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Scintillation Detectors

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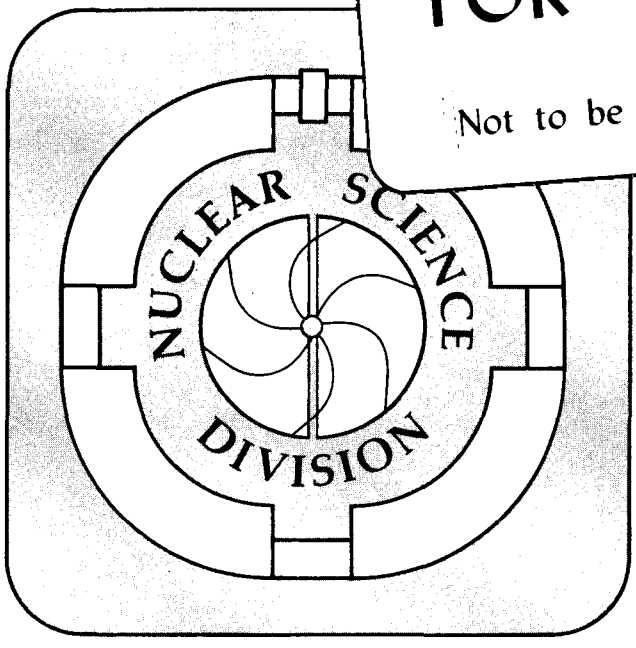

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Scintillation Detectors

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Abstract

A scintillation detector is a device which responds to ionizing radiation by emitting light. Such devices are used in many areas of scientific research and development as well as in a number of industrial applications. This article provides an overview of the physics of scintillation detectors, their production, and their uses in a number of areas of basic research and industry.

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I. Introduction

In many areas of basic scientific research, as well as in a variety of applied fields, one wishes to detect the passage of radiation through matter. The fact that some materials emit light when struck by radiation has been known for many years, and this principle is the basis for the scintillation detector. For example in 1911, Ernest Rutherford observed scintillation light produced by the interactions of alpha particles with a zinc-sulfide screen in his pioneering scattering experiments which established the existence of the atomic nucleus. Since then, a large number of different scintillating materials have been developed for specific applications in the fields of physics, chemistry, and biology. This article describes the scintillation process and some of the uses of scintillation detectors in the laboratory and in industry.

Before describing the scintillation mechanism, it is useful to briefly review the processes by which radiation is absorbed by matter. For x-rays and gamma rays (high energy photons) three processes are important: the photoelectric effect, Compton scattering, and pair production. In the photoelectric effect , the full energy of the photon is absorbed by a bound atomic electron. This ejects the electron from the atom with a kinetic energy equal to the photon energy minus the electron's original binding energy. In Compton scattering, the photon also interacts with an atomic electron but only a fraction of its energy is transferred to the electron. The remaining energy is carried off by a secondary photon whose depends on the angle of its emission relative to the direction of the primary photon. For photons with energies greater than twice the rest-mass energy of the electron ($2m_ec^2$ = 1022 keV) it is possible for them to convert into an electron-positron pair. The kinetic energy of the e^+ e^- pair is then equal to the original photon energy minus 1022 keV.

When beta particles (electrons) traverse matter, they produce atomic and molecular excitations and ionization through their collisions with atomic electrons.

Heavy charged particles, such a protons, alpha particles (^{4}He nuclei), and nuclei of heavier atoms, also make inelastic collisions with atomic electrons that lead to atomic and molecular excitations as well as ionization. For neutrons, however, the situation is somewhat different. Since neutrons are electrically neutral, the primary way in which they lose energy in matter is through their nuclear interactions with atomic nuclei. They can be scattered off the nucleus or absorbed by it. In hydrogenous materials such as paraffin or polyethylene, neutrons scattering off hydrogen nuclei produce recoiling protons which then interact as described above.

II. Physics of Scintillation Detectors

The mechanism by which energy deposited by radiation is converted into light within a scintillator is a fairly involved process and is somewhat different in inorganic and organic scintillators. In both types, however, the amount of light produced is proportional to the amount of energy deposited in the scintillator. Inorganic scintillators are made of crystals of materials such as NaI or CsI that are usually activated with an impurity such as Tl (thallium). It has been found that with an impurity concentration on the order of 1 part in 10^3 by number, there is a very efficient transfer of energy from the major constituent to the impurity. In NaI(Tl), for example, the result is that the capture of electrons and/or holes by the thallium impurity leads to excited states of the Tl^+ ion which decay by emitting the light which is observed from this scintillator.

Liquid, plastic, and some kinds of crystal scintillators are composed of organic compounds known as aromatic hydrocarbons. These materials consist of molecules containing a benzene ring structure. Within these rings, not all of the electrons that bind the atoms together are strongly localized to individual atoms. These so-called valence electrons occupy the π–molecular orbitals which extend above and below

the plane of the molecule. Absorption of radiation by these electrons can produce excited states which decay to the ground state or other excited states by emitting light. If the decay proceeds to an excited state, then the photon that is emitted has too little energy to excite another molecule from its ground state to the appropriate excited state. Thus, the scintillator is quite transparent to its own light.

Over the years, many different types of scintillators have been developed to meet a variety of radiation detection needs. The physical properties of a number of different scintillation materials are listed in Table 1. Physical properties such as density, scintillation efficiency (i.e. a measure of the fraction of deposited energy that is converted into light), the wavelength at which the scintillation light appears, and the scintillation decay constant (i.e. the time interval over which light is emitted) vary widely among the different scintillators. These differences are used to decide which scintillator is used for a particular application. High density materials containing elements with large atomic numbers have relatively high efficiencies for stopping gamma rays. Thus, compounds such as NaI(Tl), BaF_2, or bismuth germanate (BGO) are used in such applications. Plastic scintillators have very short decay constants, and thus are used in applications where there are needs for fast timing. Scintillators such as ^{6}LiI(Eu) contain nuclei that have high cross sections for neutron-induced reactions and thus are useful in neutron studies.

The process by which a complete scintillation detector system converts the energy deposited by the incident radiation into a useable signal involves several steps. As described above, the incident radiation ionizes and excites the scintillation material. Within the scintillator, some fraction of this energy is converted into light. This light travels through the scintillator and is then collected on a photo-sensitive surface. The resulting photoelectrons are multiplied and collected, thus producing a usable signal. Usually these functions are accomplished by coupling a scintillation material to a light pipe which guides the light to a photomultiplier tube. Such a

system is shown schematically in Figure 1. When photons strike the photocathode, electrons are ejected via the photoelectric effect. These electrons are then accelerated and focused onto a series of dynodes where through collisions the number of electrons is greatly multiplied. By the time the signal reaches the collection anode, it may have been amplified by more than a factor of 10^6. This signal is usually then sent to an amplifier where further shaping and amplification of the pulse is done before it reaches the data acquisition system. The size of this final signal provides a measure of the amount of energy deposited by the radiation in the scintillator.

III. Manufacture of Scintillation Detectors

Inorganic scintillators such as NaI(Tl) and CsI(Tl) can be produced as single crystal ingots up to approximately 36 inches in diameter. To produce crystals of this size, grains or small chunks of the desired chemical are put into a large crucible. The crucible is heated to high enough temperature to melt the material. The crucible is then allowed to cool at a rate which is faster on the bottom than at the top. Thus crystal growth begins at the bottom and proceeds upwards. In this way large single crystals can be grown. An example of this is shown in Figure 2, where a large crystal of CsI has just been removed from the crucible in which it was grown.

