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# INVESTIGATIONS OF THE RESPONSE OF PERSONNEL DOSIMETRY SYSTEMS IN HADRON STRAY FIELDS AROUND THE CERN 28 GeV PROTON SYNCHROTRON

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## I. INTRODUCTION

Personnel dosimetry in hadron stray fields is routinely performed at CERN with nuclear track emulsions. This method and its interpretation has been described earlier[1,2].

New ideas for personnel monitoring of neutrons have been forwarded which avoid some inconveniences in the use of nuclear emulsions. While fading of nuclear tracks can be reasonably controlled, the problem of microscopic scanning remains, and with it the need to scan considerable areas to obtain good statistics.

One new approach in personnel monitoring of neutrons consists in creating nuclear tracks in plastic which is in contact with fissionable material, whereby automatic spark counting can be used for an evaluation of the results[3,4].

The other approach makes use of thermoluminescent material sensitive to thermal neutrons ($^6$LiF), where the albedo of the neutrons escaping from the body of the person wearing the dosimeter is recorded[5]. The so-called albedo dosimeter has been developed into a system where the inherent overestimation of soft neutrons is corrected by the incorporation of detectors into one dosimeter capsule[6,7].

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## II. THE STRAY RADIATION FIELD AROUND A GeV PROTON ACCELERATOR

The stray radiation field encountered around a GeV proton accelerator consists of a whole spectrum of fast neutrons down to thermal energies with accompanying gamma radiation, high energy hadrons, and in certain areas predominantly muons.

While gammas and muons are supposed to be recorded on a personnel gamma film, the whole range of neutron energies from about 1 MeV up to the maximum hadron energy has to be covered by the nuclear track emulsion. Calibration of the neutron films with conventional isotopic sources is thus not sufficient and has to be backed up by a direct calibration in the stray field, i.e. a comparison with results from radiation surveys.

Radiation surveys around the GeV proton accelerators at CERN are performed with a multidetector set called Cerberus. The description of the method, its interpretation and evaluation, has been given earlier8,9). In a comparison with both recombination chamber and proportional counter devices a good correspondence has been found between the results from different methods10).

The main feature of the Cerberus is that the contribution of different components to the total dose equivalent rate in the stray radiation field is measured separately. Thus neutrons from thermal up to energies of 14 MeV are recorded with an Anderson and Braun moderator, operated as a Rem ionization chamber (RIC), to comply with the pulsed radiation from the accelerator. This requires a correction for its response to gamma radiation.

Hadrons above 20 MeV are detected by the activation of $^{11}C$ from $^{12}C$ in a scintillator crystal where at CERN a fluence to dose equivalent conversion factor of $2.78 \times 10^{-8}$ rem cm$^2$ is applied8).

## III. EXPERIMENTS

The experiments consisted in comparing personnel dosimeter readings with accumulated doses registered on the Cerberus. During the exposure with dose rates ranging from 10 to 100 mrem/h the cylindrical moderator of 22 cm diameter and 25 cm height, standing upright, served both as a monitor and as a phantom on which the dosimeters were fixed.

It turned out that two fundamentally different irradiation conditions could be distinguished in the course of the experiment :

(a) Normal stray radiation spectra around a shielded external proton beam where the contribution to the total dose rate from high energy hadrons ranged from 7 to 47%.

(b) Soft neutron spectra encountered both at the upstream end of the 50 MeV Linac and near the main shield of the neutrino experiment. Both places are characterized by the absence of high energy hadrons (flux density of the order of 1 $cm^{-2}$ $s^{-1}$).

## IV. RESULTS

### 1. Albedo dosimeter system

The results of the albedo personnel dosimeter system compared to the results of the Cerberus are summarized in Table 1. Included in the table are hadron and gamma doses recorded, in parallel with the routine film-badge.

Positions 1 to 5 were irradiated in the so-called hard spectrum, 6 to 10 in the soft spectrum, as explained above.

