ENERGY TRANSFER BY ALPHA-PARTICLES TO BIOLOGICAL ENTITIES OF VERY SMALL SIZE

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Abstract—The energy spectrum of the energy transferred by alpha-particles of ^{239}Pu and ^{210}Po to cylindrical subcellular units has been studied experimentally.

For this purpose a cylindrical proportional counter with tissue equivalent walls of Shonka type and with an internal diameter of 5 mm has been used. The counting gas is tissue equivalent (64·4% CH_4, 32·4% CO_2 and 3·2% N_2) flowing at a rate of 3 ml/min through a vacuum-tight vessel in which the counter is built. The alpha-particles which have an energy of about 5 MeV enter into the counter perpendicular to its axis through a hole 1 mm in diameter, their path length inside of the counter being constant within 1%. By using gas pressures between 1 and 500 torr the biological diameter of the counter has been varied between 70 Å and 3·5 μ of tissue.

The authors discuss the resolution of the counter and present measurements of the mean number of ionization that the alpha-particles produce along a track length of 50 Å.

INTRODUCTION

It is well known that the linear energy transfer (LET) of radiation is in general not a suitable parameter for describing the deposition of radiation energy on the *microscopic* level. This has been shown by Rossi and coworkers, who have measured the energy transferred to small spherical volumes by single events and have developed a new approach for describing the energy deposition by taking into account its quantification.[1-7] This approach has been shown to be very fruitful.[8] However, its practical application is limited by the fact that not all the sub-cellular biological structures that are believed to be significant for a certain biological damage can be approximated by a sphere. For the chromosome, for instance, that might be the significant structure for many observed effects, the infinitely long cylinder is probably a better model.

The purpose of this work was to study the possibility of using a cylindrical proportional counter as a "chromosome counter". The counter used and measurements of its resolution are described below.

INSTRUMENTATION

The proportional counter is shown in Fig. 1. It is cylindrical and has a diameter of 5 mm. Its wall is made from tissue equivalent plastic after Shonka.[9] The tissue equivalent counting gas was that proposed by Rossi and Failla[10] with a composition 64·4% CH_4 + 32·4% CO_2 + 3·2% N_2. When the gas pressure is 0·7 mm Hg, the diameter of the counter corresponds to 50 Å of soft tissue of unit density. This tissue layer that corresponds to the counter diameter at a certain gas pressure we will call from now on the "tissue diameter" d of the counter. The thickness of the counting wire was varied between 40 and 200 μ. For the final measurements the 50 μ wire was used because it gave a better resolution at the higher pressures. At pressures below 10 mm Hg the thickness of the counting wire had no influence on the measured deviation. The total counter was mounted on a BNC-connector passing through a vacuum-flange with which the counter was fastened in a gas tight vessel.

For the measurements of the energy transfer a small pencil beam of alpha-particles

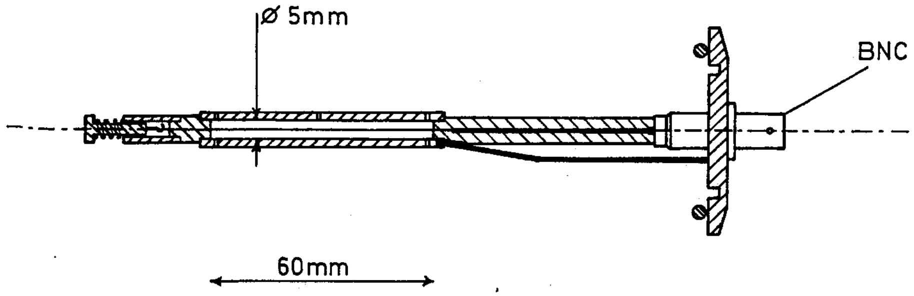

FIG. 1. Side view of the tissue equivalent proportional counter.