Plastic scintillators are usually manufactured in the form of cast sheets. However, this material is also available in rods, fibers, or beads. They are produced by mixing together a suitable fluorescent organic compound with a polymer and allowing the mixture to solidify. Commonly used mixtures include p-terphenyl dissolved in either polystyrene or polyvinyltoluene. A typical plastic scintillator paddle with a light pipe attached is shown in Figure 3.

Following the machining or forming process, the surfaces of a solid scintillator are polished. A reflective coating is usually then applied to aid in the transport of

the scintillation light to the photomultiplier. Crystalline scintillators are normally packaged inside a metal cannister so as to protect the scintillator from mechanical shocks. Liquid scintillators are also often packaged in a metal container. In both cases, the can has a transparent window on one side on which the light pipe and then photomultiplier tube are mounted.

IV. Applications of Scintillation Detectors

In the areas of nuclear and particle physics research, scintillation detectors are used in a wide variety of experiments. In gamma-ray counting experiments, NaI(Tl) detectors are used in applications where high detection efficiency, good energy resolution, and reasonably good timing properties are needed. An example of low-energy gamma rays observed in a small NaI(Tl) detector is shown in Fig. 4. A radioactive source of ^{60}Co, which emits a pair of coincident gamma rays with energies of 1173 and 1332 keV, was counted with a 7.6-cm diameter by 7.6-cm long NaI(Tl) detector. The full energy (photo) peaks of these lines are clearly seen along with a well defined "sum peak" which is produced when the full energies of both gamma rays are absorbed at the same time by the detector.

Another use of NaI(Tl) detectors is in nuclear reaction studies. In radiative capture reactions, the projectile fuses with the target nucleus and the resulting excitation energy is carried off by relatively high energy ($\gtrsim$10 MeV) gamma rays. While solid-state germanium detectors would provide better energy resolution, their detection efficiency for such high-energy gamma rays is too low for them to be useful. Therefore, in this type of research, NaI(Tl) detectors are often used. An example of a spectrum observed in the capture of protons by a target of ^{30}Si is shown in Fig. 5. The NaI(Tl) crystal used in this experiment is 25 cm in diameter and 28 cm thick. The proton bombarding energy was 25.5 MeV. The small peak near 32 MeV gamma-ray

energy corresponds to the case of leaving the resulting ^{31}P nucleus in its ground state; other peaks at lower gamma-ray energy correspond to leaving the ^{31}P in one of its excited states.

Another application of scintillation detectors is in the area of Compton-suppression. In a typical germanium detector, if a 1-MeV gamma ray enters the detector only about 20% of the recorded events will be in the full-energy peak (photopeak) and 80% will be in a continuous spectrum from zero up to the full gamma ray energy caused by Compton scattering. By surrounding a germanium detector with a suitable scintillator, one can look for events where both detectors fired simultaneously. Such events are produced by Compton scattering in the germanium detector into the scintillator and can be vetoed. An example of an annular NaI(Tl) scintillator acting as a Compton-suppressor for a germanium detector is shown in Fig. 6. Gamma ray spectra observed in the germanium detector in this system are shown in Fig. 7. A ^{54}Mn source, which emits mono-energetic γ rays at 835 keV, was counted with a 100 cm^3 germanium detector. The upper spectrum shows the response of the germanium detector without regard to what happened at the same time in the surrounding NaI(Tl) detector. One sees the 835-keV full energy peak along with a Compton continuum. The lower spectrum is what is observed in the germanium detector in anti-coincidence with the NaI(Tl) annulus, i.e. when the NaI(Tl) sees nothing. One can clearly see a large reduction in the Compton continuum by a factor which is a much as 10 in some parts of the spectrum. In a number of multi-element germanium detector arrays, such as the High Energy Resolution Array (HERA) at Lawrence Berkeley Laboratory, TESSA at Daresbury Laboratory, and the soon to be built GAMMASPHERE and EUROGAM arrays, bismuth germanate (BGO) anti-Compton shields are used instead of NaI(Tl). The reason for this is that the large atomic number of Bi and the high density of BGO means that a much smaller sized scintillator is needed to provide the same amount of Compton suppression. This

permits the germanium detectors to be closely packed together, and thus provides high efficiency for detecting the full-energy gamma ray in a germanium detector.

As can be seen in Table 1, the time dependence of the light output of scintillators varies widely. This variation has been put to a practical use in what is called a phoswich detector. This consists of two different scintillators stacked one behind the other, both of which are viewed by one photomultiplier tube. An example of this type of detector is shown in Fig. 8. This detector consists of a thin crystal of CaF_2 mounted on the end of a long plastic scintillator. A charged particle which enters the CaF_2 and comes to rest in the plastic scintillator will produce scintillation light in both materials. Due to the difference in the decay time of the light output in these two materials, the photomultiplier output signal will have two components. There will be a fast component associated with the plastic, and a slower one associated with the CaF_2. By appropriately integrating these signals, one can extract the individual signals from these two scintillators and obtain a measurement of both the energy lost in the front scintillator, ΔE, and the total energy of the charged particle, E. An example of the data resulting from a phoswich detector system is shown in Figure 9. In this case the products of the fragmentation of an ^{16}O beam by a ^{238}U target were observed by an array of phoswich detectors consisting of two different types of plastic scintillator- one with a short decay time and one with a long decay time. From the "short" and "long" gates set on the photomultiplier output signals, one obtains the ΔE and E parameters, respectively. The fact that, for a give kinetic energy, nuclei with different atomic numbers (Z) lose differing amounts of energy in the thin front scintillatior gives rise to the various bands seen in this two-dimensional plot.

Scintillation detectors have also played a major role in astrophysical studies performed in space. For example, NaI(Tl) detectors on the Solar Maximum Mission detected nuclear gamma rays at 847 and 1238 keV produced by the radioactive decay of ^{56}Co (half-life = 77 days) coming from supernova 1987a. This observation

helped to confirm that the evolution of massive stars produce a core of iron which collapses and initiates the supernova explosion. This process had been suggested long ago but, the observation of these characteristic gamma rays is one of the strongest pieces of experimental evidence that this type of nucleosynthesis actually occurs in supernovae.

In the field of medical physics, scintillation detectors have played major roles in a number of areas. Whole body counters, which are used to determine the identities and quantities of radioisotopes contained in a person , often consist of large NaI(Tl) crystals. When housed in a low-background environment, such systems are capable of detecting very small (~ nano-Curie) amounts of gamma-ray emitting radioisotopes.

Another area in which scintillators are now being widely used is positron emission tomography or PET scanning. In this procedure, a positron-emitting radioisotope, such as ^{18}F, is attached to a compound such as fluorodeoxyglucose and is then introduced into the subject's body. It is concentrated in an organ of interest where the positrons annihilate with electrons. The annihilation process produces two gamma rays, each of 511 keV which are emitted back-to-back. That is, they travel off in opposite directions from the point of annihilation. These annihilation photons are detected in coincidence in two diametrically opposed crystals. By surrounding the subject with a large number of detectors, and by finding the intersection point of all of the lines, one can determine the size and activity of the positron emitting activity. By observing the time variations in such activity one can observe various body functions in progress. A subject being counted with a PET system of 280 bismuth germanate crystals is shown in Fig. 10. PET data showing activity of the human brain taken with a system containing 600 individual crystals is shown in Fig. 11.

In the area of geological exploration, scintillation detectors also play a major role. Measurements of natural radioactivity to locate deposits of uranium and thorium in the earth's crust is a place were scintillation detectors are widely used. Low-flying

aircraft carrying large NaI(Tl) detectors make surveys of gamma-ray activity searching for the characteristic gamma rays emitted in the decay chains of ^{232}Th (2.6 MeV) and ^{238}U (1.76 MeV). Borehole measurements are performed in several different ways. Sometimes a scintillation detector is simply lowered down a whole and measurements are made of the local radioactivity. In other applications sources of either neutrons or gamma rays are also placed underground and the scintillation detector is used to measure the amount of scattered or induced activity.