Results of the albedo dosimeter were corrected for the neutron energy spectrum since different detectors in the dosimeter give information on albedo neutrons (detector i), on intermediate neutrons below 10 keV (detector m), and on incident thermal neutrons (detector a)$^{7)}$. From a comparison of these different readings with the results of the Cerberus, correction parameters for the normal stray radiation spectrum and the soft neutron spectrum encountered at CERN were calculated and are presented in Fig. 1. The two straight lines are shown in comparison with two other characteristic irradiation conditions : the neutron spectrum from the Vinča reactor moderated with heavy water, and from the unmoderated HPRR reactor at Oak Ridge without and with shielding of lucite and iron. Compared with these two neutron spectra the correction necessary in the case of the CERN spectra allows for several interesting observations :

(a) The straight lines in the diagram are shifted to the right, i.e. higher ratios of albedo to incident thermal neutrons. This confirms earlier observations that the contribution of thermal neutrons in the external stray radiation field around proton accelerators is low.

(b) The relative response of the albedo dosimeter system turns out to be small for the hard spectrum encountered in the stray field of a GeV accelerator. This is understood by the fact that lower albedo is expected for high energy hadrons in the energy range above 20 MeV than for fast neutrons.

(c) The relative response of the albedo dosimeter in the soft spectrum is found to be around one and shifted below the correction line for the moderated fission spectrum from the Vinča reactor. An expected overestimation of the albedo dosimeter in the soft CERN spectrum due to neutrons below 1 MeV is not noticed as the Rem ionization chamber to which it is compared will likewise overread the neutron dose. This overestimation is however not caused by the well known mismatch of the response curve of the Anderson and Braun moderator assembly with the fluence to dose equivalent conversion factors recommended by ICRP at intermediate neutron energies as the instrument in the case of the reactor spectra is used as a reference for dose equivalent. The overestimation results from the fact that, due to the pulsed radiation field around the accelerator, the Rem instrument has to be operated as an ionization chamber. The applied correction of its gamma response is only correct for external radiation interacting with the detector but is not valid for gamma radiation from neutron capture reactions inside the moderator which are to be expected in a soft neutron spectrum. This will increase the ionization current in the Rem chamber.

When comparing the hadron doses given in Table 1, it will be noticed that in the case of the hard spectrum (positions 1 to 5) the film-badge is always overestimating compared to measurements with the Cerberus. The overestimation may exceed a factor of 4 when using the standard calibration of the film-badge with Pu-Be neutrons, but is lowered to a factor of 2 if the results are corrected using information about the spectrum and taking into account the local contribution of high energy hadrons above 20 MeV.

The albedo dosimeter shows both over- and underestimations as the fit of the raw data to the radiation survey will naturally result in deviations in both directions for the system. In this context it should be mentioned that a single albedo detector dosimeter would underestimate the dose equivalent in a hard spectrum by a factor of up to 5.

It has already been mentioned that for soft spectra overestimations with the Cerberus could attain 30%. On the other hand it is known that in such a situation nuclear emulsions will greatly underestimate personnel exposures due to their energy threshold, which is of the order of 1 MeV. The underestimation compared to the (overestimated) radiation survey result is more than a factor of 12 as observed in the Linac area, where there is a complete absence of high energy hadrons. A factor of 5 is found for an area where a 2% contribution of high energy particles is measured.

The good correspondence between the Cerberus and the albedo system results in the case of the hard and soft spectra is not surprising as two different correction factors have been applied based on the lines in Fig. 1. The problems of this procedure in view of a possible exposure in both fields will be discussed below since a similar situation exists for the fission track dosimeter.

