ± 0.2

^aErrors shown represent statistical counting error only.

^bCopper concentration corrected for contribution to 511-k.e.v. annihilation photopeak from decay of Zn^{69} and Na^{24} .

References and Notes

1. The deep-shell x rays are often found to be excited in γ -transitions and their measurement accompanies that of the γ rays.
2. In any γ -ray detector which depends upon ionization, the mono-energetic peak which relates to the photoelectric effect is the "spectral line" we refer to here. Compton scattering is usually a more probable event and if scattered photons leave the detector smaller signals are obtained. This is the principal source of the continuum of signals below the energy of the distinctive peak.
3. It should be mentioned here that orbital electrons are directly ejected in nuclear γ -transitions as a competitive process to photon emission. The measurement of these electrons continue to play an extremely important role in nuclear spectroscopy. They provide a means for obtaining γ -transition energies with high resolution and serve as an adjunct to the γ rays themselves in determining the ratio of radiative to nonradiative transitions, an important index for the nature of initial and final quantum states. This subject is not discussed here under general γ -ray spectroscopy because it is an adjunct, not a substitute, to γ -ray measurements.
4. "Resolution" in this article refers to the full width of a peak at half of the maximum peak height. It may be indicated, as here, in terms of a percentage of the energy.
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7. Two γ rays which are in cascade can be shown to have this relation by measuring their "coincidence" in two counters. The efficiency of detection of a coincidence event is the product of the efficiencies of the two counters, hence quite low.

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17. This work was done under the auspices of the U.S. Atomic Energy Commission.