In the area of nuclear safeguards, large plastic scintillators are often used in vehicle or personnel monitoring to look for unauthorized movements of radioactive materials. In such an installation a vehicle or person drives or walks past the scintillation detector and the charcatersitc gamma rays of ^{235}U or ^{239}Pu are sought for. Walk-through systems are now in place which can detect 0.02 grams of ^{239}Pu or 1 gram of ^{235}U.

In an number of industrial situations, one is interetsed in measuring the wearing away of material from an object as a result of it being used. This is the subject of tribology, and scintillation detectors are often used in this field. For eample in the automobile industry, engine wear can be determined by implantaing a gamma-ray emitting radioisotope in the part of the engine of interest. A NaI(Tl) or BGO detector is then placed near this part and the gamma-ray counting rate is monitored as a function of the engine use. As the part is worn away, one observes a decrease in the gamma activity. By taking an identically implanted part and measuring its gamma counting rate as one quantitatively removes material from the surface, one can calibrate the technique. Through such tests, it has been found that this method is sensitive to engine part wear as small as 0.00005 inches.

Compton scattering of gamma rays from an object can be used to determine the thickness and/or distribution of material within the object. This technique is often used in the area of quality control. For example, artillery shells coming off a production line

have been irradiated with 662-keV gamma rays from a ^{137}Cs source. By measuring the number of scattered gamma rays and by comparing the result to that obtained from a standard, one can reject shells that contain voids or other imperfections. This method offers several advantages over more conventional schemes in that it is non-destructive and can be done very quickly.

Conclusions

The conversion of the energy deposited by radiation into light is the basis of the scintillation detector. Many different types of scintillators have been developed to meet a variety of needs in the field of radiation detection. Today scintillation detectors are used extensively in physics, chemistry, medicine, astrophysics, and in a number of industrial applications. With the ongoing development of new and improved scintillating materials, scintillation detectors will continue to play major roles in these fields for the forseeable future.

Figure Captions

Fig. 1. Schematic view of a scintillation detector system. The interactions of photons in a NaI(Tl) scintillator are shown along with the transmission of the resulting optical photons through a light pipe to a photomultiplier where light is converted into an electrical signal. (Courtesy of S. E. Derenzo).

Fig. 2. An ingot of CsI as it emerged from the crucible in which it was grown. (Courtesy of Bicron Corp.)

Fig. 3. A plastic scintillator paddle with a light pipe attached to it. (Courtesy of Bicron. Corp.).

Fig. 4. Gamma-ray spectrum of ^{60}Co observed in a 7.6-cm diameter by 7.6-cm long NaI (Tl) detector.

Fig. 5. Gamma-ray spectrum observed in a 25-cm diameter by 28-cm long NaI(Tl) detector from the $^{30}Si(p,\gamma)^{31}P$ reaction at a proton bombarding energy of 25.5 MeV. (Courtesy of G. Feldman).

Fig. 6. A 30-cm diameter x 30-cm long annular NaI(Tl) detector system surrounding a 110-cm^3 germanium detector. The NaI(Tl) crystal is optically divided into two halves, each viewed by seven photomultiplier tubes. In this system, the NaI(Tl) detector is used to veto events in which a gamma ray Compton scatters in the germanium detector and the scattered photon goes into the NaI(Tl) detector.

Fig. 7. Gamma-ray spectra observed in a 110-cm^3 germanium detector placed. inside the NaI(Tl) annulus shown in Fig. 6. Data with (lower spectrum) and without (upper spectrum) the NaI(Tl) anti-coincidence requirement are shown to illustrate the reduction of the continuum produced by Compton scattering.

Fig. 8. Schematic view of a phoswich detector. Two scintillators with different decay constants are stacked one behind the other and are both viewed by a single photomultiplier tube. The resulting light signal then has two components which can be separated with appropriate electronics. (Courtesy of A. M. Poskanzer)

Fig. 9. An example of data obtained from an array of plastic phoswich detectors. By performing a fast integration of the photomultiplier signal one obtains a measure of the light output from the thin front scintillator. A longer integration provides a measure of the energy deposited in the thicker and slower back scintillator. (Courtesy of Y. D. Chan).

Fig. 10. A patient being examined with a positron emission tomography system that consists of 280 NaI (Tl) crystals. (Courtesy of S. E. Derenzo)

Fig. 11. An example of positron emission tomography data taken with a PET system consisting of 600 scintillation detectors. Activity of the human brain is indicated by the white areas in the tomograph. A control patient is shown along with a patient suffering from Alzheimer's disease.

Further Reading

Birks, J. B. (1964), The Theory and Practice of Scintillation Counting, Oxford: Pergamon Press,

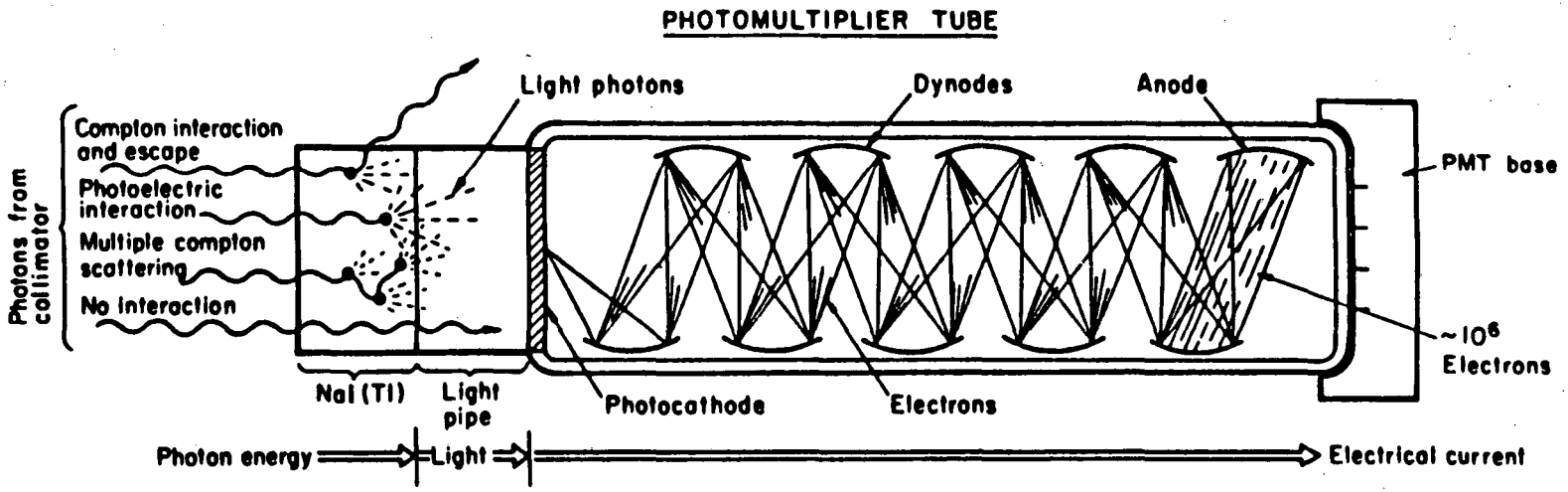
Brooks, F. D. (1979) Nucl. Instrum. Methods 162, 477-505.

Heath, R. L., Hofstadter, R., and Hughes, E. B. (1979) Nucl. Instrum. Methods 162, 431-476.

TABLE 1. Physical properties of various scintillator materials.

