Use of semiconductor detectors in high energy physics

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Various methods of detecting nuclear particles and γ rays in high energy physics by means of semiconductor detectors are described. The principle attention is devoted to questions related to use of semiconductor detectors in study of particle scattering at small momentum transfers. Spectrometry of x rays and γ rays in experiments with beam-particle stoppings in the target is discussed. Examples are given of use of semiconductor detectors simultaneously as a target. Appreciable space is given in the review to details of experimental technique.

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INTRODUCTION

At the present time the semiconductor detector (SD) of nuclear radiation is the main instrument for measurement of the energies of charged particles and γ rays in the region from several keV to hundreds of MeV. The distinctive property of an SD is its exceptionally high energy resolution, which in detection of x rays reaches 100 eV.[1,2] It is important that an SD permits measurement of spectra simultaneously over a wide range of energies and in this way provides conditions for rapid collection of statistics. Among the valuable properties of SD's are linearity and stability of their characteristics, and also insensitivity to magnetic fields and satisfactory operation at low temperatures. Of course, the main field of application of SD's involves experimental investigations in low energy physics. However, even in high energy physics there are a number of processes whose study by means of SD's is extremely effective. First among these are processes leading to production of particles and γ rays of comparatively low energy. The present review is devoted to discussion of experimental apparatus employing SD's for investigation of such processes. In order to understand the details of use of SD's in experimental physics, we shall turn first to the principal characteristics of SD's.

1. BASIC INFORMATION ON SEMICONDUCTOR DETECTORS

The material most widely used in preparation of SD's is high purity silicon. The impurity atoms remaining after purification determine the material resistivity ρ. The charge carriers can be electrons or holes. In the first case the material is referred to as n type, and in the second case, p type. n-type silicon is the initial material of surface-barrier detectors. Electrodes are deposited on a silicon surface appropriately processed. The front electrode is made of gold, which is a source of holes. Between the gold electrode and the silicon is formed a p–n junction, whose thickness W is further increased by supply of a bias voltage V, in accordance with the simple relation[3] $W \sim \sqrt{V\rho}$.

Current semiconductor technology permits detectors of thickness up to 5 mm to be obtained by this means. However, it is quite expensive to produce them. Thick detectors made of p-type silicon turn out to be 4–5 times cheaper. In this case lithium, which is a source of electrons, is introduced by drifting for compensation of the hole conduction.

In lithium-drifted detectors the thickness of the layer is practically independent of voltage beginning with a certain value. A charged particle hitting an SD leaves in it all or part of its energy, which leads to appearance of a corresponding number of electron-hole pairs. An energy of 3.55 eV is expended in formation of one pair in silicon. The low energy expenditure in formation of individual charge carriers is the principal distinctive property of SD's in comparison with other types of detectors. This energy expenditure is an order of magnitude lower than in ionization chambers, and two orders of magnitude lower than in scintillation counters.

Formation of a large number of primary charge carriers N assures small relative fluctuations of this number, which are further decreased as the result of correlations in the electron-hole-pair production process. This effect is expressed by the Fano factor $F \approx 0.1$ in the formula for the dispersion,

$$\overline{(\Delta N)^2} = FN.$$

This dispersion determines the fundamental limit of energy resolution, achievement of which is usually prevented by noise in the electronics and detector.[4] An appreciable suppression of noise is provided by cooling the detector and the input impedance of the amplifier. The effect of noise on the resolution is proportional to the capacitance of the detector, which increases with increasing ratio of detector area to thickness. A typical value of resolution for silicon detectors at room temperature is several tens of keV.

A role of no small importance is played by the rate of collection of charge carriers, which determines the rapid action of SD's. In lithium-drifted detectors the charge-collection time is

$$t = W^2/(\mu V), \tag{1}$$

where μ is the carrier mobility; at room temperature, electrons have $\mu_n = 1350$, and holes—$\mu_p = 480$ cm^2/(V-sec). For example, for $W = 0.1$ cm and $V = 200$ V, the hole-collection time is 100 nsec.

In surface-barrier detectors, if the sensitive layer does not extend to the back electrode, 90% of the charge is collected in a time equal to 2.3ρ nsec, where the material resistivity ρ is expressed in kilohm-cm. Recently surface-barrier detectors have been made which withstand high voltages; practically the entire thickness is a working region. The collection time in such detectors can be evaluated with Eq. (1). Use of SD's without "dead" layers in front and back is important for many experiments, especially if the range of the charged particle exceeds the thickness of the detector.

2. METHODS OF STUDY OF PARTICLE SCATTERING IN THE REGION OF LOW MOMENTUM TRANSFERS BY DETECTION OF RECOIL PARTICLES AND MEASUREMENT OF THEIR ENERGY

In elastic scattering of particles the region of small momentum transfers presents special interest. However, studies in this region by detection of particles scattered at small angles involves significant experiment difficulties. Therefore at the present time there has arisen and been substantially developed a new approach to study of scattering processes, based on use of information provided by the recoil particles. Here we should mention particularly studies carried out in internal beams by means of thin targets (as thin as 0.4 μ) which allow multiple traversal of beam particles through the target.[5] At an angle to the beam axis close to 90°, particles with low energy are emitted from the target; these were initially detected by emulsion chambers. In this case the emission angle of the particles and their range in emulsion are measured.

The main deficiency of the emulsion method is the low rate of collection of statistics. The technique of studying elastic-scattering processes by detection of recoil particles has acquired its contemporary form as the result of application of SD's for this purpose[6]; these detectors are free from the deficiency mentioned and permit precise measurements of emission angles and the energy or ionization loss of the recoil particles. The fact that in an SD the sensitive layer begins practically at the surface permits in principle detection of particles of very low energies, and the combination of a thin counter with a thick counter permits reliable separation of particles of different types.

A diagram of an experiment with an SD in the internal beam of an accelerator is given in Fig. 1. The first experiment was carried out at the JINR proton synchrotron, where an SD was placed in the vacuum chamber at a distance of 3 m from a thin (0.7 μ) hydrogen-containing target mounted in the path of a proton beam with energy 4 GeV. Protons with energies of several MeV or several tens of MeV were detected. The pulses from the SD's were amplified and fed to a pulse-height analyzer. The apparatus was monitored by means of a pulse generator and an α source ($E_\alpha = 5.3$ MeV), for which the resolution was 40 and 70 keV, respectively. This instrumental resolution is quite adequate, since the principal spread of the pulses in height in the experiment was determined not so much by the electronics as by physical reasons, namely by multiple Coulomb scattering of the recoil protons in the target, and by the detection solid angle. For particles which pass through the SD's, the pulse-height spread increased as a consequence of nonuniformity in the sensitive layer thickness and statistical fluctuations of the ionization loss of the particles in the SD. Typical spectra of secondary particles are shown in Fig. 2,[7] from which it can be seen that the recoil protons give clearly expressed peaks superimposed on some background level. In the course of the measurements it was established that the dominant background is from the target direction. It is interesting to note that a substantial part of this background is from particles passing through the counter, and of these an appreciable fraction are particles losing in the SD an energy of 1–2 MeV and thereby hindering identification of desired particles with the same energy. These events can be excluded (Fig. 3) if an additional counter located directly beyond the SD in front of it is connected in anticoincidence. This means, in particular, has been used in experiments at the Batavia accelerator. The experiments at the Dubna synchrotron were carried out with polymer films containing hydrogen and deuterium.