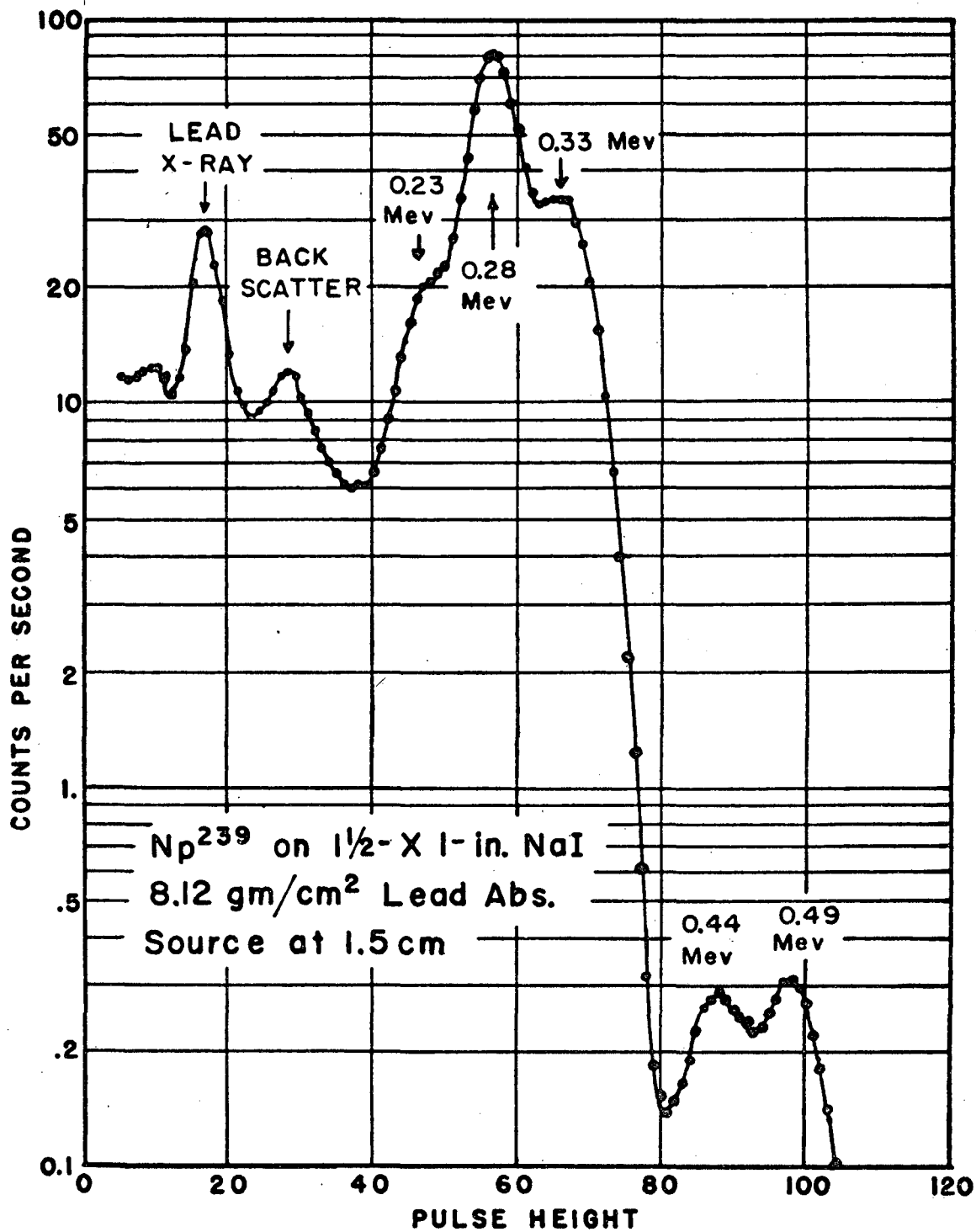


Fig. 1.

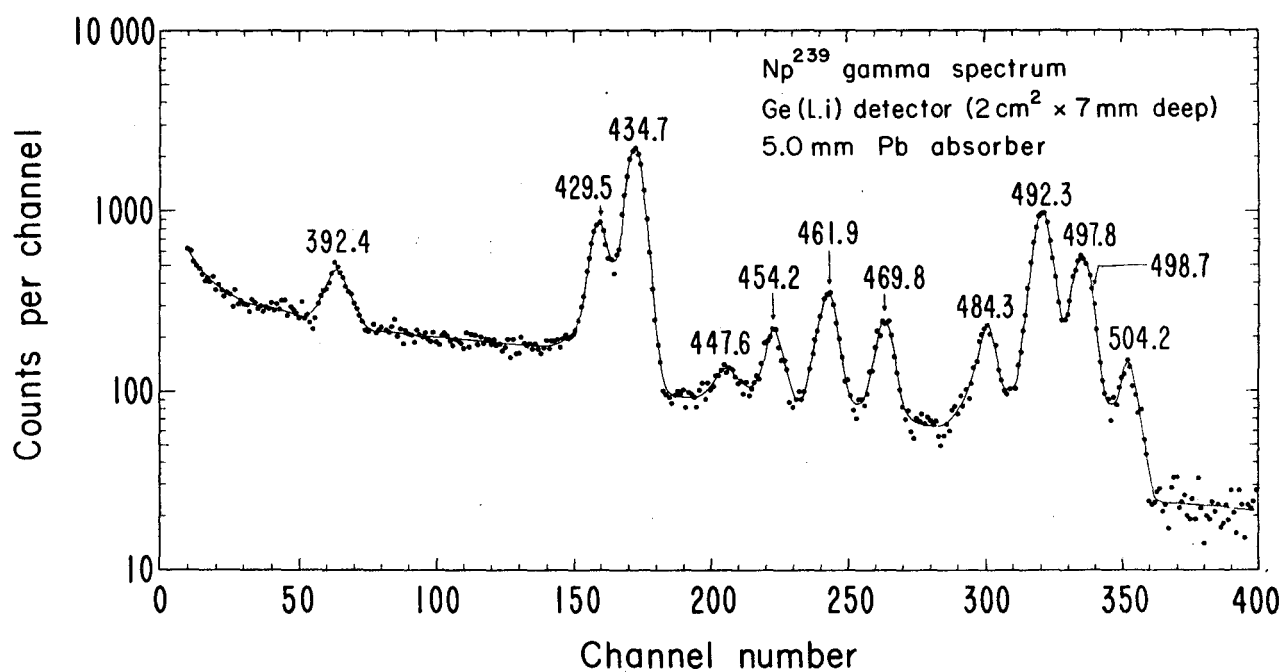


Fig. 2.