Material	Physical Form	Wavelength of Maximum Emission (nm)	Decay Constant (ns)	Density (g/cm^3)	Scintillation Efficiency* (%)
NaI(Tl)	crystal	415	230	3.67	100
CaF_2(Eu)	crystal	435	940	3.18	50
CsI(Na)	crystal	420	630	4.51	85
CsI(Tl)	crystal	565	1000	4.51	45
BaF_2	crystal	325	630	4.88	20
$Bi_4Ge_3O_{12}$	crystal	480	300	7.13	12
^{6}LiI(Eu)	crystal	480	1400	4.08	35
Anthracene	crystal	447	30	1.25	43
NE102A	plastic	423	2.4	1.032	28
NE115	plastic	395	320	1.032	10
Pilot U	plastic	425	1.36	1.032	29
NE213	liquid	425	3.7	0.874	34

* Relative to NaI(Tl)


PHOTOMULTIPLIER TUBE
Light photons
Dynodes
Anode
PMT base
Compton interaction and escape
Photoelectric interaction
Multiple compton scattering
No interaction
Photons from collimator
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NaI (Tl)
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Electrons
Photon energy
Light
Electrical current
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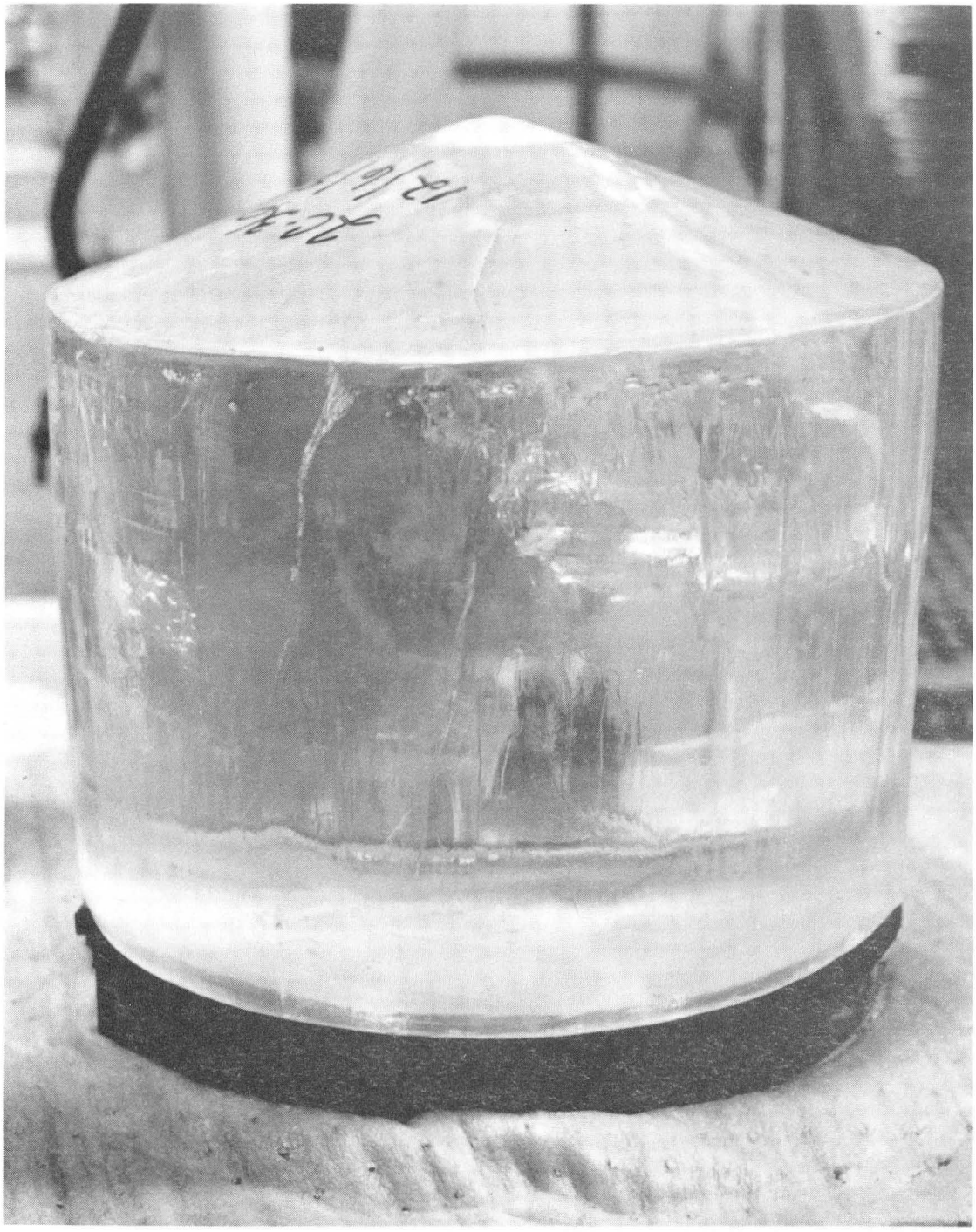
Figure 1



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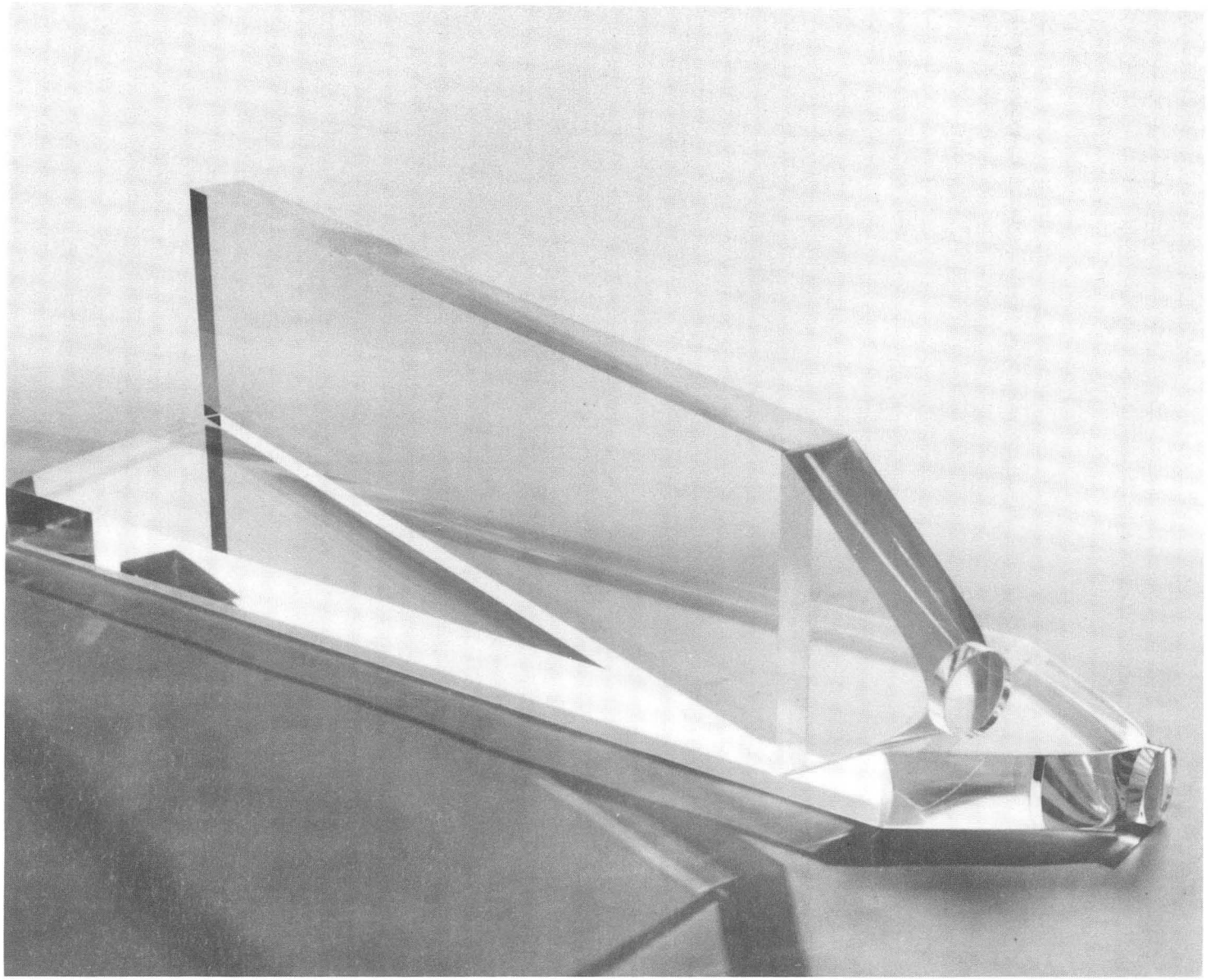

