Laboratori Nazionali di Frascati

LNF-71/56

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Estratto da : Health Phys. 21, 273 (1971)

Health Physics Pergamon Press 1971. Vol. 21 (August), pp. 273–280. Printed in Northern Ireland

USE OF TRANS-STILBENE CRYSTAL TO MEASURE THE DOSE EQUIVALENT IN A MIXED γ-n FIELD

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(*Received* 20 *July* 1970; *in revised form* 2 *October* 1970)

Abstract—The possibility of using a trans-stilbene crystal to measure the dose equivalent in a mixed γ-n field is studied. We obtain that each of γ-rays and neutron signals, separated by pulse shape discrimination, gives a good dose equivalent response to the respective radiation component. For the neutrons we obtain a good dose equivalent response in the range from 0.1 to 10 MeV (where the elastic scattering is predominant) by suitable saturation of the pulses produced by recoil protons. For the γ-rays we directly measure the absorbed dose in the scintillator because of its tissue equivalence up to several MeV. In the range of γ-rays exposure up to about 0.2 R/hr, the sum of the two measured contributions is constant, within the experimental errors, when we vary the relative dose intensity, keeping the total dose rate fixed.

I. INTRODUCTION

THE GREAT diversity of the biological effects produced by different ionizing radiations complicates the problem of evaluating the risk in a mixed field. It is well known that to take into account these differences it was introduced for protection purposes a quantity called the "dose equivalent" (*DE*), defined as the product of absorbed dose, quality factor (*QF*), dose distribution factor, and other modifying factors.[1,2]

In practice the problem of the measure of the dose equivalent in mixed γ-n fields is very important, because of the remarkable difference in the *QF* of γ-rays and neutrons.

The use of organic scintillators can be useful, in the dosimetry of a mixed γ-n field, because of their good tissue equivalence and because some of them offer the possibility to discriminate γ-rays and neutrons.[3–5] This latter fact, as we shall see in the following, can be used to measure separately the contribution to the total dose equivalent due to each radiation component using a single detector, a stilbene crystal.

We have chosen a stilbene scintillator instead of the cheaper organic liquid scintillators, now more and more used in γ-n discrimination problems, because it is less critical in the work conditions. This fact is fundamental to obtain a response to neutrons proportional to the dose equivalent in a very simple way.

II. DOSE EQUIVALENT FROM NEUTRONS

In the energy range from 0.1 to 14 MeV, elastic scattering gives the most important contribution to the neutron dose. In the following we shall neglect the other contributions to neutron dose. This approximation is quite crude in the energy range from 10 to 14 MeV, where non-elastic scattering becomes important and gives a contribution to the neutron kerma and to the neutron dose of the order of 20%. Nevertheless this approximation can be accepted even in this energy range, if used only for protection purpose. Moreover within 0.1 and 14 MeV, the distinction between absorbed dose and kerma is negligible except at volumes so small that the wall effects of recoil nuclei become important.

In Fig. 1 the neutron kerma $K(E_n)$ due to elastic scattering only, calculated from the data of ref. 6, is given versus neutron energy E_n (upper curve) together with the contribution $K_p(E_n)$ due to recoil proton (lower curve). The relative contribution of the hydrogen and the other important elements in the tissue, like