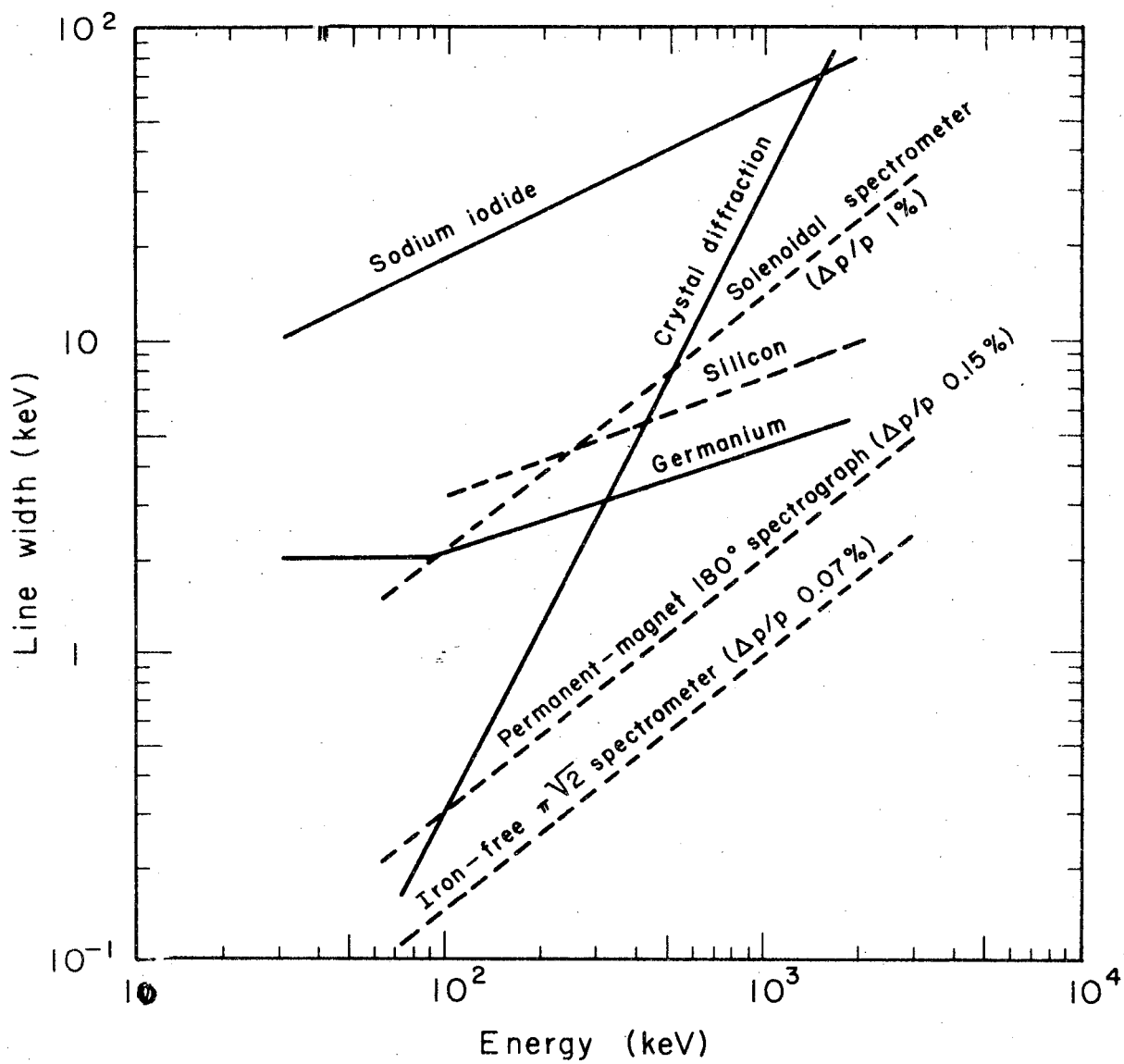


Fig. 3.

