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Gamma-ray line investigations with the Durham γ-ray spectrometer

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The study of γ-ray lines of astrophysical origin has become more interesting with the introduction of cooled solid state detectors having a very good energy resolution, *ca.* 1–2 keV at 100 keV, and *ca.* 2–3 keV around 1 MeV. Some of the single crystal spectrometers currently in use in γ-ray astronomy are capable of detecting lines with intensities *ca.* 3×10^{-3} ph $\text{cm}^{-2}\,\text{s}^{-1}$ when used on balloon experiments. This is close to the γ-ray intensities predicted from some celestial γ-ray sources. Knowing the γ-ray background precisely and with a reasonable although lengthy observation time it should be possible to detect lines from candidate celestial sources, for example neutron stars, Seyfert galaxies or the galactic centre.

In Durham, we have recently started a systematic programme to investigate γ-ray lines by using an actively shielded high purity Ge detector cooled by liquid nitrogen. A sectional view of the spectrometer is shown in figure 1. The active NaI(Tl) shielding elements A_1 and A_2 limit the opening angle of the telescope to 5.2° (f.w.h.m.). The basic crystal has a γ-ray detection efficiency of 23% relative to a standard 3 in × 3 in (7.62 cm × 7.62 cm) NaI(Tl) detector at 1.33 MeV and an energy resolution of 2.5 keV at the same energy. An interesting variation from a conventional γ-ray line spectrometer is the Compton polarimeter consisting of four elements of NaI(Tl) (detectors P1, P2, P3 and P4) around the crystal.

The first flight of the apparatus was in August 1979 at Palestine, Texas and it lasted about $6\frac{1}{2}$ hours. The primary aim of this flight was to study the variation of the counting rates of the various detectors as a function of atmospheric depth and also to study the float background spectra. The successful study of the various contributions to the background counting rate in the atmosphere leads not only to a better assessment of the detector performance but also to an estimate of the locally produced γ-ray background which is a feature of a shielded γ-ray detector.

Figure 2 shows the variation of counting rate of the Ge detector in the energy range 0.09–8.8 MeV, as a function of time and atmospheric depth. These counting rates were obtained from a Poisson fit to the interval distribution of events recorded in the so-called secondary a.d.c. (top curve). Pulse height analysis was made with a 14 bit a.d.c. (i.e. main a.d.c.) and a back-up system having 10 bit resolution (i.e. the secondary a.d.c.). The actual recording rate (lower curve) when corrected for apparatus dead time agrees well with the true rate (histogram). The counting rate shows a maximum at the Pfotzer maximum (*ca.* 100 g cm^{-2}) as expected and decreases by a factor of *ca.* 1.8 at float (4.3 g cm^{-2}). The dead time of event recording at float altitude is *ca.* 16% for the secondary a.d.c. and *ca.* 60% for the main a.d.c.

For each event a digital word containing the information defining which detectors had been triggered is also recorded. Vetoed and unvetoed γ-ray spectra for the Ge detector at various

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altitudes were subsequently obtained by using these data. Figure 3 shows one such pair of uncorrected spectra, summed over about 60 min during balloon ascent. After correcting for events vetoed owing to chance coincidence, it is found that the spectrum of vetoed Ge events is *ca.* 10% of the unvetoed spectrum (figure 2). Unfortunately this flight was not sufficiently successful to furnish all the details we expected to obtain. The high voltage for the photomultipliers failed just before the balloon reached float altitude. As a consequence, we have spectral information only up to about the Pfotzer maximum. Later, Ge γ-ray spectra are available with passive NaI(Tl) shielding alone but they are not very useful as they are dominated by background. The discussion here will be limited to γ-ray energies between 0.09 and 0.8 MeV; there are some interesting line features in this energy region of the vetoed spectrum and they are summarized in table 1.