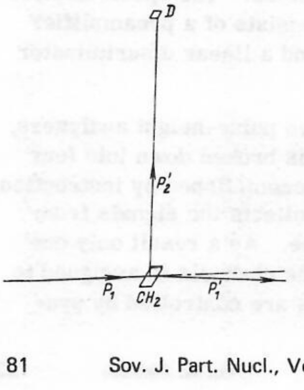

FIG. 1. Diagram of proton elastic scattering at small angles.

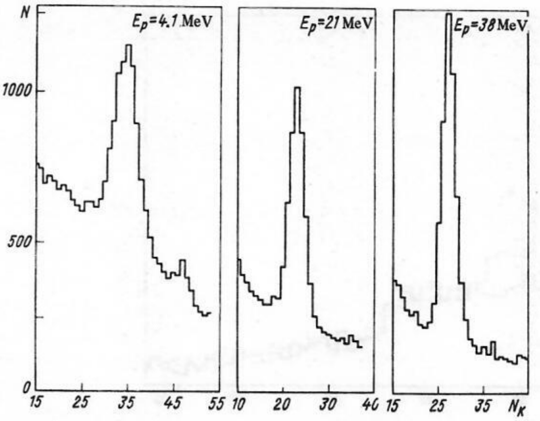

FIG. 2. Spectra of secondary particles from a thin polyethylene target.

Figure 4 shows measurements of the differential cross section for pp and pd scattering. The measurements were made in the following momentum-transfer intervals: $4\times10^{-3} \leqslant q^2 \leqslant 7\times10^{-2}$ (GeV/c)^2 for pp scattering and $8\times10^{-3} \leqslant q^2 \leqslant 6\times10^{-2}$ (GeV/c)^2 for pd scattering. We recall that between the momentum transfer q^2, the mass M, and the kinetic energy E of the particle we have the simple relation

$$q^2 = 2ME.$$

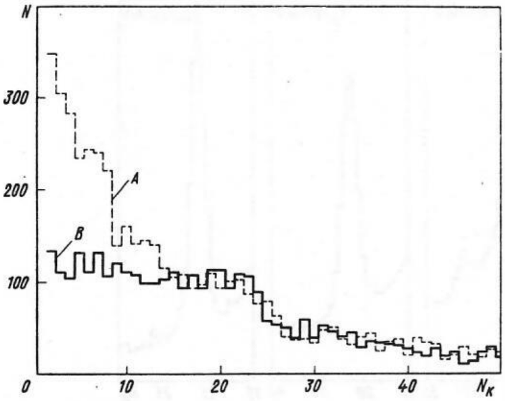

FIG. 3. Spectrum of background secondary particles: A—normal appearance; B—with rear counter connected in anticoincidence.

For example, a momentum transfer $q^2 = 0.01$ (GeV/c)^2 corresponds to a proton energy $E_p = 5.3$ MeV and a deuteron energy $E_d = 2.7$ MeV. The error in measurement of the differential cross section is determined by the error in monitoring (5–7%). The relative error in the case of pd scattering is of the order of 2–3%.

The experimental points outside the Coulomb region are fitted by the curves of the form

$$d\sigma/dq^2 = (d\sigma/dq^2)_0 \exp(-bq^2).$$

For pp scattering the slope parameter is $b = 7.9 \pm 0.7$ (GeV/c)$^{-2}$, and for pd scattering $b = 36 \pm 0.7$ (GeV/c)$^{-2}$.

Targets

A serious problem in designing experiments in the internal particle beam of an accelerator is the inadequate radiation stability of a polyethylene target. Under the action of an intense flux of particles the film darkens and is destroyed as the result of radiation damage and local heating. In vacuum, where the heat transfer from the film is poor, local heating is significant. To increase the length of service of a target, a design has been proposed in which the place of bombardment of the target is continually changing.[8] The target arrangement is shown in Fig. 5.

A film in the form of a disk is fastened in the central part with a metallic disk which is mounted on a motor axis and rotates. Under the action of centrifugal forces, the film extending beyond the metallic disk is straightened out and lies in the plane of rotation. A distinctive feature of the target is the fact that there is no mounting or support for the film except the simple metallic disk located in the region where the particle beam does not pass. The rotation provides a continuous change of the point of bombardment and in this way a substantial increase in the length of service of the target.

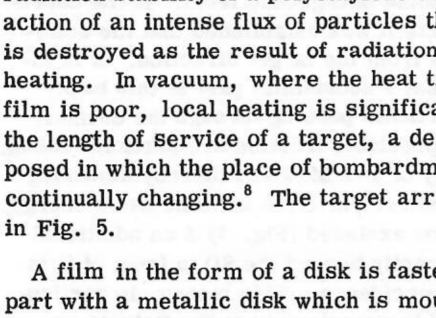

FIG. 4. Differential cross sections for an energy 4.0 GeV: 1—pp scattering; 2—pd scattering.

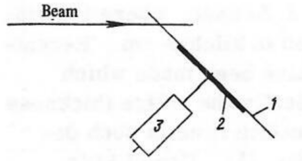

FIG. 5. Target arrangement: 1—polyethylene film; 2—aluminum disk; 3—motor.

Target problems have been solved fundamentally by use of hydrogen and deuterium gas-jet targets.[9] The density of the jet is 10^{-7}–10^{-6} g/cm^3, and the width is 12–15 mm, which provides normal conditions for carrying out experiments in proton accelerators. At the present time a complete range of experiments have been carried out in various accelerators both with gas targets and solid targets, including rotating ones.

Experiments in an electron beam

The semiconductor technique for detection of recoil particles has been applied to measurement of differential cross sections for elastic ep scattering.[10] This experiment is of interest first of all because it permits determination of the behavior of the electric form factor of the proton G_E near zero momentum transfer and obtaining direct information on the electric radius of the proton. The experiment was carried out in a rotating target of polyethylene film of thickness 3 μ and diameter 140 mm. The diameter and thickness of the metallic disk were 80 and 1 mm, respectively. A motor with a speed of 3000 rpm and a power of 2 W was used. The lifetime of the target was 50–70 hours in the beam with an average current of 200 μA.