Gamma doses are likewise presented in Table 1. A rather good correspondence is found between the gamma doses recorded on the films and those measured with the Cerberus in hard spectra. The gamma dose recorded with the albedo system in these situations turns out to be a factor 2 higher. In the case of a soft spectrum there is a good agreement between the film-badge and the albedo dosimeter for the gamma doses, whereas the Cerberus reads roughly a factor of 2 lower. This latter phenomenon can however be explained by the fact that the gamma component in the measurement of the Cerberus is evaluated by the difference in reading of the TE chamber and the $CO_2$ chamber, both measuring in "free air". Moreover, the dosimeters were fixed to a phantom and will thus record the gamma emission of possible $(n,\gamma)$ reactions in the moderator. However, this apparent underestimation with the Cerberus is largely compensated for, as explained above, by the overestimation in the hadron component during radiation survey.

## 2. Fission track dosimeter

The results of the fission track personnel dosimeter are given in Table 2, compared to the results of the Cerberus and the film-badge. The dose equivalents given in column 5 have been calculated from the rough data of sparks counted automatically and by using the proposed conversions of 1 spark corresponding to 12.5 mrem below the $^{232}$Th and 1 spark corresponding to 0.16 mrem below the $^{235}$U irradiator[11]. As can be seen, with this calibration the differences between the hadron doses determined with the Cerberus and those accumulated on the fission track dosimeters are great.

The dosimeter presently used at the SIN accelerator consists of a combination of a $^{232}$Th and a $^{209}$Bi irradiator, the latter having a spallation threshold for hadrons of 60 MeV with a maximum cross-section of only 0.2 barn at 600 MeV (Fig. 2). Due to its high threshold and small cross-section the sensitivity of this reaction is so low that only in a hard spectrum and with a rather high dose a significant number of sparks can be observed; e.g. in position 14 an accumulated dose of 5.3 rem gave rise to 20 sparks in the plastic foil behind the bismuth irradiator.

More promising is the combination of $^{232}$Th and $^{235}$U as radiatiors for plastic foils, as can be seen from the energy dependent cross-section curves represented in Fig. 2. These data were taken from several recent references[12-16]. While the neutron fission for $^{235}$U is about one order of magnitude higher for neutrons in the eV range than for MeV neutrons, the cross-section is nevertheless always higher than the one for $^{232}$Th. However, there will be a good discrimination against slow neutrons in $^{232}$Th due to the rapid onset of the (n,f) reaction around 1 MeV. Other hadrons than neutrons in the stray radiation field above 10 MeV are supposed to be detected as well, as can be seen from the plotting of the protonic fission reaction in $^{232}$Th.

The idea of combining two detectors covering two different energy ranges for dosimetric purposes was used with success in a megarad dosimeter around the PS[17].

Track density or fluence to dose equivalent conversion factors were determined for the fission track dosimeter by regarding only the four measurements which were performed in the hard spectrum (positions 11 to 14). By minimizing the expression :

$$\sum_{i=1}^{4} (H_{Cerberus} - \alpha\, N_{^{232}Th} - \beta\, N_{^{235}U})^2$$

the following conversion factors were obtained :

$\alpha = 4.23 \pm 1.41$ mrem/spark and

$\beta = 3.03 \pm 0.35$ mrem/spark

when $N_{232_{Th}}$ and $N_{235_U}$ respectively are the number of sparks recorded behind the different fissionable materials. By employing the calculated conversion factors the correspondence with the accumulated hadron dose equivalent as determined by the Cerberus is excellent. The errors given in the table are however considerable and refer to the statistical precision depending on the total number of sparks counted.

The film-badge shows the usual overestimation in the hard spectrum compared to the survey results. In addition, a limitation of nuclear track emulsions becomes obvious as doses accumulated in positions 12 and 14 could not be evaluated due to the high density of tracks.

Using the conversion factors optimized for the fission track dosimeter in the hard spectrum for measurements in a soft spectrum (positions 15 and 16), at least 30% of the dose equivalent recorded with the Cerberus is detected, whereas the film-badge, as has been mentioned previously, underestimates the dose by a factor of 12 in this case, i.e. stray radiation field from the Linac.