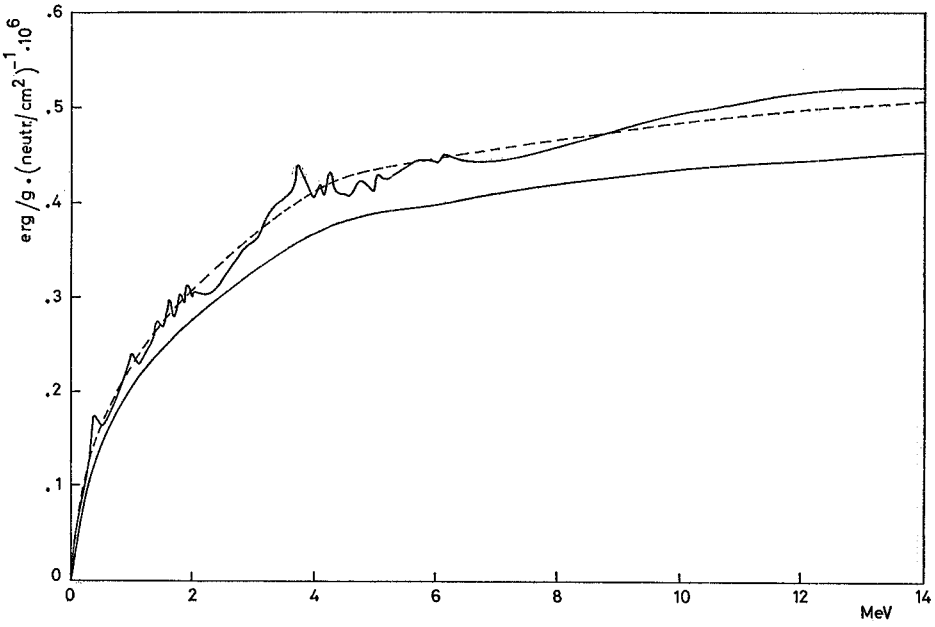

FIG. 1. Neutron kerma, due to elastic scattering in tissue, versus energy (upper curve). Contribution of recoil protons (lower curve). Contribution of recoil protons multiplied by 1.12 (dotted line).

oxygen, nitrogen and carbon, is approximately constant versus neutron energy, with the protons contributing, on the average, about 85–90%. We can see (dotted line of Fig. 1) that it is possible to obtain a good approximation $K'(E_n)$ of $K(E_n)$ if we put:

$$K'(E_n) = (1 + q)K_p(E_n) \qquad (1)$$

where $q = 0.12$ is independent of neutron energy.

According to Equation (1) one can say that, whenever a proton absorbs an energy E, an average energy qE is absorbed by the other elements in the tissue. As the quality factor $[(QF)_0 \simeq 20]$ of heavy recoil nuclei in the tissue is independent of energy and of type of nucleus, we can write for the dose equivalent $(DE)_n$ from neutron of energy E_n:

$$(DE)_n = (DE)_n' = \int_0^{E_n} dE P_H(E_n \to E) \times E\langle (QF)_p' \rangle_E \qquad (2)$$

where $P_H(E_n \to E)$ represents the probability that a neutron of energy E_n can produce a proton of energy within E and $E + dE$ in one gram of tissue and

$$\langle (QF)_p' \rangle_E = \langle (QF)_p \rangle_E + q(QF)_0$$

where $\langle (QF)_p \rangle_E$ is the average quality factor of a completely absorbed proton of energy E.

In Fig. 2 the dose equivalent due to a proton completely absorbed in tissue is given versus the proton energy (full line). This curve has been calculated from Rossi relationship[7] between QF and LET. In the same figure the dotted line represents $E \cdot \langle (QF)_p' \rangle_E$: its meaning is that of "proton effective dose equivalent". This quantity can be used to take into account the contribution from heavy recoil nuclei, within the approximations discussed above.

In Fig. 3 the neutron dose equivalent (dotted line) calculated by equation (2) and Fig. 2, is compared with the neutron dose equivalent from elastic scattering (upper curve). From this comparison it follows that, within the precision usually required in the dose equivalent measurements, the neutrons can be considered as interacting only with hydrogen, with the condition that the effective QF of the protons is given by Equation (3).