Measurement of the background was carried out with a thin stationary carbon target. However, it is technically very difficult to prepare a pure carbon film of thickness ≈ 2 μ; hydrogen impurities usually exist in the film. In this connection another solution of the target problem was found—use of a thin film of fluorinated plastic (C_2F_4) consisting only of carbon and its near neighbor in atomic number fluorine.

The structural arrangement of the experimental apparatus is shown in Fig. 6. The internal electron beam passes through a thin polyethylene target. Recoil protons emitted at angles close to 90° are detected by a series of semiconductor detectors. The spectrometric circuitry for each detector consists of a preamplifier PA, a linear amplifier LA, and a linear discriminator LD.

Spectra are measured by two pulse-height analyzers, in each of which the memory is broken down into four groups. The subdivision is accomplished by instruction signals from a mixer which collects the signals from four channels into a single line. As a result only one ADC is used and a fourth of the channels is assigned to each detector. The analyzers are controlled by syn-

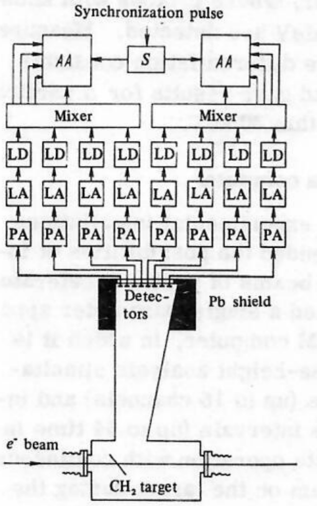

FIG. 6. Structural arrangement of an experiment for study of electron elastic scattering.

chronization pulses from the accelerator, which are repeated at the line frequency. The dump of beam particles onto the target lasts about 1 msec. Approximately during this time the analyzers accept signals from the detectors. The shaper F provides for regulation of the duration and delay of the control signals. This permits selection of the most favorable time intervals for particle detection and rejection of intervals with intense interference from the high-frequency generators in the accelerator, and also from neighboring targets during parallel operation.

A distinctive feature of the experiment is the very high background level from the target in the region of energy deposition below 1 MeV. Background pulses on the screen of an oscilloscope connected to the output of a linear amplifier are convenient for observing the operation of the accelerator and target and setting the necessary intensity of the electron beam.

In the experiment we used linear discriminators, without which the analyzer was heavily overloaded and readings remained only in the region of the earliest channels, which were filled with background pulses. Pulse discrimination provides a normal range of operation of the analyzer—about one pulse per cycle. It is important that the discrimination is carried out before the mixer. In discrimination after the mixer, pulse-height distortions arise as the result of pileup of background pulses and noise from various channels.

Detectors of various areas and thicknesses were used in the experiment. The use of long detectors—40×10 mm—is important. Prepared from n-type silicon with resistivity $\rho = 6$ kilohm-cm, these detectors for a voltage of 350 V have a thickness of 0.8 mm, which corresponds to the range of protons with energy about 11 MeV.

Such detectors, located at a distance of 1.5 m from the target, permit measurement of recoil-proton spectra continuously over a wide range of kinematic angles. After background subtraction, these spectra provide information on the behavior of the differential cross section as a function of momentum transfer. Here we have excluded only the edges of the spectra, which are smeared out as the result of multiple scattering of the

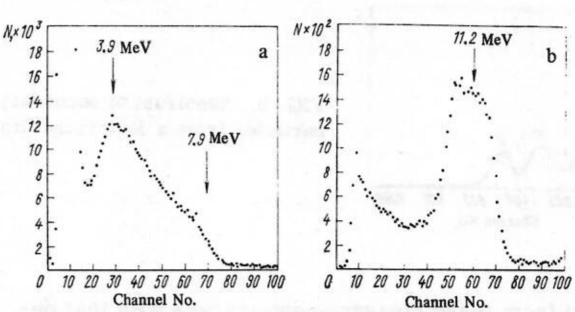

FIG. 7. Spectra of secondary particles emitted from a polyethylene target placed in an electron beam.

recoil protons in the target and the nonpoint geometry of the beam and target. One of these spectra is shown in Fig. 7a, and Fig. 7b shows a spectrum measured by a narrower detector. Information from narrow detectors is used as auxiliary information, particularly for study of the behavior of the background in different parts of the spectra. The high level of collection of statistics is shown in Fig. 8.

Experimental results obtained in the accelerator at Erevan have shown that in the region of low momentum transfers the function $G_E(q^2)$ is satisfactorily described by the dipole formula

$$G_E(q^2) = (1 + Aq^2)^{-2}.$$

The value of the proton radius $R = 0.79 \pm 0.04$ fermi ob-

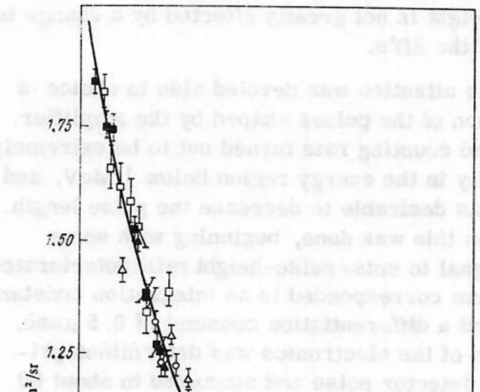

FIG. 8. Differential cross sections for elastic electron–proton scattering at 4.4 GeV.

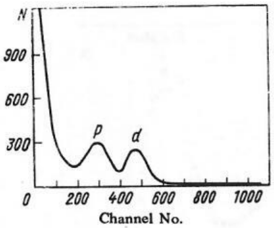

FIG. 9. Spectrum of secondary particles from a deuterated film.

tained from these measurements agrees with that determined previously at large q^2.

At the Erevan accelerator measurements have also been made with a polyethylene film in which 95.2% of the hydrogen was replaced by deuterium.[11] In order to separate the deuteron and proton peaks, the long detectors were rotated by 90° in comparison with the location in the experiment described above and in addition collimators with a window width of 3 mm were placed in front of them. A typical spectrum with well resolved deuteron and proton peaks is shown in Fig. 9. Since the differential cross sections for elastic *ep* scattering in the region of small momentum transfer have already been determined, comparison of the number of counts in the two peaks permits information to be obtained on the cross section for scattering of electrons by deuterons.

As we have mentioned above, the experiments utilize surface-barrier SD's of large area. Their capacitance depends on the applied voltage and amounts to 100–200 pF. It is important to choose a preamplifier[12,13] whose output pulse height is not greatly affected by a change in capacitance of the SD's.