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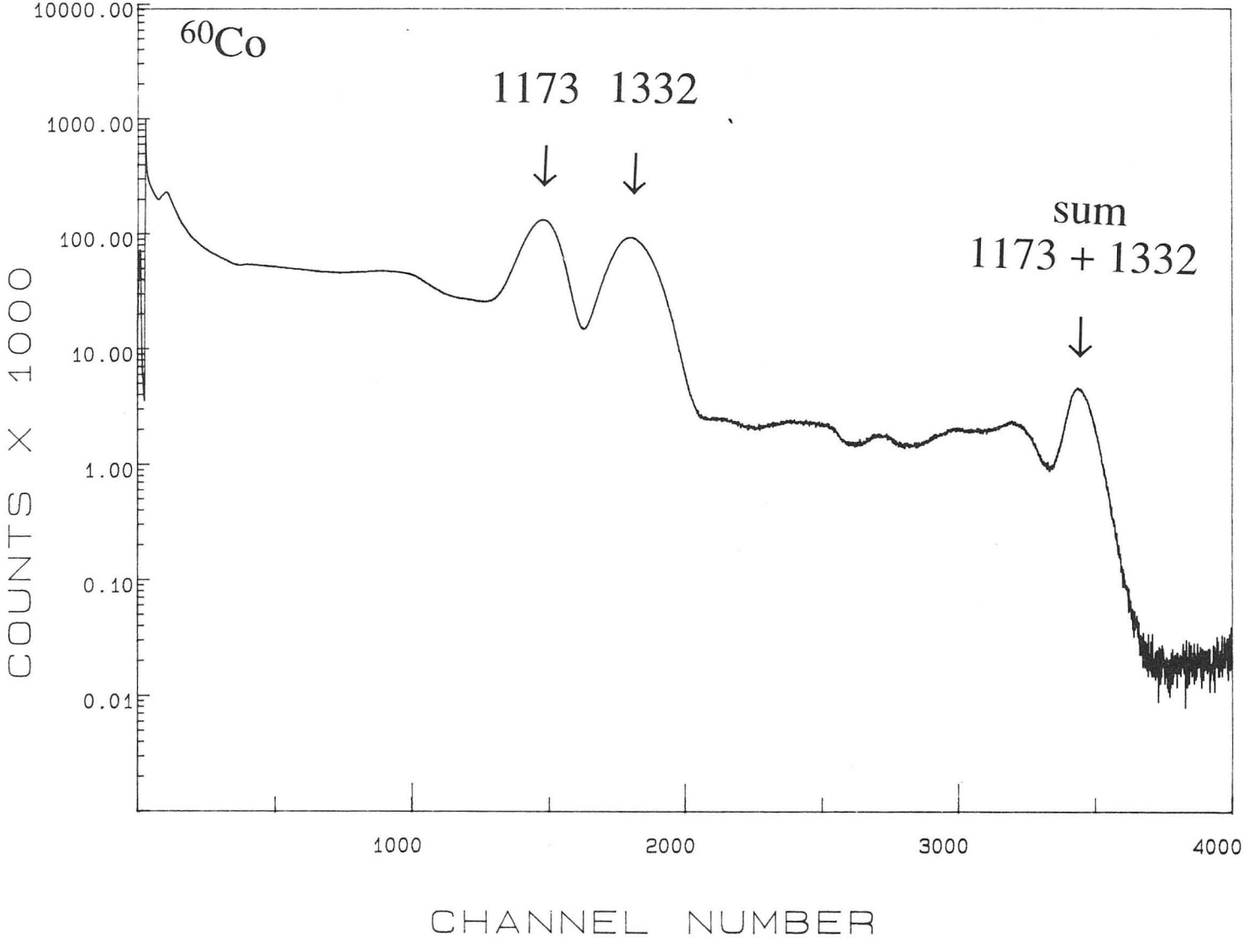
Figure 3



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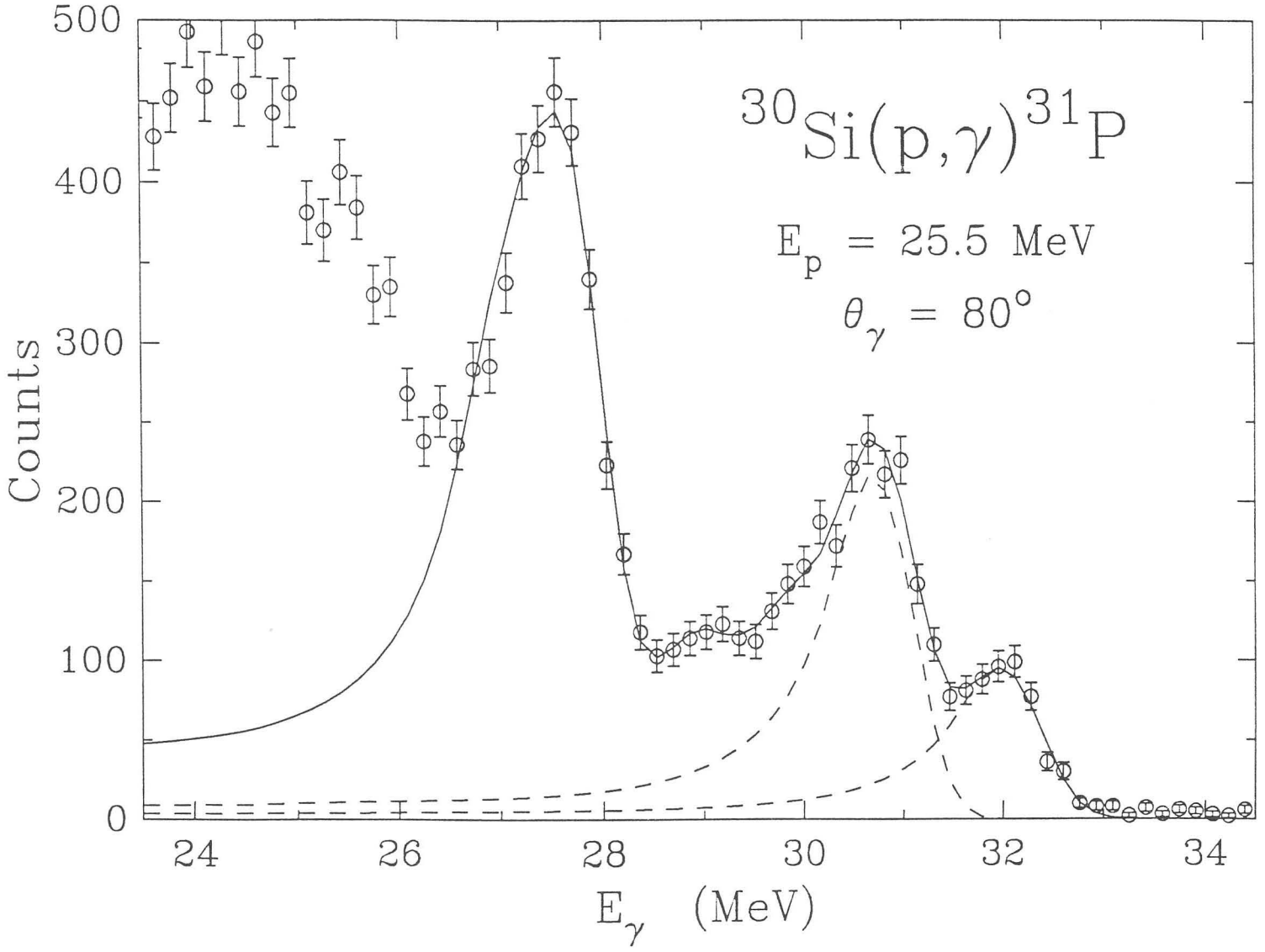