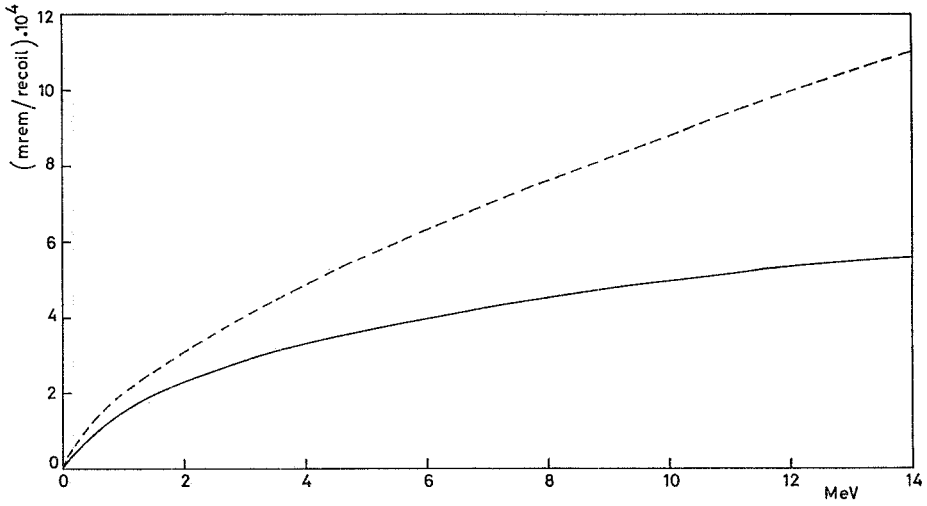

FIG. 2. Proton dose equivalent (full line) and proton "effective" dose equivalent (dotted line) versus energy.

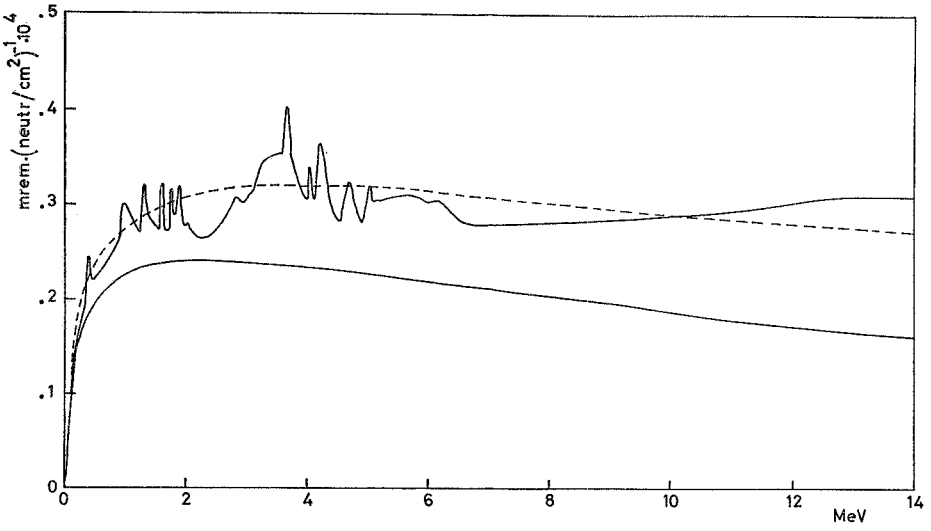

FIG. 3. Neutron dose equivalent in small element of tissue in free space versus neutron energy (elastic scattering only). Calculated from equation (2) and Fig. 2 (dotted line). Calculated from ref. 6 (upper curve). Contribution of protons (lower curve).

Finally if we call $(DE)_{\gamma+n}$ the dose equivalent in a mixed γ-n field, and $D\gamma$ the absorbed dose from γ-rays, we can write neglecting nonelastic scattering:

$$(DE)_{\gamma+n} = D\gamma + (DE)_n' \qquad (4)$$

where γ-rays QF has been taken equal to unity.

III. DESCRIPTION OF THE INSTRUMENT

The separation of the contribution of the two kinds of radiation in a mixed γ-n field, using a stilbene scintillator, is feasible by means of the shape difference in the light pulses produced by electrons and protons respectively. Among the numerous techniques used there are some that

use the fact that the spatial charge between the dynodes, at low values of polarization voltage, depends on the shape of the pulse.[8] Using this fact, since the slow component of the light pulse is comparatively higher for protons than for electrons, it is possible by means of a suitable saturation of the phototube, to obtain clearly separated pulse amplitude in a wide energy range of the two ionizing particles.