Considerable attention was devoted also to choice of optimal duration of the pulses shaped by the amplifier. The background counting rate turned out to be extremely high, especially in the energy region below 1 MeV, and therefore it was desirable to decrease the pulse length. However, when this was done, beginning with some length, the signal to noise pulse-height ratio deteriorated and the optimum corresponded to an integration constant of 0.2 μsec and a differentiation constant of 0.5 μsec. The resolution of the electronics was determined primarily by the detector noise and amounted to about 60 keV.

Let us consider another important circumstance which can arise in operation with short pulses. We are speaking of the accuracy of the calibration constants obtained with α sources. Actually, to a good approximation the energy expenditure in formation of a given number of charge carriers does not depend on the type of particle. However, the charge collection time T depends on the particle range, since the mobilities of electrons and holes, which move in opposite directions, differ by almost a factor of three. In order to avoid a dependence of the pulse height on the range of the particle and therefore on the type of particle, the duration of the shaped pulse must be chosen to be significantly greater than T. In the case discussed T does not exceed 20–30 nsec, i.e., this condition is satisfied. The accuracy in the α-particle calibrations is checked experimentally in an electrostatic generator, where protons with known energies in the range 5–9 MeV are detected. Measurements were made with three differentiation constants: 0.5, 1.0, and 3.0 μsec, and gave results for α particles and protons which agree within 30 keV.

Automated installation with a computer

Use of a computer in the experimental installations with SD's substantially extended the possibilities of investigations in the internal beams of proton accelerators. Zabiyakin *et al.*[12] constructed a single-parameter apparatus coupled to a BÉSM-3M computer, in which it is possible to carry out a pulse-height analysis simultaneously on several channels (up to 16 channels) and independently in several time intervals (up to 64 time intervals). The latter permits operation with continuous dumping of the primary beam on the target during the acceleration process, which provides information immediately over a wide range of energies. It is important that measurements of the energy dependence of differential cross sections simultaneously at many points assures the minimal effect of instability of the apparatus with time.

The structural arrangement of the electronic apparatus for eight detectors (1–8) used in experiments at the Serpukhov accelerator[13] is shown in Fig. 10. The events recorded by the SD's are independent, and therefore, aside from accidental coincidences, at a given moment of time a signal arrives only from one detector. Analysis of the pulse heights of signals from all channels is accomplished by one block, which transforms the pulse height to a seven-digit number. Another block provides a four-digit number for the detector number. These two numbers together comprise one "event." Four events form one machine word in the intermediate memory. The forty-fifth digit of the machine word is zero and is a signal for pulse-height information. The latter arrives every 16 msec and is labeled by numbers produced by a time encoder. The start of the operation of this block is associated with a definite start energy, which is specified by a signal corresponding to the accelerator magnetic field value produced. The time information is stored in the intermediate memory and, together with the monitor counts of three scintillation

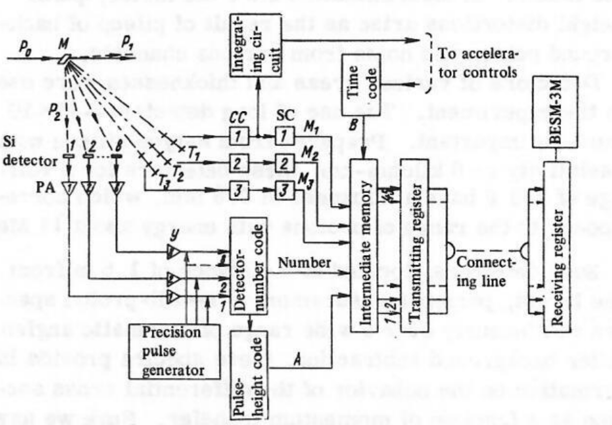

FIG. 10. Structural arrangement of electronic apparatus with semiconductor detectors.

telescopes, forms the second machine word, the forty-fifth digit of which is labeled by unity.

The apparatus constructed, with thin targets and SD's, has permitted important physics results to be obtained, including measurements of the shape of the diffraction peak of elastic scattering in the momentum-transfer interval near $q^2=0$, and investigation of the real part of the scattering amplitude over a wide range of energies, both at the Serpukhov accelerator and at higher energies (50–300 GeV) in the Batavia accelerator,[14] where the experimental apparatus was similar to that described above.

Use of position sensitive semiconductor detectors

In the accelerator at Batavia, successful use has also been made[15] of position-sensitive semiconductor detectors, which simultaneously with measurement of the energy provide information on the place of entry of the particle into the detector. This is accomplished by introduction of two special contacts on the opposite ends of the back electrode (Fig. 11). The charge arising on detection of a particle is distributed between the two contacts with inverse proportionality to the resistance of the path traveled. The resistance is proportional to x for one contact and y for the other. Thus, the signal at one of the contacts is proportional to $E_1 = xE/(x+y)$. The signal received from the front electrode gives the total value E. The ratio of the signals E_1/E determines the place of incidence of the particles, usually with an error of 2–3% of the detector length for $E \approx 5$ MeV. The linearity of the detector depends substantially on the uniformity of the material resistivity and the parallelness of the silicon plates. If E_1/E is close to zero or unity, then distortions arise as the result of the effect of electronics noise and nonlinearity at the edges. With reduction of the particle energy, the noise has a greater effect and the region of boundary effects increases. In addition to nonlinearity in the region of small E_1/E, inefficiency of detection can also occur, particularly if the level of accompanying background processes is high. Nonlinearity and inefficiency at the edges make it necessary to introduce appropriate limitations on the detector area used. In spite of this, position-sensitive SD's are generally a promising tool for a number of investigations.

Identification of particles from their ionization loss and energy

Effective separation of particles in mass is provided by a combination of thin and thick SD's connected in co-

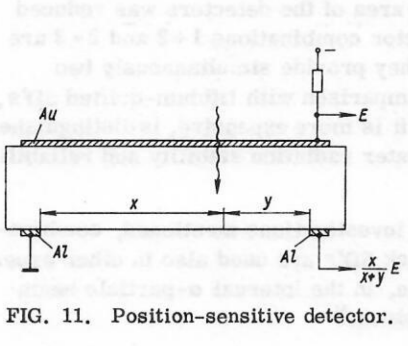

FIG. 11. Position-sensitive detector.