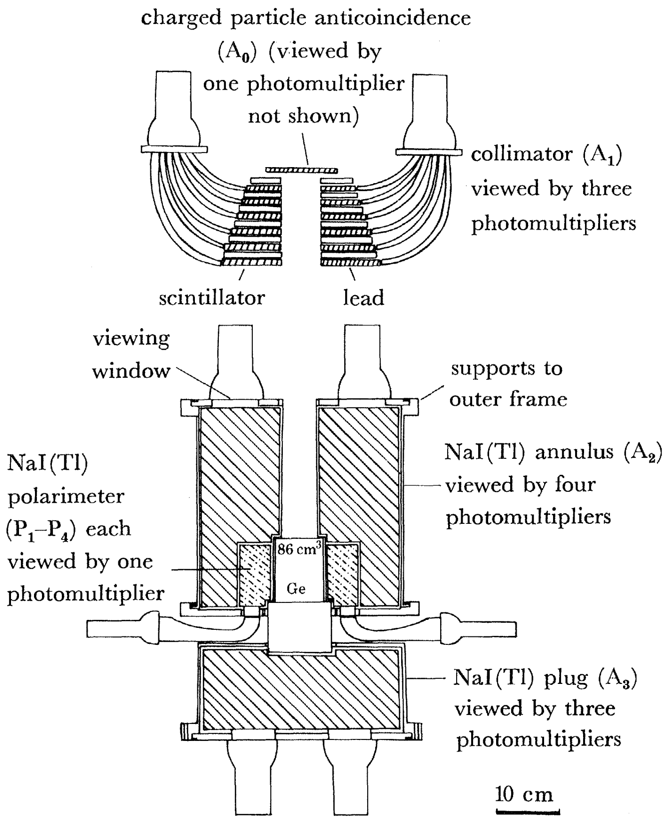

FIGURE 1. A sectional view of the balloon-borne semi-conductor γ-ray spectrometer showing the arrangement of the Ge(HP) detector, the NaI(Tl) shields, and the lead–plastic sandwich collimator.

TABLE 1. COUNTING RATES OF BACKGROUND LINES SEEN IN THE ACTIVELY SHIELDED Ge DETECTOR

					other measurements (normalized for detector size)			
line energy / keV	origin	half-life	counting rate/s^{-1}	mean depth / g cm^{-2}	Mahoney *et al.* (1978)	depth / g cm^{-2}	Womack & Overbeck (1970)	depth / g cm^{-2}
139	^{74}Ge(n, γ)^{75}Ge^{m}	48 s	0.13 ± 0.04	$280 \begin{Bmatrix} +360 \\ -170 \end{Bmatrix}$	0.15	2.9	0.11	4.7
198	^{70}Ge(n, γ)^{71}Ge^{m}	20 ms	0.34 ± 0.04		0.3		0.18	
511	e^{+} annihilation	—	0.19 ± 0.03		0.08		0.07	

It can be seen that almost all the background lines (except that at 511 keV) are seen only in the vetoed spectrum, signifying the necessity of active shielding. The origin of these background lines as suggested in table 1 is mainly in the interaction of atmospheric neutrons with the Ge. This is complicated by the existence of five different stable isotopes of Ge in a natural Ge crystal. The relative difference in line intensities are mainly due to the differences in relative abundances, neutron absorption cross sections, branching ratios and intrinsic full energy peak efficiencies.