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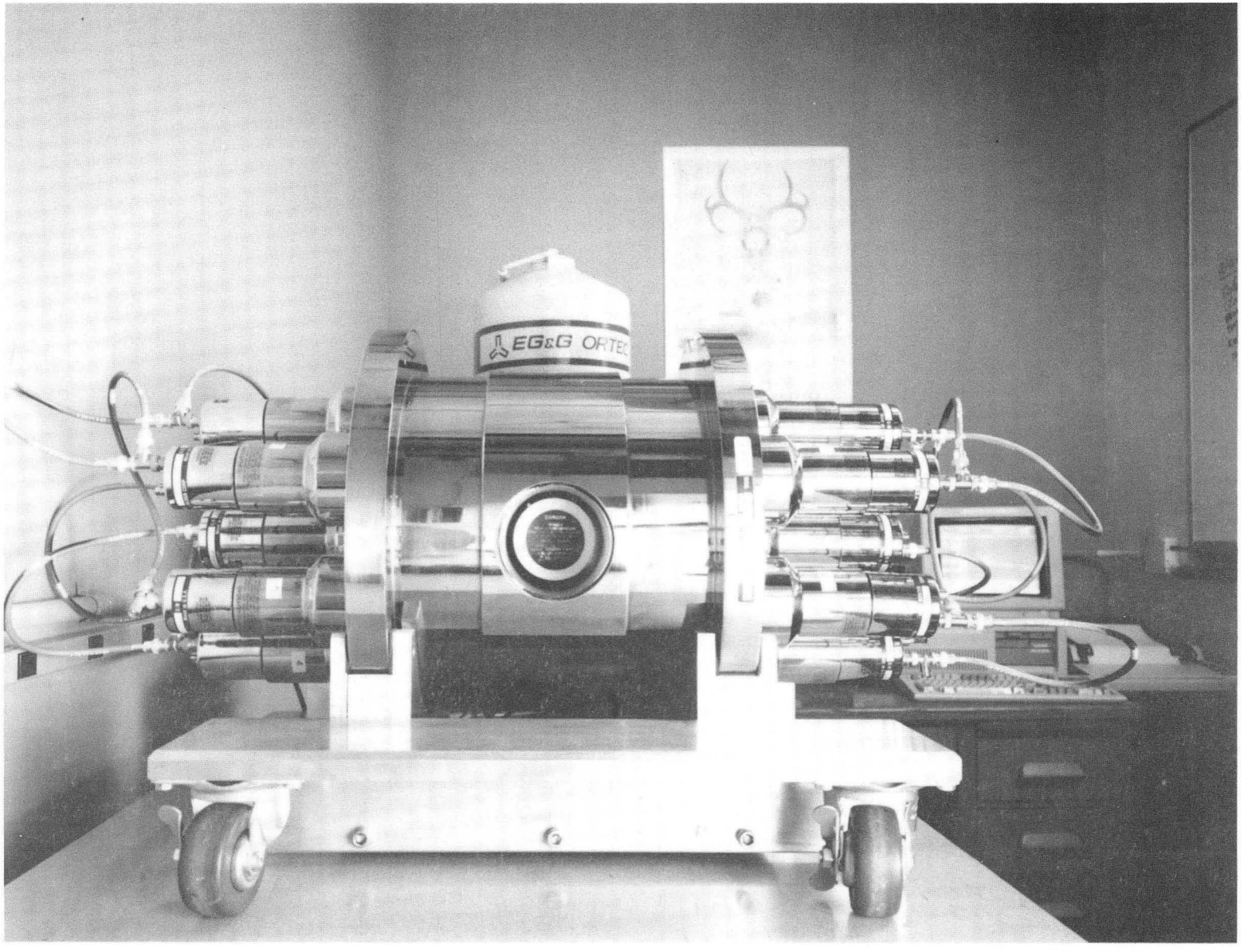