With respect to neutrons contribution to the total dose equivalent we shall reach our goal, within the approximation showed in Fig. 3, if we obtain a response to protons versus energy that fits the dotted line of Fig. 2. In this work we have tried to obtain this fitting by suitably varying the saturation of the phototube, compatibly with the need of γ-n discrimination. Our hope that this way of operation could be successful was based on the fact that the ratio between slow and fast components in stilbene light pulse increases with LET[9] and hence with QF of the ionizing particle. In addition if the saturation is raised, pulse height becomes an increasing function of this ratio under the same conditions of light production. Then we can expect that a suitable saturation for the same absorbed energy gives a pulse height increasing with QF, as required to fit the dotted line of Fig. 2.

To measure γ-rays dose it is enough to measure the light produced by them; indeed stilbene is tissue equivalent up to several MeV and the light linearly depends on energy of γ-rays. With respect to the contribution to the light coming from neutrons, it can be shown that, for the same contribution to the total dose equivalent, the light from the neutrons represents in our scintillator only some percentage of the light from γ-rays. However for higher precision, or when small scintillators are used, this contribution can be strongly reduced by anticoincidence with the saturated signal after the γ-rays have been discriminated.

In Fig. 4 is shown the block diagram of our instrument. A 2 in. dia., 1 in. thickness cylindrical scintillator is assembled on a 6810A phototube. The voltage-divider arrangement of the phototube is shown in Fig. 5. Two signals L and S are taken from the 11th and 14th dynode respectively. The signal S is saturated by means of the voltage regulation V between the anode and the last dynode (see Fig. 5). The dynodes D_{12} and D_{13} are supplied independently and the H.V. is put equal to the voltage difference between D_{11} and ground. In this way the stability of working conditions is guaranteed even at relatively high dose rate.

The signal S is saturated and amplified (see

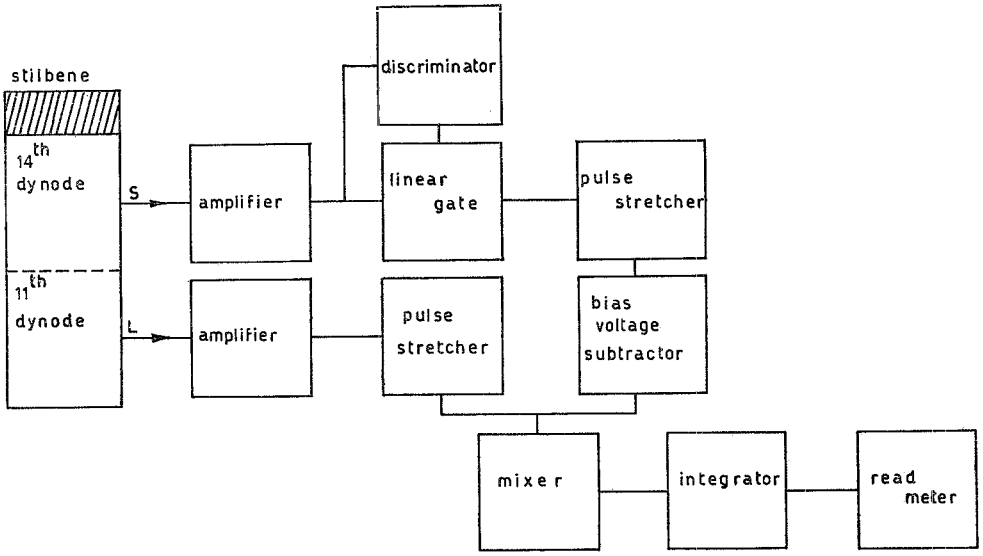

FIG. 4. Block diagram of the dosimeter.