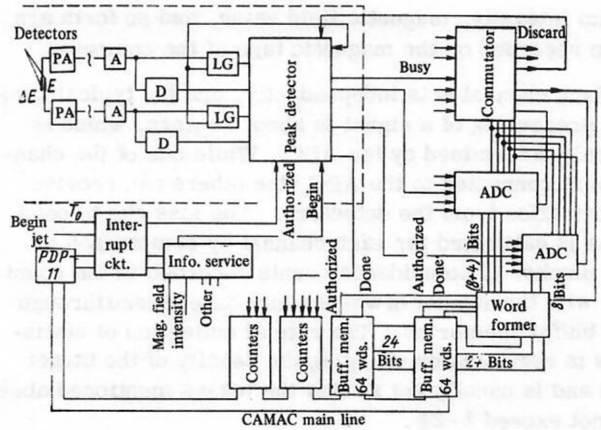

FIG. 12. Structural diagram of electronic apparatus with paired SD's.

incidence. The first detector measures the ionization loss ΔE, and the second, when the particle stops in it, measures the energy $E-\Delta E$. In particular, in the installation described below,[16] detectors of thickness 0.2 and 2 or 5 mm are used, which completely contain the ranges of protons with respective energies up to 19 and 32 MeV and deuterons up to 23 and 42 MeV. The detectors have an area of 1 cm^2. The structural arrangement of the electronic apparatus, designed for sixteen identical channels, is shown in Fig. 12, where we have shown in detail the electronics belonging just to one pair of SD's. Amplified pulses from the SD's are split and sent in two directions: to linear gates LG for subsequent pulse-height analysis and to discriminators D connected to a coincidence circuit for the signals from the thin and thick detectors. The coincidence-selection device is located in the block called peak detector. The third signal required for a coincidence is the signal from the interruptor circuit connected with a PDP-11 computer. The coincidence signal opens the linear gate, and the peak detector produces two analog voltages equal to the heights of the signals reaching it from the thin and thick SD's, and in this case a "busy" signal appears. A commutator systematically scans all channels with a frequency of 5 MHz. On reaching the busy channel, the commutator stops, and the analog voltages are transferred through a multiplexer to two ADC's which produce eight-digit numbers corresponding to the heights of the pulses being analyzed. These two numbers occupy the lower sixteen bits of a 24-digit word, which is formed in a mixer and stored in one of the two fast buffer memories designed for 64 words each. The four next bits carry information on the number of the channel in which the event occurred. The ADC stop signal restores the peak detector and allows the commutator an additional search for busy channels. When one buffer memory turns out to be filled, it is disconnected and the data from it are removed to a computer along a CAMAC main. By that time the other buffer memory is capable of receiving data, i.e., the collection of statistics is not interrupted. In the CAMAC main the readings of the counters connected to the outputs of the coincidence circuits are also recorded. In addition to the data from the detectors, information on the particle beam intensity, magnetic field value, and so forth are also recorded on the magnetic tape of the computer.

Each channel acts independently, and the typical time for processing of a signal is about 10 μsec, which is mainly determined by the ADC. While one of the channels is connected to the ADC, the others can receive information from the detectors. The loss due to dead time is estimated for each channel by comparison of the number of coincidence counts recorded in the counters with the number of words which have passed through the buffer memories. The rate of collection of statistics is regulated by changing the density of the target gas and is usually set so that the losses mentioned above do not exceed 1–2%.

The peak detectors transmit the pulse-height information practically without distortion over a wide range of pulse rise time. This is important, since the thickness and accordingly the charge-collection time in SD's differ considerably. The charge-collection time amounts to tens of nanoseconds in thin detectors and about 1 μsec in thick lithium-drifted detectors. The nonlinearity of the electronics is measured by means of a pulse generator with automatically changing pulse height and does not exceed ±1 channel.

The apparatus works in the pulsed mode. A typical duration of the gas jet is 150–200 msec. As a rule, three such jets are used in course of 1 sec (the rise time of the accelerator magnetic field) and the time interval corresponding to the duration of the jet is broken down into a series of subintervals (usually eight), which was accomplished by supplying control signals to the peak-detector gate through the interruptor block. The time separating these signals is 5 msec or more, which, like the duration of the signals, was specified by the program. At the beginning of each such signal, service information is recorded in the computer, on conclusion of which a signal permitting data to be received from the SD's is sent to all detectors.

The typical nature of the information received from the two SD's in operation with a deuterium target is shown in Fig. 13, which was photographed from the computer display screen. An individual point on the figure designates one event; the energy loss in the front SD is plotted along the vertical axis, and that in the rear

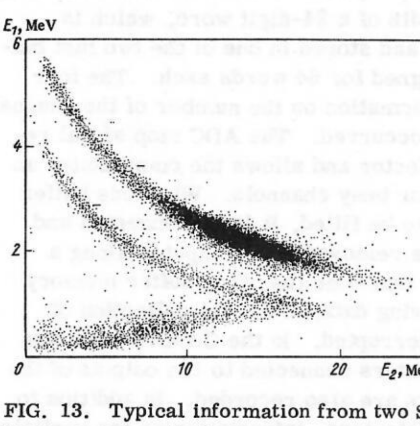

FIG. 13. Typical information from two SD's, photographed from computer display screen.

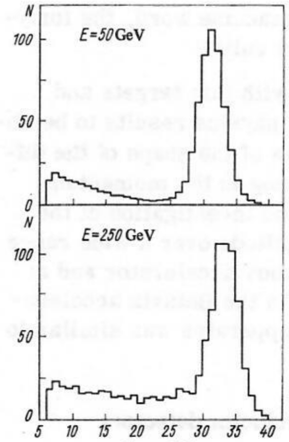

FIG. 14. Spectrum of deuterons for two proton-beam energies.

SD—along the horizontal axis. Two groups of particles: deuterons and protons—are clearly evident. The region with the greatest density of points is due to recoil deuterons arising in the scattering process. The thickness of the first detector, which is 200 μ, is traversed by deuterons and protons beginning with respective energies 6.5 and 5.0 MeV. With increase of the energy, more and more of it is dissipated in the second detector, until the particle begins to leave the second detector. Here there is formed a point (more precisely, a region) of inflection, and the energy dissipation in the second SD then decreases. This region refers to particles with a known range of 2.2 mm in silicon for the case corresponding to Fig. 13, and it can be used for calibration.

The width of the peak due to elastic scattering (Fig. 14) of particles in experiments with a gas target is determined mainly by only the jet dimensions. We note that the location of the peaks depends slightly on the proton-beam energy.

