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A NEW TYPE OF INTERNAL PAIR FORMATION SPECTROMETER

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A new type of internal pair formation spectrometer is described which makes use of the high resolution capabilities of semiconductor diodes. The instrument consists of two silicon detectors forming a $dE/dx+E$ telescope for the positron-electron pair and two NaI(Tl) scintillation counters for detecting the positron annihilation quanta. With present techniques the optimum energy resolution is 0.07% at 10 MeV. The instrument has been designed for applications in neutron capture spectroscopy.

For determining the multipolarity of high-energy gamma-ray transitions use can be made of the internal conversion process and, indeed, magnetic spectrometers have been applied in neutron capture spectroscopy up to several MeV 1). An alternative process which can yield information about gamma-ray transitions is the internal pair production, i.e. the emission of a posititron-electron pair instead of a gamma ray. While the internal conversion coefficient is small for low atomic numbers and decreases with increasing transition energy, the dependence of pair formation upon atomic number is only slight and the coefficient increases with increase of gamma-ray energy. A comparison of both processes is given in table 1. Over a wide range of energy and atomic number utilizing pair formation may be preferable to internal conversion.

Most of the presently available information on internal pair production has been accumulated by means of magnetic spectrometers 2). In this paper a new instrument is proposed which makes use of the high resolution and coincidence capabilities of semiconductor detectors.

A schematic lay-out of the spectrometer setup is shown in fig. 1. The system consists of two silicon detectors and two NaI(Tl) scintillation counters operated in a fourfold coincidence. The semiconductor diodes are stacked to form a $dE/dx+E$ telescope. They determine the total kinetic energy of the positron-electron pair when both particles are emitted into this solid angle. The annihilation quanta arising from the positrons stopped in the E-counter are selected by the scintillation detectors which are shielded against direct radiation from the gamma-ray source, the dE/dx-detector and the surrounding material. Using this principle the detection efficiency for electromagnetic radiation can be reduced by several orders of magnitude compared to that for charged particles. This is extremely important for the performance of the instrument since the spectrometer is used in direct geometry without applying electric or magnetic fields to the positrons and electrons.

For the design of the apparatus the following aspects have to be considered. The dE/dx-counter should be

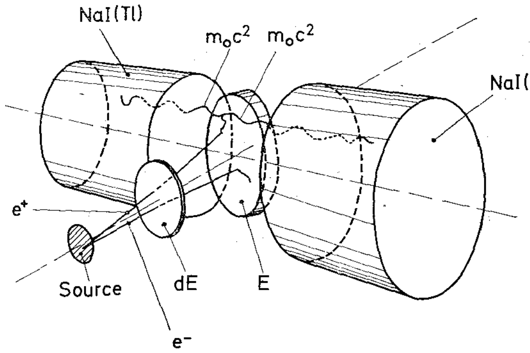

Fig. 1. Schematic view of spectrometer setup.

TABLE 1
Comparison of internal pair formation and internal conversion. Coefficient ($\times 10^4$).

	$Z=33; k=5$[a]			$Z=84; k=5$			$Z=84; k=7$		
	ED	EQ	MD	ED	EQ	MD	ED	EQ	MD
Conversion[b]	0.32	0.53	0.52	4.72	10.8	15.4	2.8[c]	6.0[c]	6.7[c]
Pair formation[d]	9.6	5.3	4.1	8.8	4.5	3.5	13.9	8.0[c]	

[a] The energy, k, is given in units of mc^2.
[b] From tables of Sliv and Band 2).
[c] Extrapolated values.
[d] Interpolated values from exact calculations performed by Jaeger and Hulme 3).

kept very thin (100–200 μm). The electrons then suffer only a small energy loss and reach the E-detector with high counting probability. In addition, more than 99.84% of the gamma rays emitted into the telescope pass through a 150 μm detector without undergoing any interaction, if their energy is higher than 2 MeV. For electrons with energies $\geqq 500$ keV the specific energy loss is nearly independent of energy and amounts to 0.35–0.40 keV per μm silicon. Thus those events which involve the passage of two particles through the counter can be pulse-height selected. If a positron is detected in the E-counter the paired electron is emitted into the telescope with marked probability since the two particles are highly correlated in angle. A photon can produce a fourfold coincidence when it is Compton-scattered in the $\mathrm{d}E/\mathrm{d}x$-counter causing a signal of appropriate amplitude and when the secondary photon undergoes external pair production in the E-detector. The probability for the occurrence of such an event is certainly less than 4×10^{-6}. Another process which may give rise to spurious coincidences is the interaction of the primary photon by external pair production in the $\mathrm{d}E/\mathrm{d}x$-counter with emission of the positron into the second detector.