MUB-5333

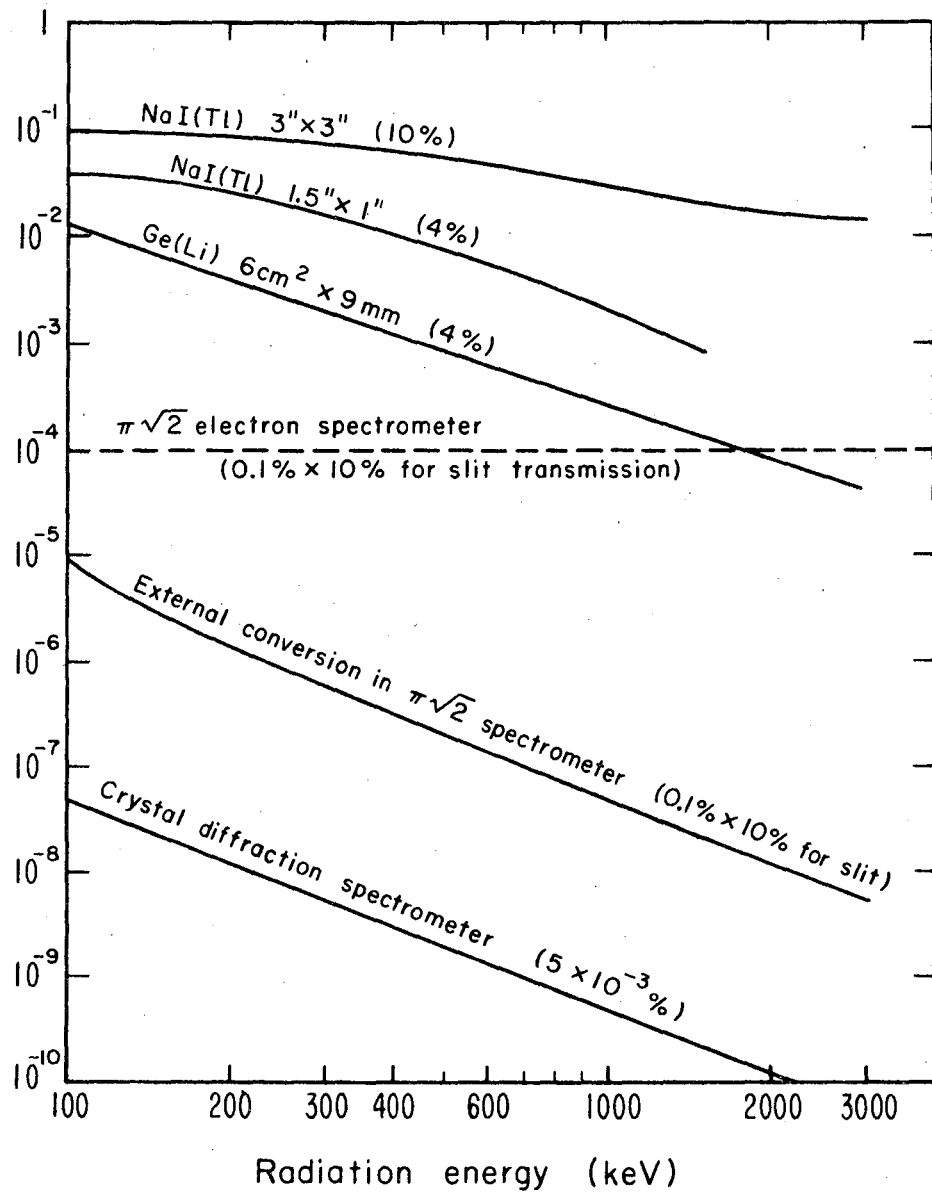
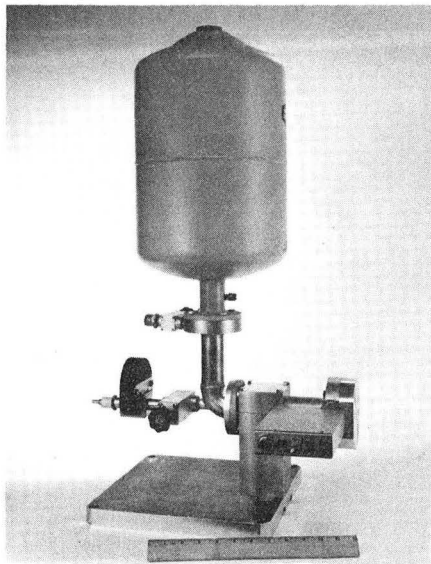
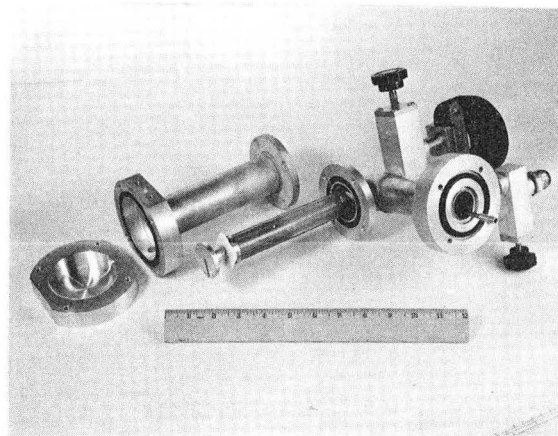