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Figure 6

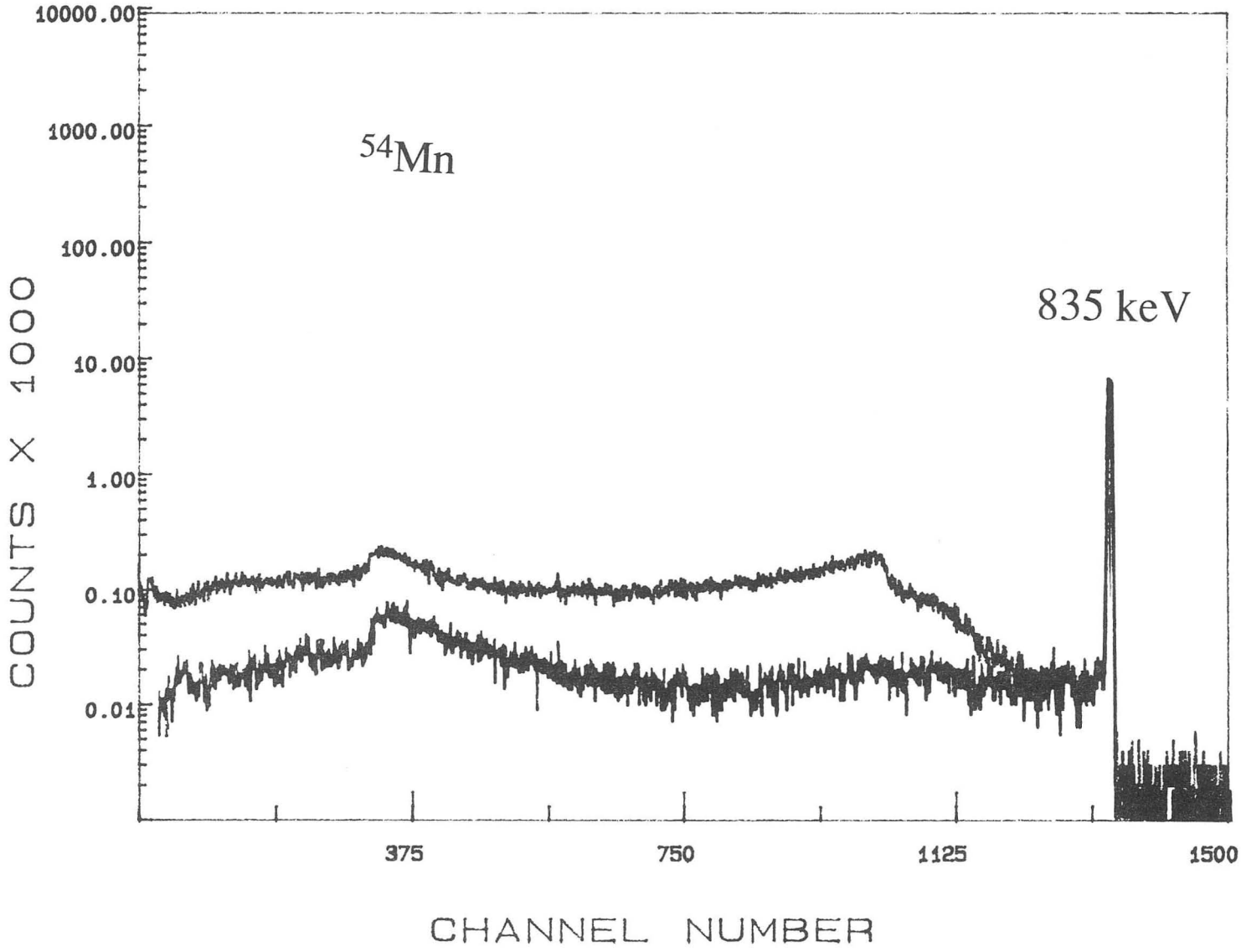

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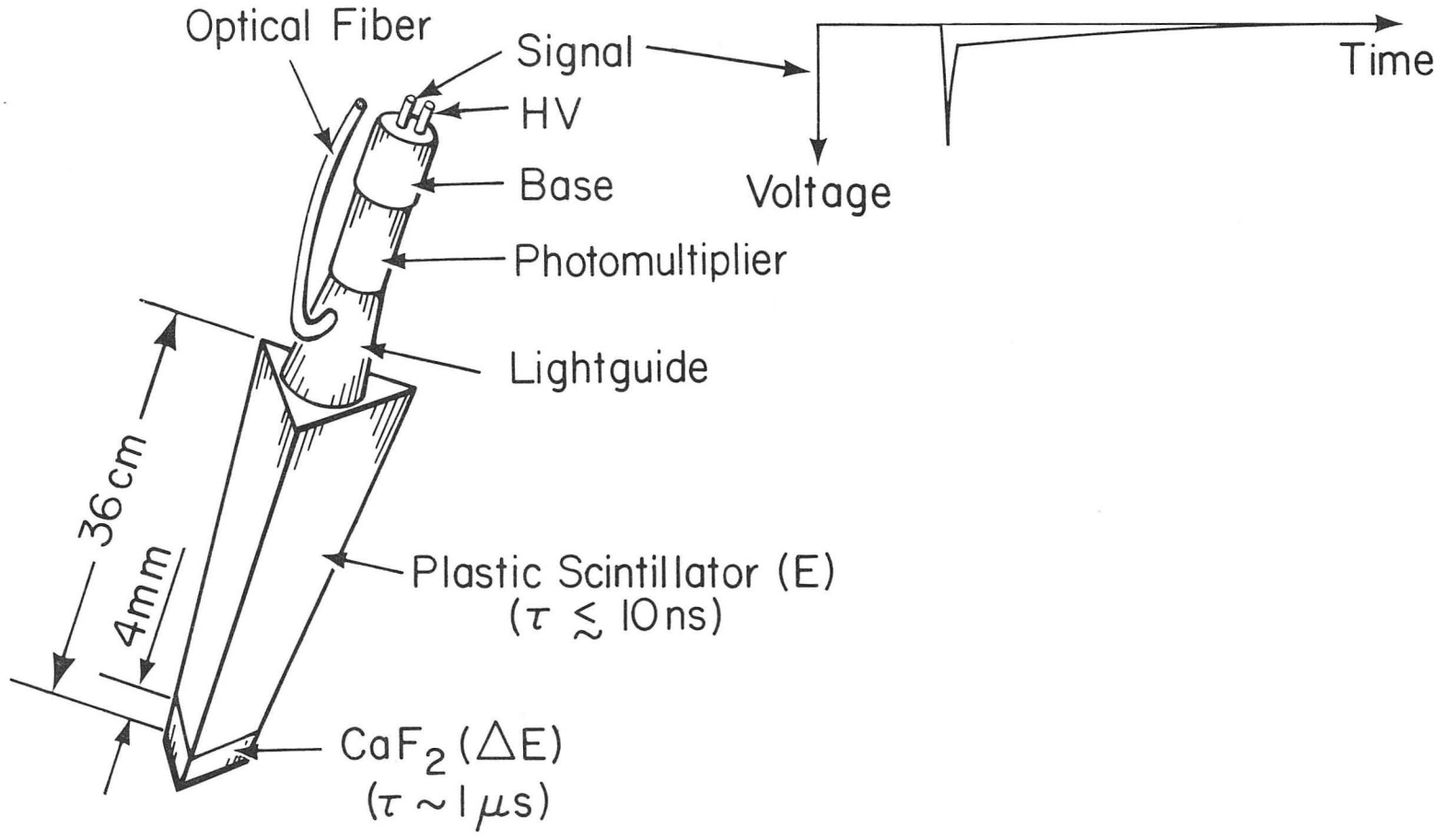
Figure 7



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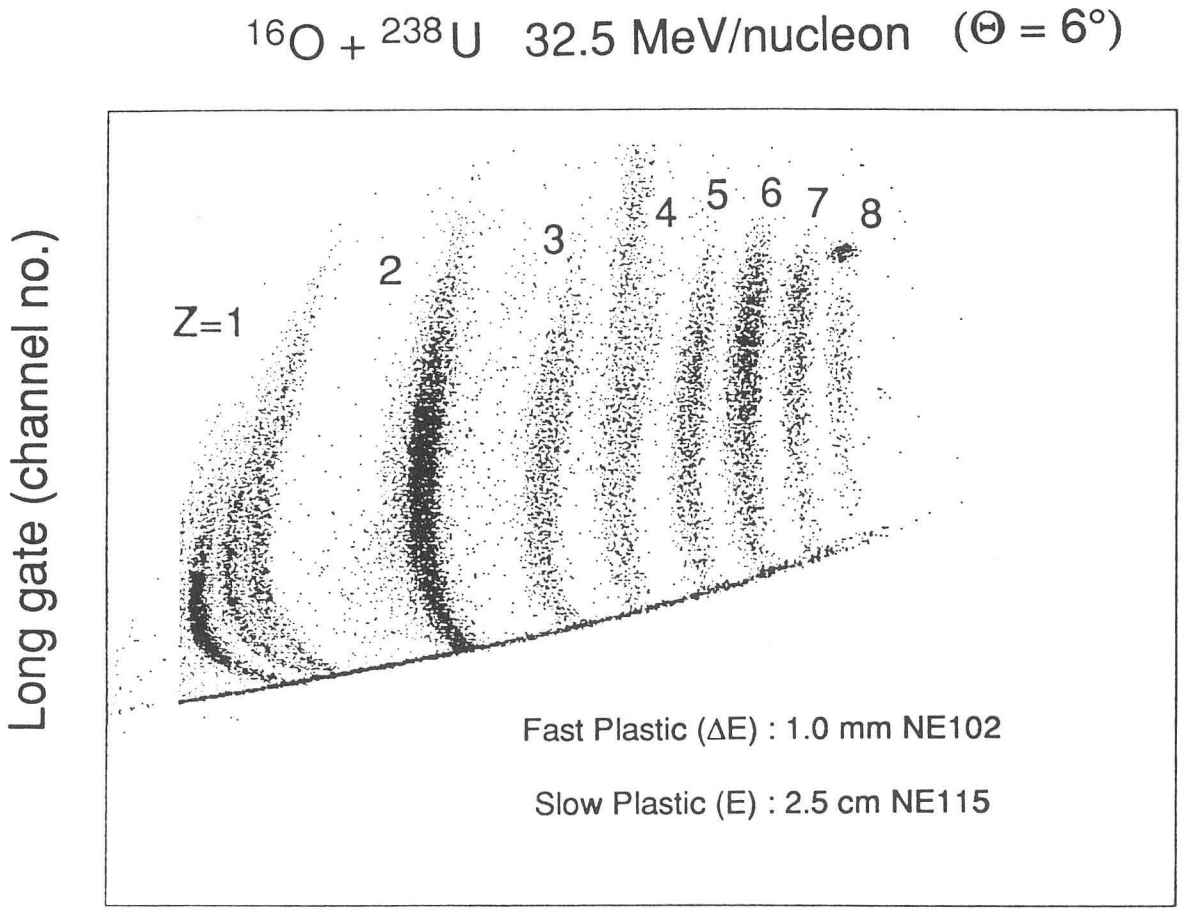