Taking into account the pulse-height selection in the $\mathrm{d}E/\mathrm{d}x$-spectrum the corresponding probability can be estimated to be less than 6×10^{-5}. Finally, the probability for pair production in the E-counter with backscattering of the electron into the $\mathrm{d}E/\mathrm{d}x$-detector is certainly $< 10^{-5}$. These upper limits are well below the values for the internal pair formation coefficient. The estimates are based on a thickness of 150 μm for the transmission counter and a depletion depth of 5 mm for the E-detector. They are valid for primary energies between 2 and 10 MeV. The gamma-ray attenuation coefficients have been taken from the Grodstein report^{4}).

The solid angle defined by the telescope should be as large as possible in order to minimize the influence of the positron-electron angular correlation on the detection efficiency. For obtaining the total coefficient this influence has to be taken into account since the angular correlation though being strongly correlated to small angles is dependent on gamma-ray multipolarity. The corresponding correction is decreasing with increasing transition energy.

In all components of the spectrometer high input rates are unavoidable. Pole-zero cancellation, baseline restoration and pileup rejection should be provided in order to prevent rate-dependent distortions of the pair spectrum. Timing for the NaI(Tl) detectors should be as fast as possible. The optimum energy resolution which can be obtained with present techniques is 0.07% at 10 MeV.

A spectrometer of the design described above has been developed for application in neutron capture spectroscopy. First tests with a conversion electron source have shown that no distortion of the electron spectrum occurs when a gamma-ray source is added which has a strength more than three orders of magnitude higher than that of the electron source. At a high-flux reactor a spectrometer may be realized which is able to determine both the total coefficient and the angular distribution. In this case two or more telescopes are required.

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HIGH RESOLUTION PARTICLE-DETECTORS PRODUCED BY ION-IMPLANTATION

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High resolution particle detectors are produced by ion-implantation technique. It is shown that the improved performance is due to the fact that well-channeled ions at relative low energy and low ion-concentrations minimize bulk damage effects.

Forming thin n- or p-contacts on p- or n-type semiconducting materials by ion-implantation technique should have some advantages compared with diffusion- or surface-barrier techniques:

a. First of all ion-implantation can be performed at low temperature (annealing temperatures up to 300°C often are sufficient). Therefore minority-carrier lifetime is not reduced by defects produced at high temperature.

b. The incident ion-beam has a high chemical purity due to analysis by mass-separator techniques.

c. Ion-doped junctions are more stable to changes of ambient atmospheres and of vacuum than surface barrier-counters.

d. One can easily get different concentration profiles of the impurity atoms by changing energy and intensity of the ion beam and can thus look at the influence on diode performance^{2}). So far, however, no influence on the diode properties has been observed.

On the other hand a serious disadvantage is that the incident ions produce highly damaged regions forming a lot of traps and recombination centers. Indeed the first workers^{1,2}) who produced particle detectors by ion-implantation techniques obtained no promising results. The detectors had high reverse currents and bad resolution compared with counters fabricated by diffusion or surface-barrier techniques. First good results in producing particle detectors by ion-implantation were reported by Kalbitzer et al.^{3}). We were able to confirm his results and we pointed out^{4}) that the improved performance may be due to the fact that well-channeled ions and relative low ion-concentrations minimize bulk damage effects. This conclusion could be proved now in comparing measured lifetimes and concentration profiles of particle-detectors produced with well aligned and non-aligned ion beams.

Boron and phosphorus ions were produced by means of an inverted magnetron ion-source^{5}) and after acceleration analysed in a semicircular magnetic field similar to that described by Browne and Buechner^{6}). Well etched and cleaned n-type silicon slices (10000–135000 $\Omega\cdot$cm, 22 mm dia., 0.3–4 mm thick) cut normal to the 111-direction within 0.5° were clamped in masks with 10–15 mm dia. opening. Ion energies up to 10 keV were used; moving the Si-slices with constant velocity behind a slit-diaphragm normal to the incident beam we got an uniform implantation with ion concentrations up to 10^{13} ions/cm^2 for B and 10^{15}/cm^2 for P. The diodes were usually annealed for 10 min at 300°C and mounted on special holders for tests. No surface protection was used so far.