Fig. 4.

MUB-7217



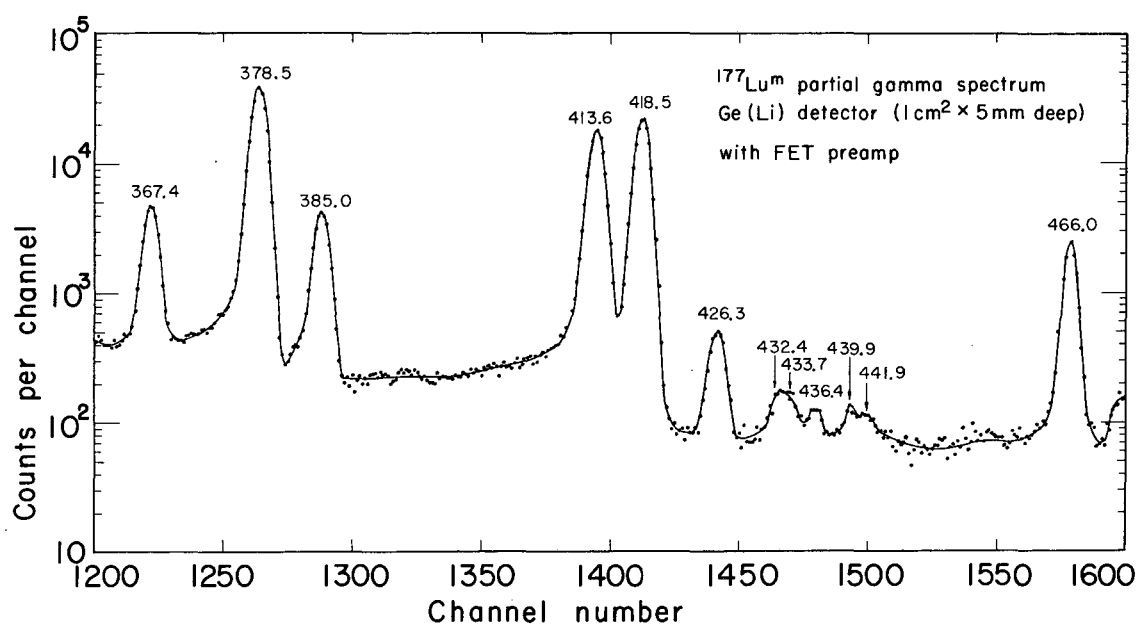
(a)