from ^{210}Po was used that traversed the counter perpendicular to its axis. The geometrical relation between the counter and the alpha-source is shown in Fig. 2. The alpha-particles passed into the counter through a hole of 1 mm in diameter. In order to prevent scattering at the inner surface of the hole, an aperture of 0·1 mm diameter in an aluminium foil 50 μ thick was put in front of the counter. The source was placed a little to one side of the line between the wire and the aperture, so that the particles could not come into collision with the central wire. The counter length of 60 mm, giving 30 mm at both sides of the pencil beam, is effectively infinitely long when its tissue diameter d is bigger than 400 Å.[11] With smaller sizes the more energetic δ-rays could reach the counter ends. However, this had no influence. Comparative measurements ($d > 100$ Å) with a similar counter having a length of only 30 mm gave the same results.

Figure 3 shows the instrumentation in form of a block diagram. All measurements were made with a constant gas flow of 3 ml/min passing through a metal gas-tight vessel containing the counter and the source. The pulses had a mean frequency of 10^4 cpm and a rise time of less than 0·2 μsec. The pulses were shaped in the main amplifier first by a differentiating and then by an integrating network, both having a time constant of 0·8 μsec. With this setting the noise level of the electronic system was about 600 electrons at the input of the preamplifier.

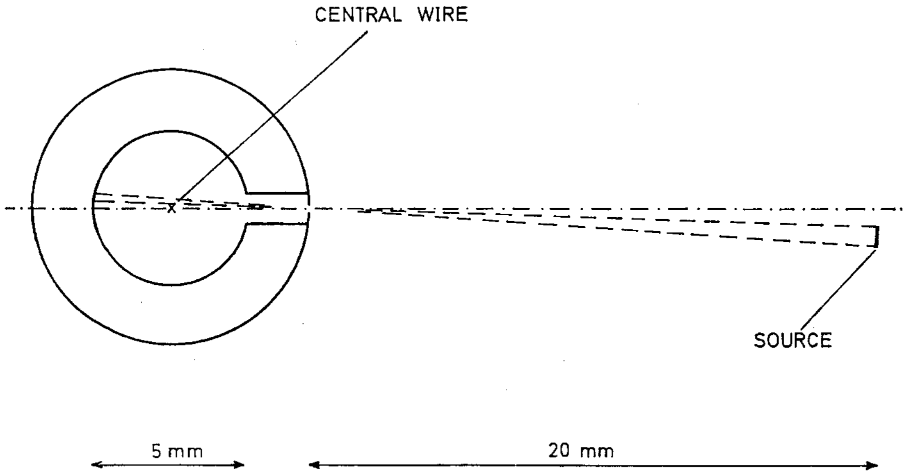

FIG. 2. Geometrical relation between counter and source. The alpha-particles enter through an aperture of 0·1 mm and pass through the counter without coming into collision with the central wire.

MEASUREMENTS

The alpha-source was shielded with 1.05 mg/cm^2 Al which caused a standard deviation of 1·3% in the particle energy. This deviation, measured with a solid state detector, was regarded as sufficiently small for the present purpose.

The energy transfer to the counter, and its spectral distribution, were measured at tissue diameters between 100 Å and 3·5 μ. At tissue diameters below 100 Å the peak of the energy spectrum began to disappear in the noise. Fig. 4 shows the spectrum measured at 240 Å as an example at low tissue diameters d. It is, like all other spectra measured at $d < 0.3\ \mu$, very close to a Poisson distribution. For the bigger tissue diameters the Gaussian distribution was a better approach. For the analysis of the measured standard deviations, that are shown in Fig. 5, it was assumed that the mean pulse height $\bar{E}$ of any measured pulse height spectrum is equal to the product of the mean values of the different components that contribute to the observed deviation:

$$\bar{E} = \bar{L}\,\bar{N}\,\bar{M}\,\bar{V}\,\bar{A}\,\bar{R}$$

from this follows

$$\frac{\sigma_E^2}{\bar{E}^2} = \frac{\sigma_L^2}{\bar{L}^2} + \dots + \frac{\sigma_R^2}{\bar{R}^2}$$

The factors influencing the observed deviation are:

1. $\frac{\sigma_L}{\bar{L}}$ is the standard deviation of the mean energy transfer L of the alpha-particles to the counter.
2. N is the number of the ion pairs formed per energy unit.
3. M is the electron multiplication which would occur in an ideal proportional counter in which the region of multiplication at the central wire is infinitely small.
4. The factor V takes into account that the region of multiplication is not infinitely small.
5. A describes the constant deviation that is due to mechanical imperfection of the counter (central wire, counter ends, etc, $\sigma_A/A \approx 2\%$).
6. R is the electric amplification factor

$$\frac{\sigma_R}{\bar{R}} = 5\cdot5\% \text{ for } R = 2^{11},$$

$$\frac{\sigma_R}{\bar{R}} \leq 1\cdot2\% \text{ for } R \leq 2^9.$$

The standard deviation of the product MVA is the so called counter resolution. In Fig. 5 the measured deviation $\frac{\sigma_E}{\bar{E}}$ is shown.

The standard deviation of V which is calculated in the appendix is also drawn in Fig. 5. The comparison shows that the deviation of the factor V, which takes into account that the region

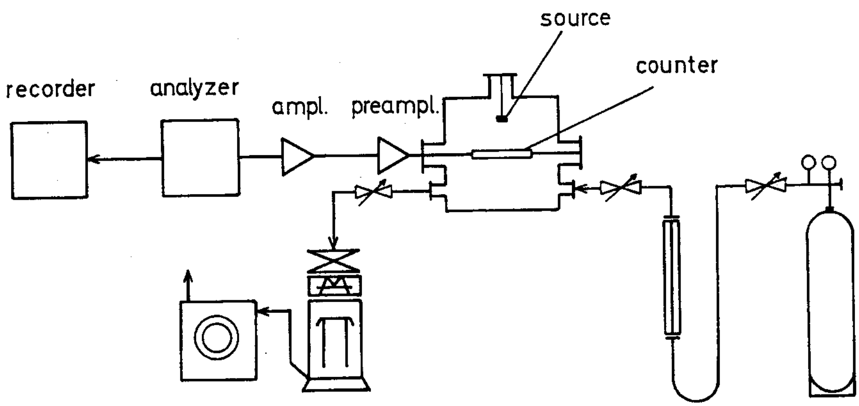

FIG. 3. Block diagram of the total instrumentation.

of multiplication is not infinitely small, is surprisingly low.

It can be concluded, therefore, that the counter has worked like a normal proportional counter.

The contribution of the components L, N, and M to the measured deviation $\sigma_E{}^2/\bar{E}^2$, unfortunately, cannot be evaluated by experimental methods. However, it can be shown theoretically[12] that the straggling of the energy transfer gives by far the biggest contribution (about 90%), whereas the deviation of N, the so called Fano fluctuation and the deviation that is caused by the multiplication process contribute to $\sigma_E{}^2/\bar{E}^2$ with about 10% only. Within the limits of accuracy, the measured deviation $\sigma_E/\bar{E}$ is therefore equal to the fluctuation of the energy transferred by alphas of about 5 meV to tissue of thickness d.

AVERAGE ENERGY PER ION PAIR

At tissue diameters between 1 μ and 3·5 μ the counter was used as a pulse ionization chamber to measure the differential average energy per ion pair along small track lengths. The results are shown in Table 1.

The second column gives the mean LET of the alpha-particles in the counter. It is the