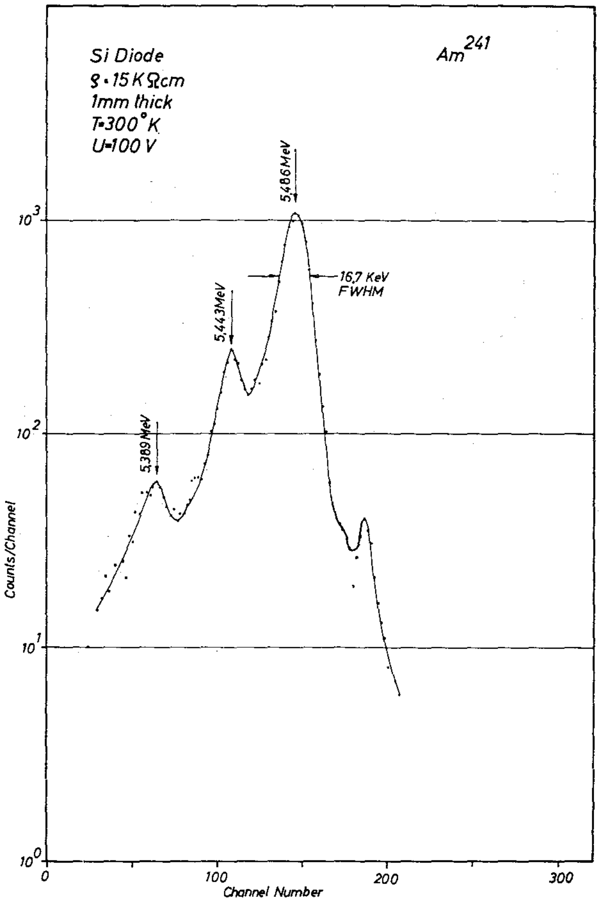

Fig. 1. The response of a 1 mm thick ion-doped counter, of area 80 mm^2 to ^{241}Am alpha-particles.

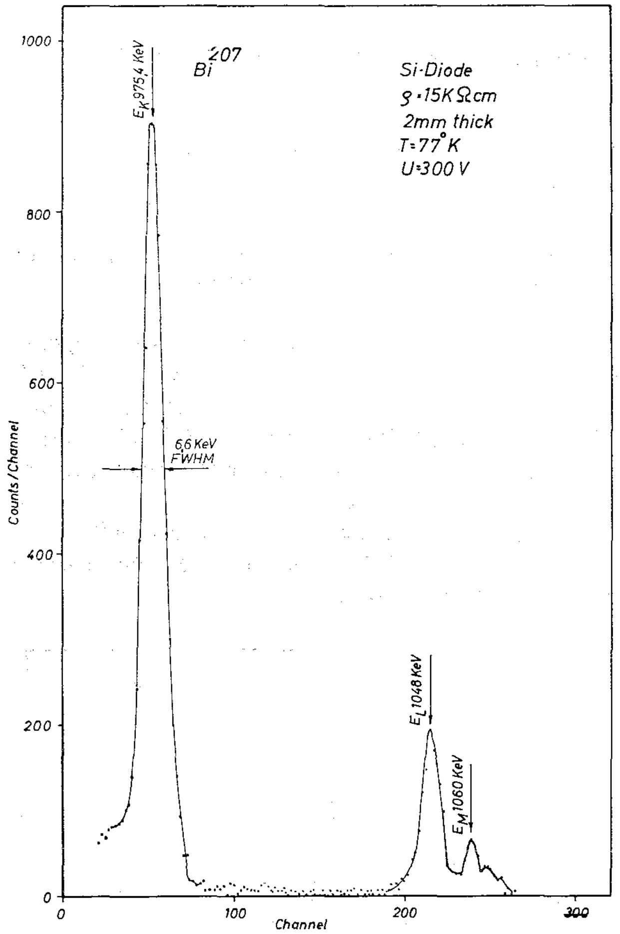

Fig. 2. The response of a 2 mm thick ion-doped counter, of area 100 mm^2, to ^{207}Bi internal conversion electrons.

Counters produced by well aligned ion beams parallel with the 111-direction showed as good *I-V*-characteristics and lifetimes of minority-carriers as has been measured for surface-barrier-detectors^7). For example fully depleted 3 mm thick devices (135000 $\Omega \cdot$cm, 500 V, $\tau = 1$–2 msec) typically show reverse currents of 2–3 μA at room-temperature and 1–3 nA at liquid nitrogen temperature. The n-n$^+$-back contact proved to be a good non-injecting contact, even when the space charge reaches the back-contact. On the other hand diodes, produced with non-aligned ion beams from the same slices, show life-times of 50–150 μsec and reverse currents of 10–50 μA at 500 V and 300° K comparable with results in ^{2}).

The implanted ion concentration profiles on annealed diodes were examined by sheet resistivity measurements together with slow etching and weighing techniques. It could be shown that the concentration profiles of diodes produced by well aligned beams have a tail of channeled ions, with a range at least two times that of non-channeled ions of the same energy. The space charge-region in the p$^+$-contact extends into this "tail" region where bulk damage is well reduced and life-time conserved. Figs. 1 and 2 show the resolution for α-particles measured at room temperature and conversion electrons detected at liquid nitrogen temperature. The measurement conditions are given in the figures.

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