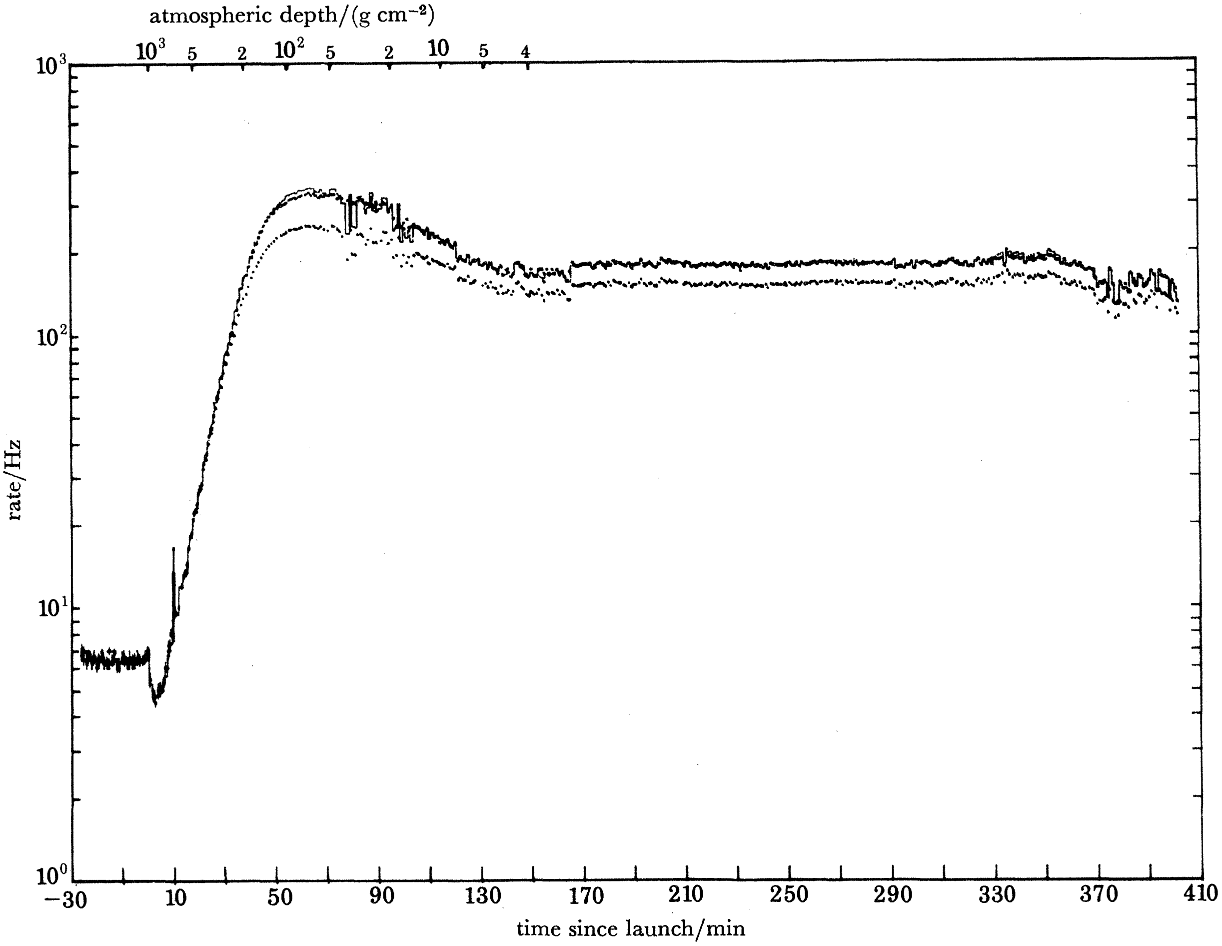

FIGURE 2. Plot of the integral photon counting rates in the energy range 0.09–8.8 MeV from the cooled Ge(HP) detector as a function of time since launch (lower scale) and atmospheric depth (upper scale). (i) Lower set of points are the event recording rates in the secondary a.d.c. (ii) Upper set of points are the true rates as calculated from an interval distribution to the events in (i). (iii) Histogram refers to the event recording rates corrected for system dead time.

A quantitative estimate of the counting rate under the 139 keV line shows that the main contribution comes from resonant absorption of *ca.* 104 eV neutrons by ^{74}Ge, the abundance of which is 36.7 %. The calculated counting rate from this process accounts for about 56 % of the observed rate. The rest presumably comes from reactions like ^{76}Ge(n,2n) ^{75}Ge^{m} and ^{76}Ge(p,pn)^{75}Ge^{m}.