A characteristic feature of the spectra is presented in the presence of a significant number of events to the left of the peaks, which is due primarily to processes of the diffraction-dissociation type, $p+d \to X+d$. Measurements of such spectra permit valuable information to be obtained on the behavior of the differential cross sections $d^2\sigma/dq^2dM_x^2$ over a wide range of mass M_x in a proton beam with energy 50–400 GeV.[17] Investigations have been carried out in deuterium and hydrogen targets. In addition to the apparatus shown in Fig. 12, a modification has been used in which each channel had three surface-barrier detectors of thickness 0.15, 1.5, and 5 mm. As a result of the high beam intensity (10^{13} protons per cycle) and the proximity of the detectors to the target (1.5 m), the area of the detectors was reduced to 0.15 cm^2. Detector combinations 1+2 and 2+3 are convenient in that they provide simultaneously two ranges of q^2. In comparison with lithium-drifted SD's, this type, although it is more expensive, is distinguished by significantly greater radiation stability and reliability of operation.

In addition to the investigations mentioned, combinations of thin and thick SD's are used also in other experiments, for example, in the internal α-particle beam of the JINR synchrotron.[31]

Technical features of use of semiconductor detectors

The degree of separation of particles, particularly deuterons and protons, on the basis of their ionization loss and energy is determined first of all by the thin detector, specifically by the statistical fluctuations in the energy dissipated in this detector. The width at half-height of these fluctuations is Δ (keV) $= 14Z\sqrt{W(\mu)}$.[18]

In the case under discussion the semiconductor-detector thickness is $W = 200\ \mu$, the charge of the particle is $Z = 1$, and $\Delta \approx 200$ keV. The ionization loss itself is proportional to W. Consequently, the separation of particles is improved in proportion to $\sqrt{W}$, but here a higher energy is required of the particle in order to penetrate into the second, thick detector.

In spectrometric measurements an extremely important role is played by correct calibration of the apparatus. The edge of the spectrum $E_1 + E_2$ (see Fig. 13) can be used for energy calibration. However, the accuracy of calibration in this case does not always turn out to be satisfactory, as the result of the spread in the edge portion of the spectrum. A calibration can be carried out by using the known relation between energy and the emission angle γ from the target of a recoil particle with mass M and velocity β in an elastic collision:

$$E = (2M\beta^2 \sin^2\gamma)/(1-\beta^2 \sin^2\gamma),$$

where γ is measured from the perpendicular to the beam axis. In practice it is not a simple thing to find the angle $\gamma = 0$ from the experimental geometry with sufficient accuracy, and therefore it is necessary to have a series of measurements at different angles, from which it is possible to extract the appropriate calibration values.[32]

In our opinion, the two calibration methods described above are best used as a check in addition to the principal method consisting of bombardment of the SD by α particles of known energy and checking the linearity of the channels by means of a pulse generator. It is convenient to use a pulse generator with a linearly varying amplitude, in order to fill all channels of the ADC with good statistics. The nonlinearity appears in the extreme groups of channels. In addition, the dependence of the channel number N on pulse height can turn out to be shifted up or down as a whole and in this way to change the origin. By discarding a certain number of initial and final channels in studies with the apparatus shown in Fig. 12, and using the method of least squares in the computer analysis, it is possible to obtain very reliable calibration curves of the type $E = AN + B$, where A and B are constants. Calibration of the rear detector is technically difficult. In principle it is possible to calibrate only the front detector, if its thickness is accurately known. If the ionization loss of the particle in the front detector is known, it is easy to find the total energy of the particle.

When a series of SD's placed at different angles to the particle beam is used, it is necessary to know accurately the ratio of their areas. Use of a strong source, for example, such as $^{241}_{95}$Am, permits the sensitive areas to be compared with an accuracy of better than 1%. In the case considered, this source was placed exactly at the location of the gas target. Actually we determined not the area of the detectors themselves, but of the collimators located in front of them, by means of which the sensitive areas are most simply made identical. Two forms of collimation were used: In one of these the collimator was made thicker than the two detectors taken together, and was placed at the entrance to the front SD; in the other case, the collimator was placed between the two SD's, which permitted a substantial decrease in collimator thickness and accordingly a reduction of the scattering by the collimator walls. We note that in the second case events with particles passing through the collimator material are not completely rejected. Nevertheless such events are not difficult to exclude, since they have a different relation between the energy loss in the thin and thick detectors (Fig. 15). In the figure the solid curve refers to particles passing through the collimator opening, and the dashed curve is a possible curve for particles whose path goes through the collimator material. The dashed curve lies below the solid curve, but the two extreme points A and A' have the same abscissa value. Let E_1, E_2, and E_c be the energies dissipated in the detectors and in the collimator. The appearance of E_c leads to an increase in the threshold value of particle energy at which the latter enters the second detector, i.e., the origin of E_2 will correspond to a smaller value of E_1. The degree of decrease of E_1 increases with increasing ratio of the thicknesses of the collimator in the first detector. After the collimator the particle has an energy $E_2 = E - (E_1 + E_c)$, which is completely lost in the second detector as long as the particle does not pass out of this detector. The points A and A' correspond to the same particle range after the collimator, equal to the thickness of the second detector, and therefore they have the same abscissa values.

In use of SD's it must be kept in mind that at the edges of the detector electrodes the field has a fringing shape, which leads to a corresponding uncertainty in the effective area of the SD. It is necessary to have collimators such that the detected particle does not pass into the region of weakened electric field. This is important first of all for thick (5 mm) detectors, since in them the particle can be deflected appreciably toward the edges as the result of multiple scattering or scattering by the collimator walls. Charge produced in the weakened field is collected more slowly, which can result in decrease of signal height and accordingly errors in the

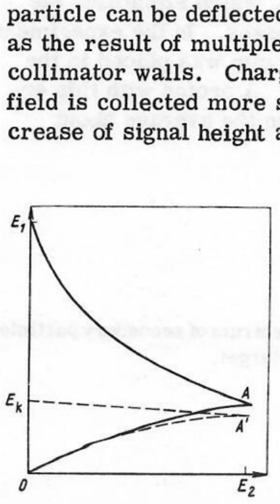

FIG. 15. Use of collimators between SD's.

measurements. This shows up particularly in work with short pulses.

As we have noted previously, in the case of short pulses a dependence of the pulse height on the charge-collection time can arise, which is affected by the range of the particle in the detector.

In addition to the effects noted above, with use of thick SD's it is necessary to take into account also counting-rate losses arising as the consequence of nuclear interactions.[19] Thus, for 35-MeV deuterons these losses amount to 1.5%.