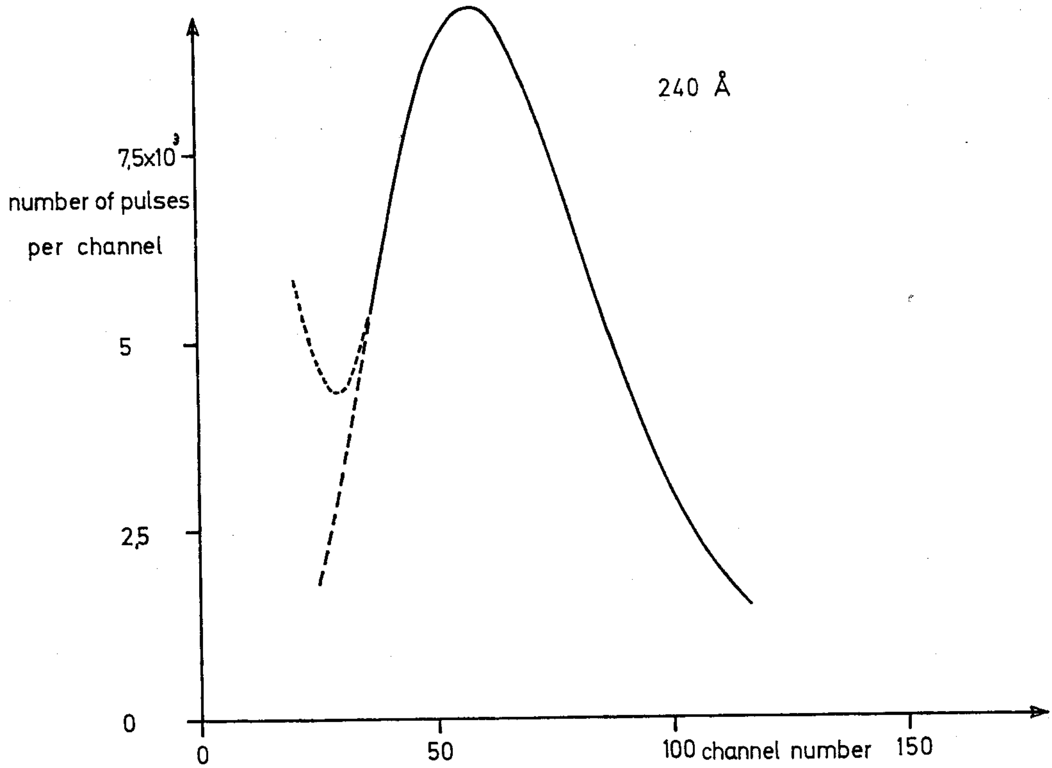

FIG. 4. Energy spectrum measured at a tissue diameter of 240 Å. Channel number 0 is equal to energy zero. The dotted line represents the noise.

TABLE 1.

LET∞ keV/μ	N	d μ	w eV
91·5	4·22 × 10^3	1·40	30·3 ± 5%
99	1·14 × 10^4	3·50	30·4 ± 5%
106	4·64 × 10^3	1·40	31·2 ± 7%

LET_∞, because the counter is big enough to absorb all δ-rays. The w-values in the last column have been calculated with the following equation:

$$w = \frac{LET_\infty \cdot d}{N}$$

They represent therefore the relation between the energy that have been absorbed in soft tissue along small particle track lengths with a LET_∞ of about 100 keV/μ and the number of produced ion pairs.

SUMMARY

A cylindrical tissue equivalent proportional counter is described, which has been used to measure the fluctuation of the energy transferred by alphas to tissue thicknesses between 100 Å and 3·5 μ. The factors that contribute to the observed standard deviation are analysed and discussed. In addition, measurements of the differential average energy per ion pair along small track lengths of alpha-particles in tissue are described.

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APPENDIX

The multiplication factor for a single electron that is produced at the point r in the counter can be described by:

$$M(r) = C . e^{K\sqrt{r}} = e^{K(\sqrt{r}-\sqrt{a})} \quad (\text{for } a \leqslant r \leqslant r_0)$$

$$M(r) = C . e^{K\sqrt{r_0}} \quad (\text{for } r_0 \leqslant r \leqslant b)$$

a is the radius of the central wire,
r_0 the radius of the region of electron multiplication, and
b the radius of the counter.