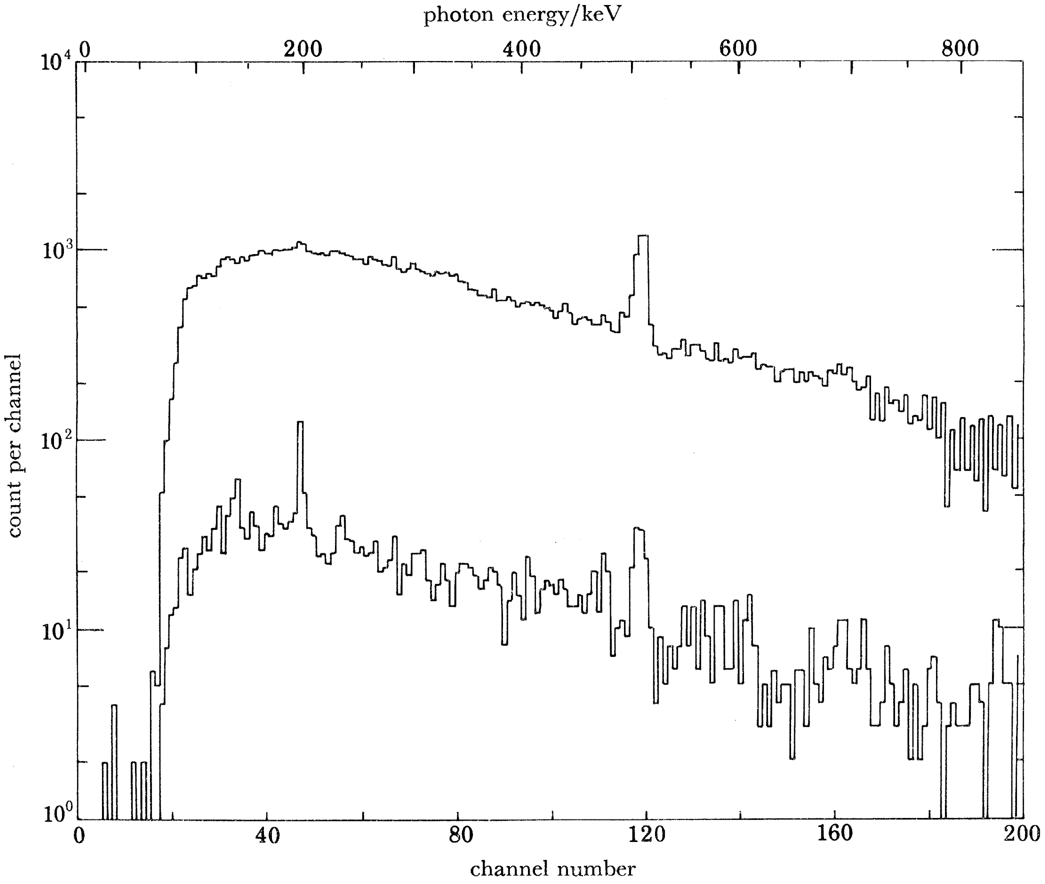

FIGURE 3. The atmospheric background spectra from the Ge(HP) detector not corrected for system dead time. The upper curve shows the differential photon spectrum with passive NaI(Tl) shielding only. The lower curve shows the differential photon spectrum actively vetoed by NaI(Tl) shields. The vetoed spectrum shows several background line features superimposed over a continuum, the strongest of which are the lines at 139, 198 and 511 keV.

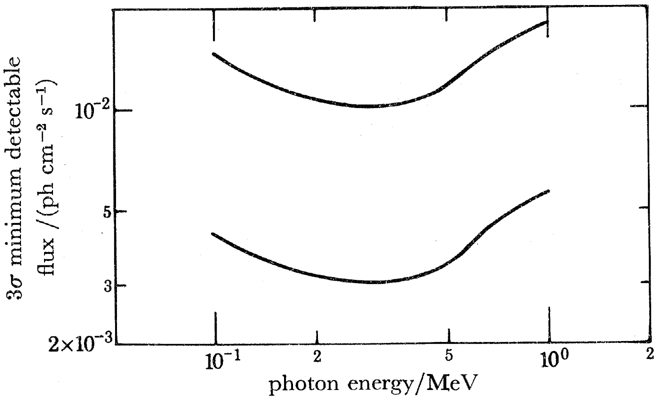

FIGURE 4. A plot of the 3σ minimum line flux from a point source (sensitivity) detectable in the γ-ray spectrometer as a function of photon energy in the range 0.1–1.0 MeV. The lower curve refers to the sensitivity with active shielding and the upper curve refers to that with passive shielding.

For comparison, also shown in table 1 are the counting rates under these lines observed by other experiments, normalized for detector sizes. Though the counting rates under the 139 keV line observed by us are consistent with those of others, it has to be noted that the depths for which these figures apply are different. The agreement may be fortuitous. It is not prudent to compare the observed line intensity under the 511 keV peak. This is because most 511 keV photons are produced by the annihilation of e^+ which are produced in the Ge crystal and in the shield. Hence this count rate is a function of the shield thickness and the design of the equipment.

Only three background lines are considered in the above discussion as they are the strongest and stand out over a smooth background. Other background lines (e.g. 175 keV, 596 keV and 691 keV) are also likely to be produced in Ge by similar processes. The available statistics do not allow us to comment on these lines as their intensity is at least an order of magnitude smaller. Further, there could be additional background lines produced in the materials around the apparatus, i.e. the aluminium, copper and lead, etc., which become apparent only when the spectra are summed over a long time. From the observed background spectra we have deduced the differential counting rate at float. From this we calculate the minimum sensitivity (3σ-value) of the spectrometer to be 3×10^{-3} and 10^{-2} ph cm^{-2} s^{-1} with active and passive shielding respectively, for a one hour observation on both source and background. Figure 4 shows a variation of the 3σ detectable line flux from a point source as a function of photon energy in the range 0.1–1.0 MeV. It can be seen from the figure that the sensitivity of the spectrometer to γ-ray lines improves by a factor of about 3 with active shielding, at all energies in the above range.

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