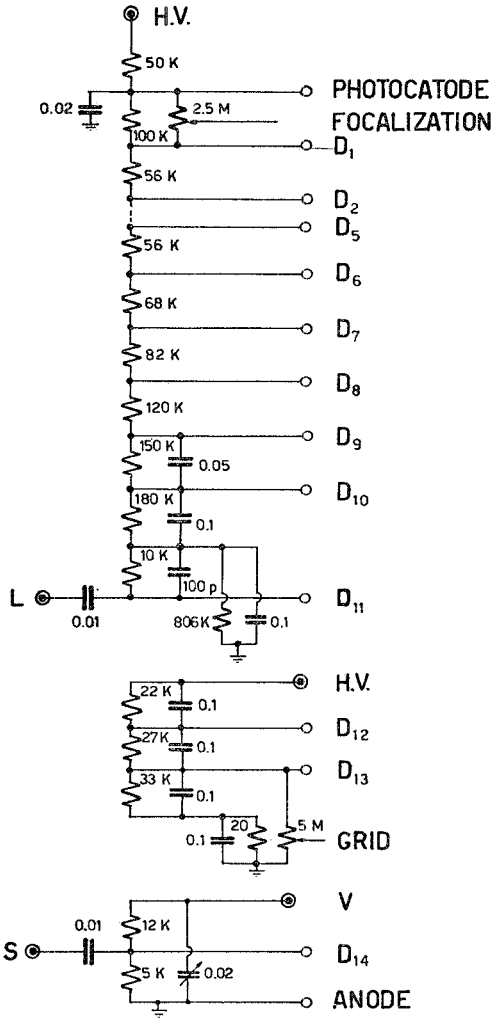

FIG. 5. Voltage-divider arrangement of the phototube.

Fig. 4), and the contribution from γ-rays is eliminated by means of a discriminator and a linear gate. Then S is linearly stretched up to a duration quite independent of amplitude. Finally it is sent to a bias subtractor and, by means of an integrator and a μ-amperometer, its average current is taken as measure of the neutron contribution to the total dose equivalent rate.

In an analogous way the signal L, which is linear with the light, is integrated and its average current is used as a measure of γ-ray contribution to the total dose equivalent rate.

To have the measure of the total dose equivalent rate the signals L and S are sent to a passive mixer and their amplifications are adjusted in such a way that 1 mrem from a ^{60}Co source gives on the instrument the same response as 1 mrem from a Po–Be source.

IV. PERFORMANCES

The amplitude of the saturated pulse has been analysed versus the corresponding amplitude of the linear one by means of a 512 multichannel LABEN. A Po–Be source, that has a broad neutron energy spectrum from 0 to about 10 MeV, has been used to this purpose. Figure 6 gives the results obtained with a phototube voltage supply of about 2,000 V, at various voltages between the last dynode and anode. In Fig. 7 the experimental data are compared with the theoretical curve of proton "effective" dose equivalent (Fig. 2 dotted line). The experimental data are those corresponding to the Fig. 6(d), and the comparison is made starting from a bias equivalent of about 80 keV-proton, subtracted from saturated signal in order to obtain a better agreement. These data are reported versus the proton energy using the pulse height to energy relationship of ref. 8.

Figure 8(a,b,c) shows the amplitude of the integrated and saturated signal versus the dose equivalent due, separately, to γ-rays and neutrons at different values of the discriminating threshold corresponding to 0.35, 0.45 and 0.6 MeV-proton respectively. In these measurements the mixed γ-n field has been obtained by means of a Po–Be and a ^{60}Co source and the contribution of γ-rays from Po–Be source has been neglected.

It can be seen that the sum of the linear and saturated signals is independent of the relative contribution of the γ-rays and neutrons to the total dose equivalent up to exposure rate of about 0.15 R/hr. In Fig. 9 these results are plotted versus the dose equivalent rate at a threshold value of 0.6 MeV-proton and for different compositions of the mixed field.

V. CONCLUSIONS

It can be seen (Fig. 8) that the γ-rays contribution to the saturated signal increases approximately as D_γ^2 at low discrimination threshold and faster at higher threshold values. This is a characteristic effect of pile-up of the electronics.