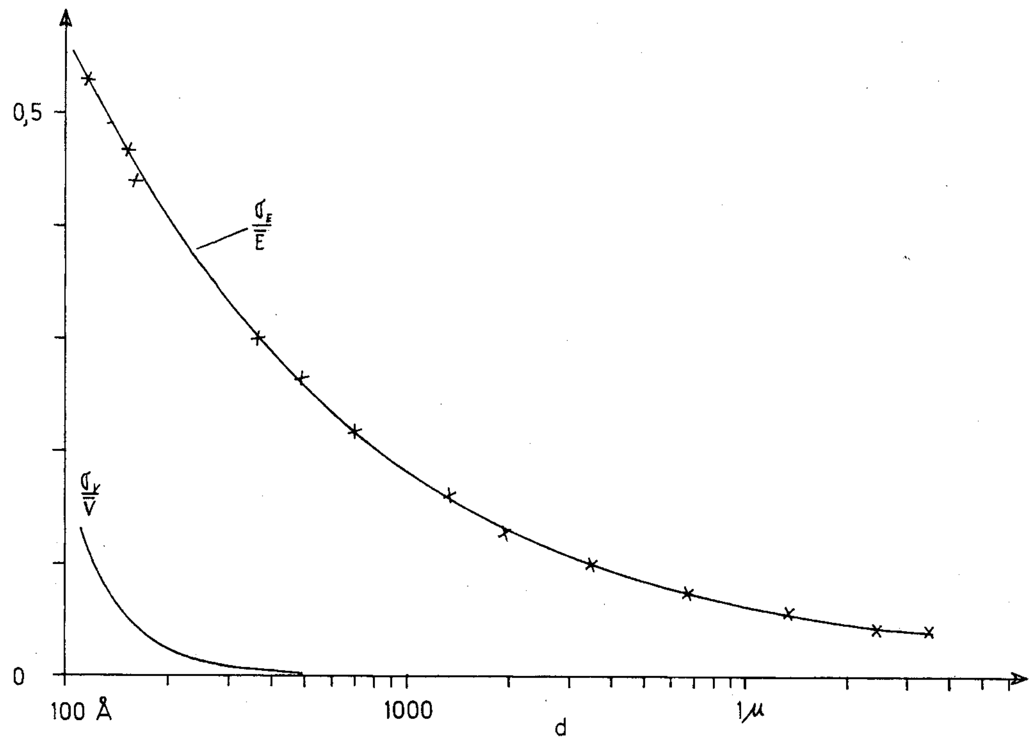

FIG. 5. Measured and calculated standard deviations as a function of the tissue diameter d.

Under the assumption that the ionizations are uniformly distributed in the counter, the distribution function of $M(r)$ is

$$\psi(M)dM = 2\pi r dr = \frac{4\pi}{K^4} \cdot \frac{(\ln M/C)^3}{M} dM$$

From this follows

$$\overline{M(r_0)} = \frac{1}{\pi(b^2 - a^2)}$$

$$\left\{ \int_1^{M(r_0)} M(r) \cdot \psi(M)dM + M(r_0) \cdot \int_{M(r_0)}^{M(b)} \psi(M)dM \right\}$$

$$= \frac{\int_1^{M(r_0)} M(r)\psi(M)dM + M(r_0)\pi(b^2 - r_0^2)}{\pi(b^2 - a^2)}$$

and

$$\overline{M^2(r_0)} =$$

$$\frac{\int_1^{M(r_0)} M^2(r)\psi(M)dM + M^2(r_0)\pi(b^2 - r_0^2)}{\pi(b^2 - a^2)}$$

The desired mean square deviation of V is finally

$$\frac{\delta_V^2}{\overline{V}^2} = \frac{\overline{M^2}}{\overline{M}^2} - 1.$$

For the evaluation of this formula the radius of the multiplication region r_0 has been defined by

$$I = \int_{r_0}^{r_0 + \Omega} F\,dr = \frac{U}{\ln b/a} \ln(1 + \frac{\Omega}{r_0})$$

where I is the mean ionization potential, F the electric field strength and Ω the mean free path of the electrons. It has, therefore, been assumed that the region of electron multiplication begins there, where the electron gains sufficient energy for ionization between two collisions.

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