(b)

ZN-4762

Fig. 5



MUB-31026

Fig. 6

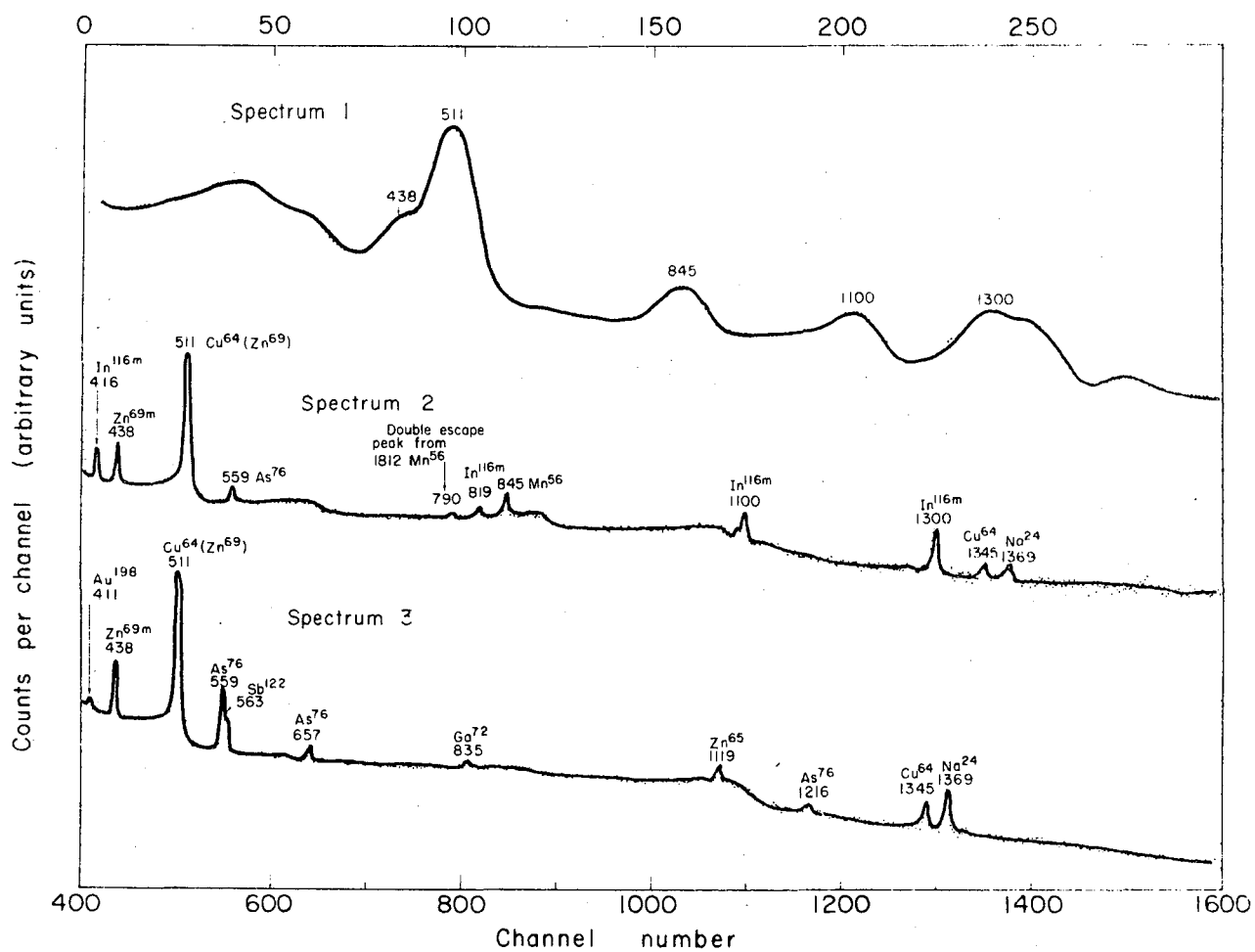


Fig. 7.