3. INVESTIGATION OF COHERENT PROCESSES INVOLVING NUCLEI

A valuable property of a semiconductor detector is the linearity of its characteristics, i.e., the rather strict proportionality between the signal height and the energy dissipation, regardless of the type and energy of the particles detected. This greatly facilitates identification of recoil nuclei arising in interaction of primary particles with the material of various targets. A spectrum of well separated ^{4}He and ^{3}He nuclei obtained in study of coherent scattering of protons by a gaseous helium target[20] is shown in Fig. 16. The experiment was carried out in the external proton beam of the CERN accelerator with an energy of 24 GeV and an intensity of 10^{12} particles per cycle. The detectors had areas of 44×7 mm and were located at a distance of 80 cm from the target at angles from 90 to 57° to the beam axis. The angular resolution, which was 4 mrad, was determined by two collimators. The energy of the detected ^{4}He nuclei was 24–33 MeV. The ionization loss and energy of the particles were measured. The best separation of ^{4}He and ^{3}He nuclei is accomplished with use of two thin detectors for measurement of the ionization loss. In addition to elastic scattering, it is possible to observe also the contribution of the inelastic process $p+{}^4\text{He}\rightarrow N^*_{1/2}+{}^4\text{He}$ in the region of masses M_{N^*} equal to 1500 and 1688.

Heavier nuclei from coherent processes can be detected[21] with use of a silicon detector simultaneously used as the target. Silicon as a target is interesting in that most of its nuclei (92.2% ^{28}Si and 3.1% ^{30}Si) have zero spin and zero isotopic spin, which simplifies the analysis of the interaction processes. In the experiment a silicon detector of thickness 1 mm was placed in the path of a 730-MeV proton beam. A proton with this energy dissipates in the detector on the average about

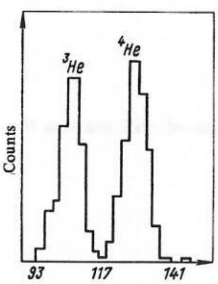

FIG. 16. Spectrum of secondary particles from helium target.

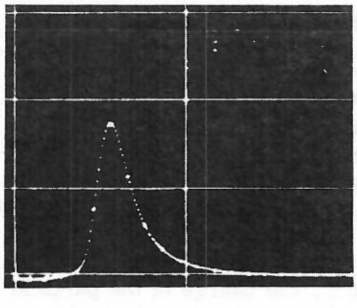

FIG. 17. Pulse height spectrum due to fast protons.

400 keV; the spread in ionization loss is characterized by a Landau spectrum (Fig. 17). On formation of a silicon recoil nucleus and its stopping in the detector, the energy of this nucleus is added to the ionization loss of the transmitted proton. As the result the signal from the SD is increased by an amount uniquely related to the proton-scattering angle. If this angle is fixed, for example, by a scintillation counter, it is possible to observe a spectrum similar to that shown in Fig. 18. In this spectrum we can see two peaks, the second of which belongs to the coherent interaction. The first peak—the background—corresponds to simple passage of protons through the SD with simultaneous operation of the scintillation counter.

Detection of silicon recoil nuclei can be used for preliminary selection of coherent interactions and for production of triggering signals, for example, for spark chambers intended for a more detailed study of a process. Thus, experiments have been designed[22] for the pion beams of the CERN and IHEP accelerators. In these experiments events are selected in which three or more pions are formed in targets of various materials. Semiconductor detectors are used as a dynamic target permitting effective separation of coherent events accompanied by production of silicon nuclei with energy near 400 keV. Detectors of thickness 0.2 and 1.0 mm are used. The target consists of five such detectors. The desired events are considered to be those in which only in one of the detectors does there occur an energy dissipation exceeding the energy of the incident relativistic pions by an amount of the order 400 keV. Fluctuations in the Landau spectrum in the direction of high ionization loss are naturally an interefering factor. From this point of view detectors of smaller thickness

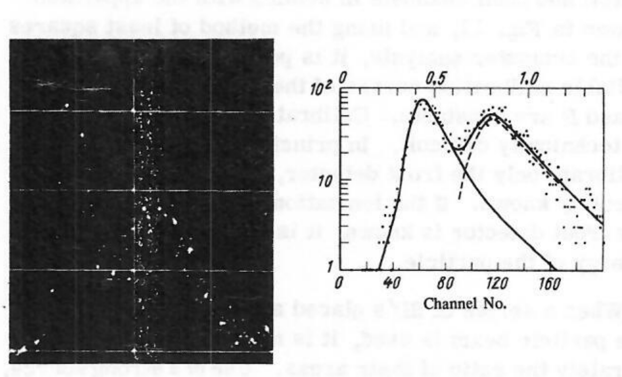

FIG. 18. Spectrum for the case of detection of silicon nuclei.

are preferable. However, as the result of the high capacitance of thin detectors, the difficulties associated with electronics noise arise. In practice the situation is further complicated by the relatively high intensity of the pion beam, and also by the effect of interference from the spark chambers. These circumstances have led to development of a special type of amplifier which permits spectrometric measurements to be made with rather short pulses.[23]

4. DETECTION OF γ RAYS

Extensive application of semiconductor detectors is found at the present time in γ-ray and x-ray spectrometers for radiation produced as the result of capture of muons or other particles in an atomic orbit with a large quantum number and a subsequent transition to lower energy states. In this case SD's made of germanium (atomic number $Z=32$, whereas for silicon $S=14$) have a higher efficiency. We recall that the photoeffect is proportional to Z^5, the Compton effect to Z, and pair production to Z^2. A major advance was the development of germanium detectors of coaxial design permitting working volumes to 100 cm^3 or more to be obtained. The efficiency of such detectors approaches the efficiency of scintillation counters with sodium iodide, and the energy resolution is an order of magnitude or more higher.

A typical experiment with detection of γ rays in large accelerators is described by Wiegand.[24] In this experiment kaon stoppings in various targets are detected; the SD's are located around the target. In order to cover the wide energy range of 15–550 keV, SD's of three different types are used simultaneously. Data up to 60 keV are obtained from a lithium-drifted silicon detector 3 mm thick, data in the range 60–300 keV from a plane germanium detector 13 mm thick, and data for higher energies are obtained from a germanium detector of coaxial configuration. The principal interest in the experiment is in the reaction $\overline{K}+N\to\overline{\Sigma}+\pi$ with subsequent capture of $\overline{\Sigma}$ hyperons and transition of these hyperons to other states. It is important that the spin of the $\overline{\Sigma}$ hyperon is 1/2, and therefore the emitted x-ray spectrum should contain doublet lines which carry information on the magnetic moment $\mu_{\overline{\Sigma}}$ of the $\overline{\Sigma}$ hyperon. Unfortunately, the expected shift between the lines is small (only about 300 eV), and therefore it is practically

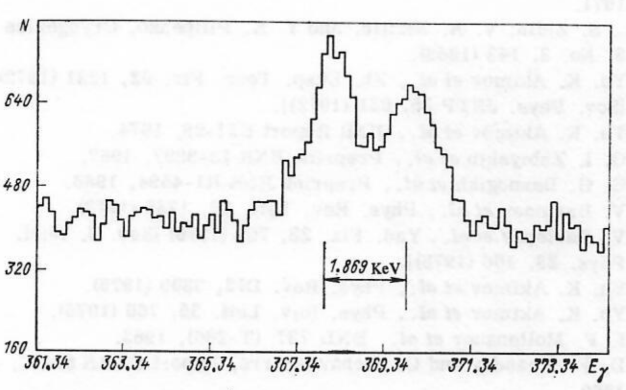

FIG. 19. Spectrum of γ rays.

impossible to separate them. Nevertheless, the existence of a doublet leads to a corresponding broadening of the peak, which permits definite conclusions to be drawn regarding $\mu_{\overline{\Sigma}}$. In particular, Roberts[25] has obtained by this technique a value $\mu_{\overline{\Sigma}}=-1.48\pm0.37$ nuclear magnetons.