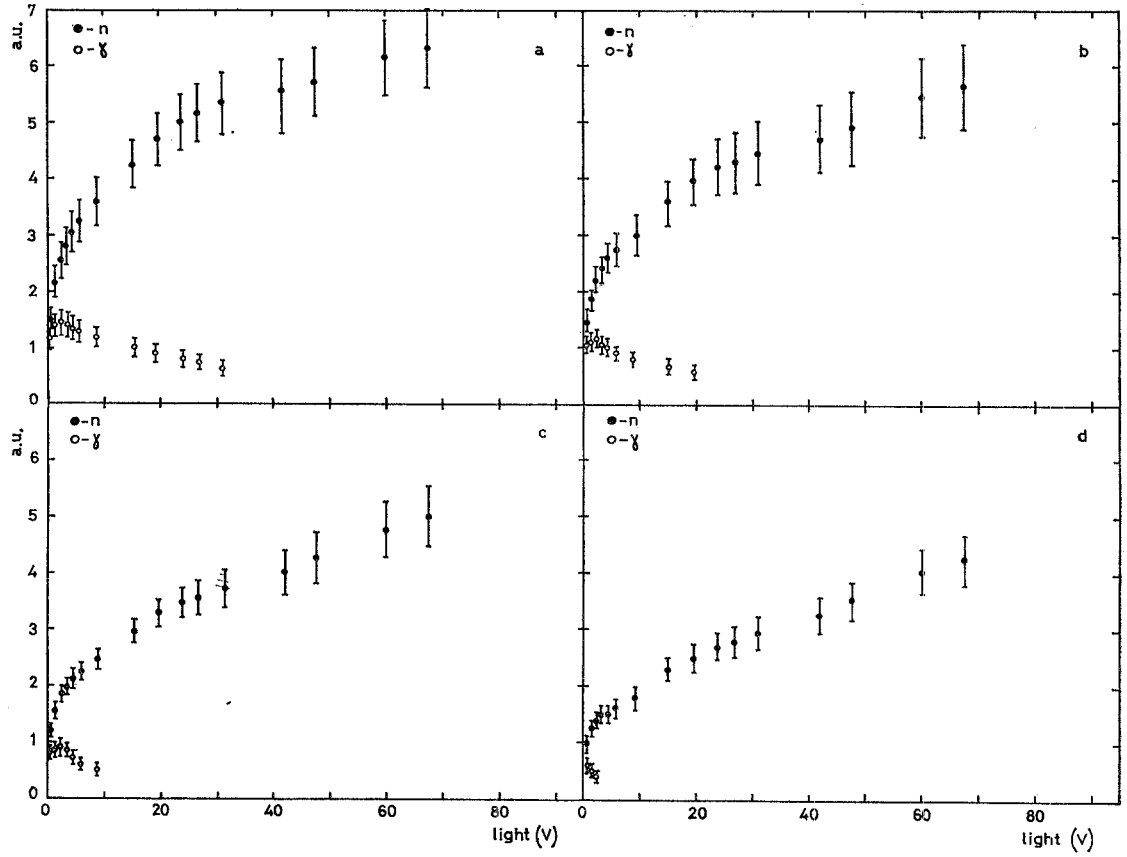

FIG. 6. Neutron and γ-rays saturated pulse height in arbitrary units versus light. Experimental points of (a), (b), (c) and (d) are relative to different voltages between last dynode and anode, corresponding to 17, 15, 13 and 11 V respectively.