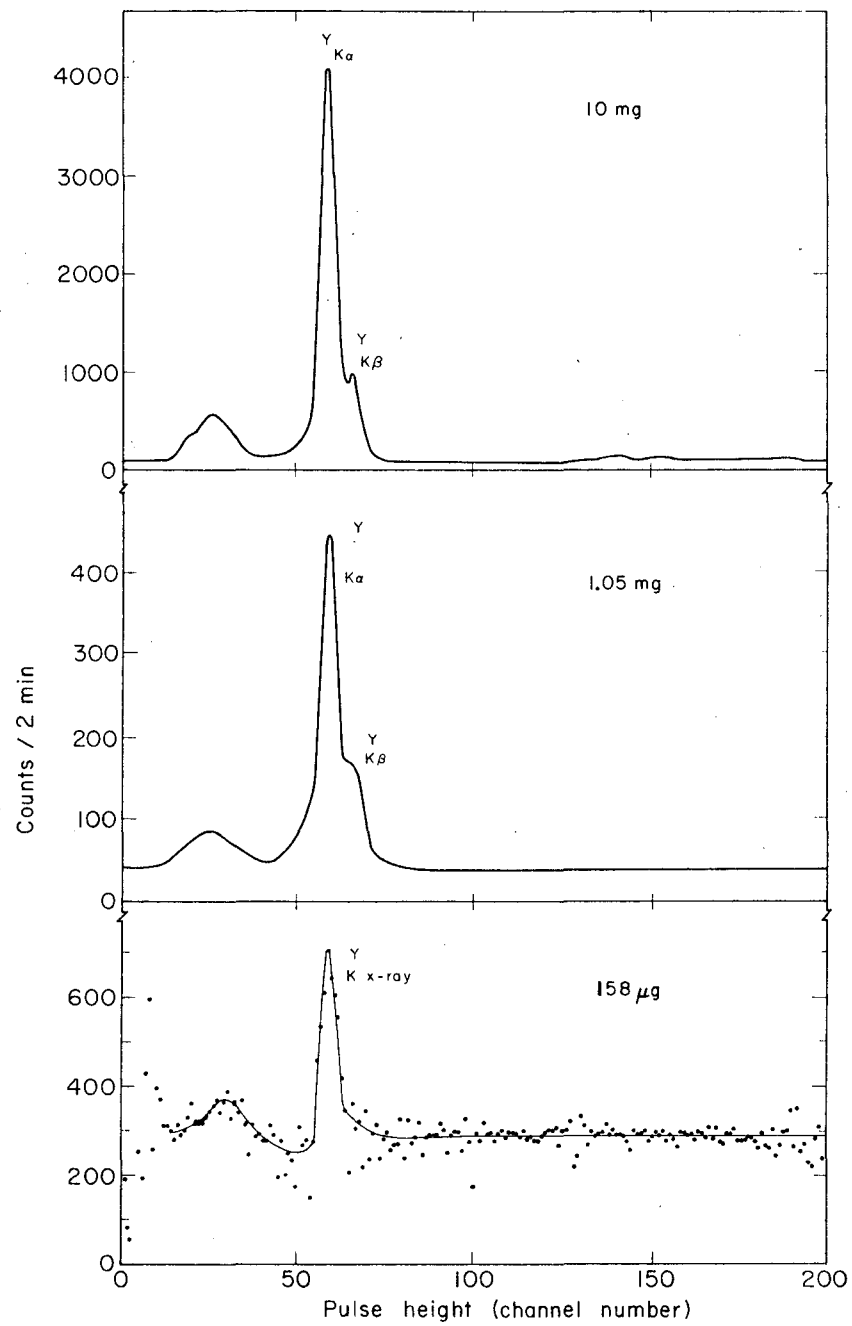


Fig. 8.

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