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Figure 9

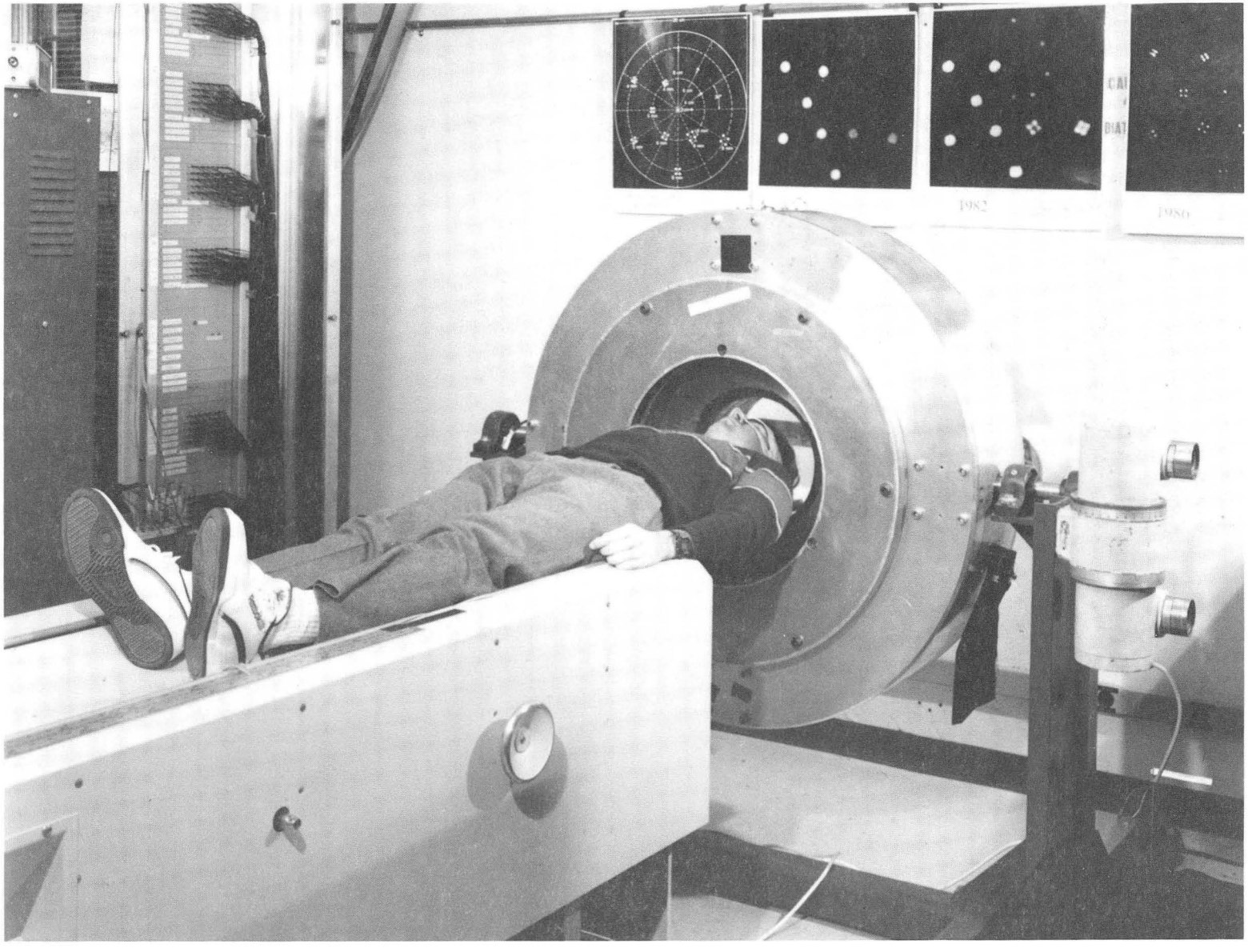

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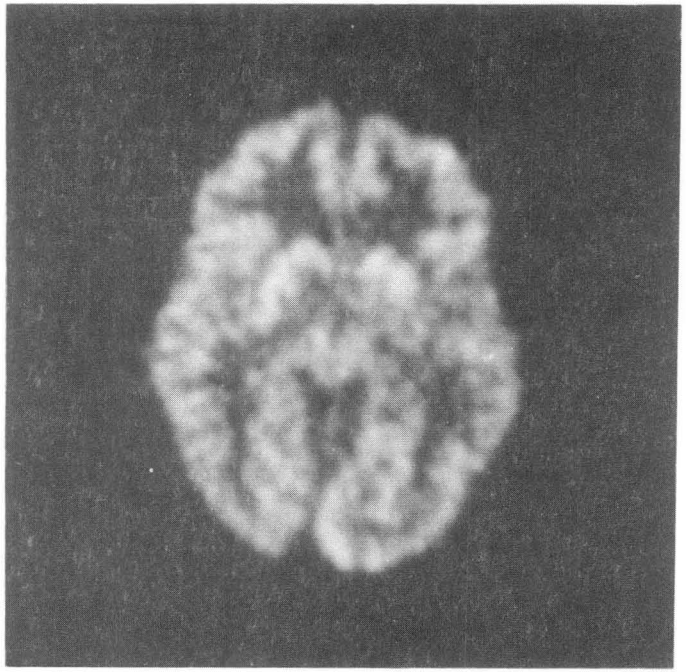
Figure 10

PET 600

Control



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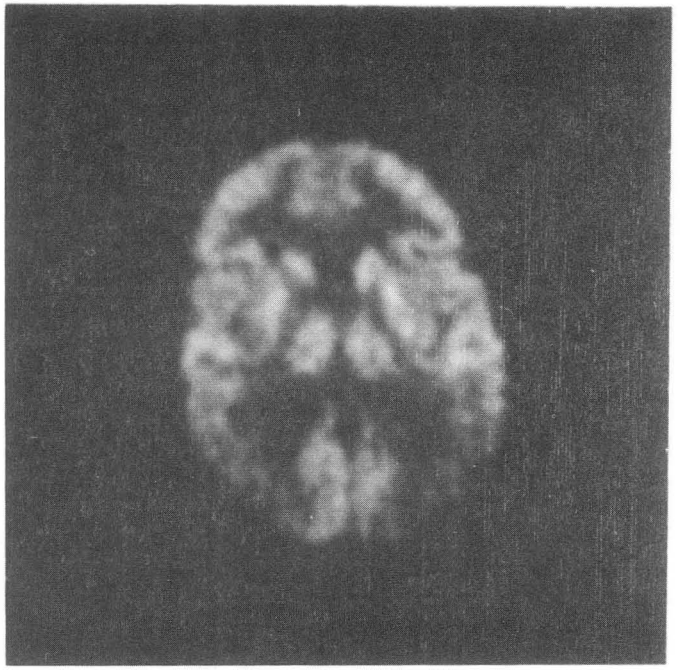

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Figure 11

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