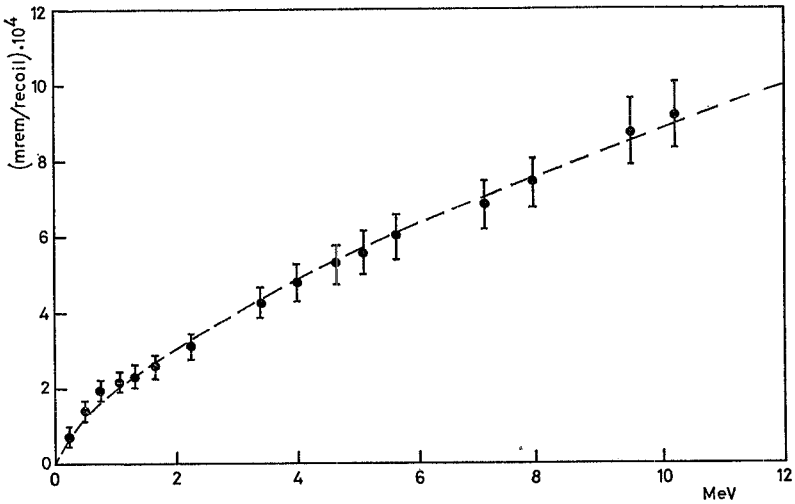

FIG. 7. Theoretical curve and experimental points of protons "effective" dose equivalent versus energy.