The doublet nature of the lines appears significantly more distinctly in events arising in capture of antiprotons (Fig. 19).[26] On the basis of these spectra the value $\mu_{\bar p}=-2.790\pm0.021$ nuclear magnetons has been obtained for the antiproton. Germanium spectrometers are used at the present time in accelerators of widely different energies. For example, detection of γ rays emitted by various nuclei formed in bombardment of a uranium target with a 300-GeV proton beam has been discussed by Schedemann and Porile.[27] The events were identified by two germanium detectors connected in coincidence. The experiment yielded data on the cross section for production of various nuclei in the range $A = 24$–140.

5. GERMANIUM DETECTORS FOR CHARGED PARTICLES

The usual field of application of germanium detectors is primarily for gamma spectroscopy. These detectors up to the present time, are prepared on an extensive scale only from germanium compensated by lithium. Such detectors must be maintained at all times at a low temperature, which is inconvenient, and for detection of charged particles experimenters prefer to use silicon detectors, which are capable of being kept and used at room temperature. However, germanium is a heavier material than silicon and current technology permits construction of rather thick germanium detectors in which particles of relatively high energies can come entirely to rest. For example, in germanium a range of 15 mm corresponds to the following energies of protons, deuterons, and pions: 115, 155, and 55 MeV.

A major achievement of technology is the production of ultrapure germanium; detectors of this material can be kept at room temperature and need be cooled only to reduce noise during the experiment. In addition, ultrapure germanium permits preparation of detectors with practically no dead layer on the front face and with a small dead layer on the back face, which, according to Amann, may be as small as 120 μ in a detector 15 mm thick and 33 mm in diameter.[28] The same article[28] describes measurements with 102-MeV protons. It is pointed out that the number of nuclear interactions is 9% of the number of protons recorded. As a result of such interactions there occurs a reduction of the signals, which, as can be seen from Fig. 20, have a rather smooth distribution in the energy region 40–101 MeV and do not greatly affect the width of the main peak. These two facts are important in study of inelastic processes, which give signals located to the left of the elastic-scattering peak.

In order to use thick SD's for detection of positive pions, it is necessary to take into account pion decay.

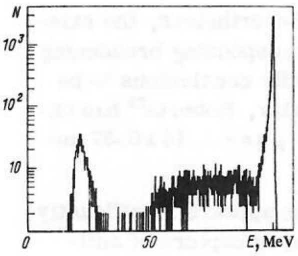

FIG. 20. Pulse-height spectrum from protons with energy 102 MeV.

The lifetime of the pion is 26 nsec and it decays to a neutrino and muon with energy 4.12 MeV, which in turn decays with a lifetime of 2.2 μsec into two neutrinos and a positron. The length of the pulses from the SD's usually exceeds the time of the first decay, and therefore there will always be added to the energy dissipation of the pions in the SD's the constant energy of the muons. Positrons also give an addition to the energy, but this is a variable quantity since some of the positrons stop in the detector while others leave it. In addition, the moment of the second decay may either coincide with the pulse from the pion or may occur later. As a result the second decay leads to a lengthening of the spectrum in the direction of high energies. Distortions of the spectrum by positrons are decreased by the following three means: exclusion of the microsecond decay pulses with an appropriate shortening of the pulses, introduction of anticoincidence counters around the SD's, and use of a special circuit which rejects events with pileup of pulses. With the combined use of these three methods it is possible to obtain pion spectra of satisfactory shape.[28]

A serious problem in the application of SD's to studies in the vicinity of intense particle beams is their limited lifetime with respect to radiation damage. For example, for the germanium detector discussed above a deterioration of the energy resolution from 2.2 to 16 keV was found after incidence on it of 10^9 neutrons/cm^2.

In regard to the permissible doses for SD's, it must be kept in mind that these depend on the thickness of the detector. In fact, with decrease of the thickness the number of dislocations in the semiconductor falls off and the SD's are capable of accepting a larger radiation dose per unit electrode area. To this we can add that lithium-drifted detectors are more sensitive to radiation than SD's of pure material.

6. DETECTION OF RELATIVISTIC PARTICLES

A relativistic charged particle loses an energy equal to 380 keV in a silicon layer 1 mm thick. The pulse-height distribution from the detector is described by a Landau spectrum (see, for example, Fig. 17). In work with large accelerators difficulties arise usually as the result of the presence of high levels of background counting rates, which imposes corresponding requirements on fast action of the amplifiers. Electrical, electromagnetic, and sometimes even acoustic interference may also be quite important, and it is necessary to shield the detectors and amplifiers carefully from these disturbances. For detection of relativistic particles it is desirable to use detectors of thickness about 2 mm or more. However, it must be recalled that with increasing thickness of an SD the charge-carrier collection time rises correspondingly. The relatively slow action of thick SD's limits the region of their application. SD's are inferior to scintillation counters both in speed and in size and therefore cannot compete with the latter in detection of relativistic particles. However, in individual specific conditions SD's turn out to be extremely convenient as a detector of fast particles. For example, it is possible to place SD's inside a hydrogen bubble chamber[29]; semiconductor detectors operate satisfactorily at liquid-hydrogen temperature and they can be used for appropriate selection of the events. Thus, an SD can be placed in a beam in front of the rear wall of the hydrogen chamber[30] and its signals, arising from particles which have not interacted, can be used as anticoincidences in analysis of the photographs.

CONCLUSION

The use of SD's in high energy physics permits a large number of interesting experiments to be set up in the internal and external beams of accelerators. A remarkable feature of these experiments is the comparatively low cost of the apparatus used. Further extension of the field of application of SD's in studies in high-energy particle beams will involve first of all an increase in the size of SD's, and also use of position-sensitive detectors which measure not only the energy but the coordinate of a particle. There is no question but that progressive semiconductor technology will open up even broader possibilities for improvement of these detectors and for development of new types.

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