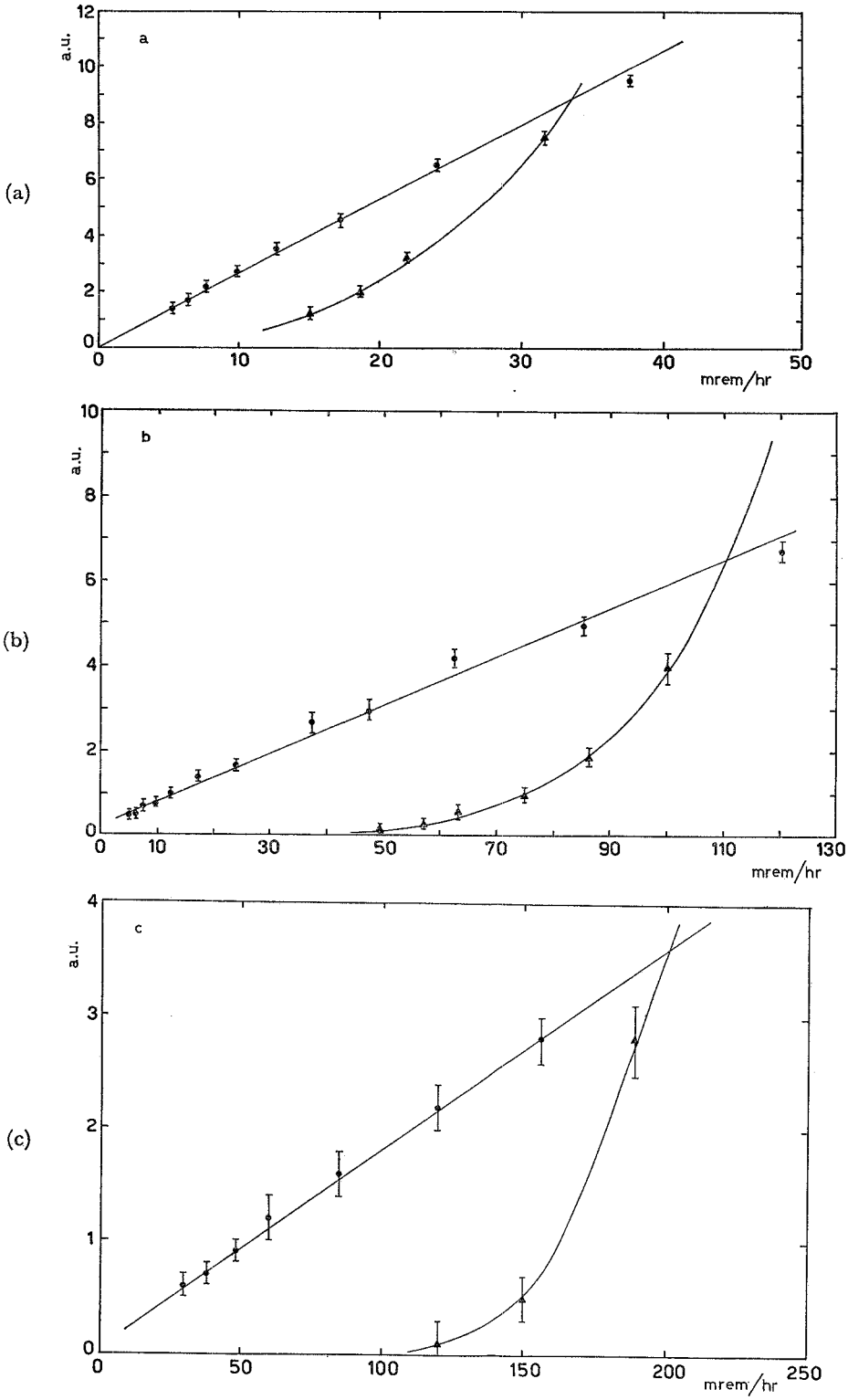

FIG. 8. Saturated signal in arbitrary units versus dose equivalent: Δ from γ-rays, ● from neutrons; curves (a) (b), and (c) correspond to 0.35, 0.45 and 0.6 MeV-proton of discriminating threshold respectively.

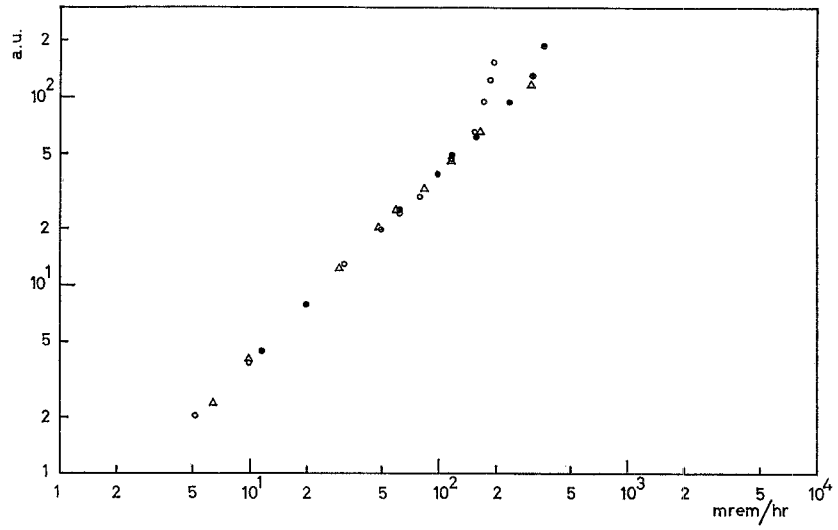

FIG. 9. Response of our dosimeter in arbitrary units versus dose equivalent in mixed fields of different composition: Δ neutrons only, ○ γ-rays only, ● γ-rays and neutrons contributing in about equal ratio to the total dose equivalent.

Indeed the counting rate capability of our electronics is about 10^5 counts/sec and this rate is of the same order of the one produced by γ-ray exposure rate of 0.1 R/hr in a 2 in. × 1 in. stilbene scintillator. This effect can be strongly reduced by using faster electronics and smaller scintillators. It must be noted that it is not convenient to use an electronic equipment whose counting rate capability is better than 10^6 counts/sec, because the slow component of the light pulse has a constant time decay of several hundreds of nsec. However it can be easily argued that a stilbene scintillator of 1 cm × $\frac{1}{2}$ cm could be used up to an exposure rate of several R/hr even with our electronics.

Owing to the relatively small sizes and to the fact that it is possible to have measures of *DE* by only one detector the use of our dosimeter seems very promising both for protection and for research purposes. In fact it can allow *DE* measures even in small regions (embodied, for example, in phantoms or in shielding materials) with negligible disturbance.

Moreover the use of this instrument seems of interest for measuring *QF* of γ-n mixed field when it is employed together with a tissue equivalent chamber. Within the limitation in the energy range and γ-ray dose rate discussed before, we think that this fact could be useful near high energy accelerators, where remarkable variations of the quality factor of the mixed field are possibly related to the various shielding configurations and to the different work conditions of the machines.

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