The remarks about the recorded gamma doses are the same as for dose measurements with the albedo dosimeter system.

## V. CONCLUSIONS

Although it seems premature to draw a final conclusion about the response of some new types of possible personnel dosimeters for hadron stray fields around high energy proton accelerators, some general remarks can be made.

An ideal personnel dosimeter, covering in its response to dose equivalent the wide range of hadron energies encountered, does not exist.

By limiting the discussion to the usual condition of a hard spectrum, i.e., where at least 10% of the dose is due to hadrons of energies above 20 MeV, both the albedo dosimeter system and the fission track dosimeter show some advantages compared to the film-badge due to their better recording of the hadron dose.

The maximum dose equivalent which can be evaluated without losing linearity is about 1000 rem for the albedo dosimeter system and 50 rem for the fission track dosimeter using automatic spark counting techniques. It can reach 5 krem when processed in other ways.

Without any knowledge about the irradiation conditions the film-badge will, when standard calibration with Pu-Be neutrons is used, always overestimate the dose equivalent in a hard spectrum, and this could reach or even exceed a factor of 4 compared to radiation survey results. When looking at all the comparisons made in a hard spectrum it can be seen that, in order to cover all the spectral conditions encountered and never permit an underestimation to occur, the general overestimation cannot be significantly reduced by introducing a somewhat less conservative interpretation of the nuclear tracks in the emulsion.

In these experiments both the albedo system and the fission track dosimeter have been matched to the results of the Cerberus, which naturally leads both to an over- and an underestimation under the different spectral conditions. If a sufficiently conservative correction is applied, which in all cases (like for the film-badge) will result in an overestimation, these new devices may read at the maximum a factor of 2 higher than the results obtained from radiation survey measurements. Their energy independence for dose equivalent determinations is much better than that of the nuclear track emulsion.

In the case of a rare but possible exposure at CERN of personnel to a soft neutron spectrum, the application of the hard spectrum correction factor will result in an overestimation of the dose equivalent by the albedo dosimeter system of a factor of 4. Under the same conditions the fission track dosimeter will underestimate, but will still record roughly 40% of the dose equivalent.

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## TABLE 1

Comparison of hadron and gamma doses between Cerberus, Albedo dosimeter system and CERN film-badges

| | CERBERUS | | | Albedo dosimeter system | | CERN film-badge | | | |
|---|---|---|---|---|---|---|---|---|---|
| Position | $H_h$(mrem) | Contrib. for hadrons $>$ 20 MeV | $H_\gamma$(mrem) | $H_h$(mrem) | $H_\gamma$(mrem) | $H_h$(mrem)* | $H_\gamma$(mrem) | $\frac{H_h(\text{albedo})}{H_h(\text{Cerberus})}$ | $\frac{H_h(\text{film-badge})^*}{H_h(\text{Cerberus})}$ |
| 1 | 271±14 | 0.33 | 27 | 234 | 75 | 308 | 40 | 0.86 | 1.14 |
| 2 | 719±37 | 0.34 | 70 | 620 | 155 | 826 | 70 | 0.86 | 1.15 |
| 3 | 688±35 | 0.26 | 63 | 736 | 115 | 1600(2730) | 90 | 1.07 | 2.33 (3.97) |
| 3 | | | | 775 | 110 | 1500(2560) | 80 | 1.13 | 2.18 (3.72) |
| 3 | | | | 725 | 120 | 1260(2150) | 90 | 1.05 | 1.83 (3.13) |
| 3 | Mean value for three dosim. | | | 745±26 | 115±5 | 1450±170 | 87±6 | 1.08±0.01 | 2.11±0.07 |
| 4 | 2042±103 | 0.47 | 186 | 1520 | 385 | 2760(7730) | 180 | 0.74 | 1.35 (3.79) |
| 4 | | | | 1270 | 425 | 2245(6290) | 140 | 0.62 | 1.10 (3.08) |
| 4 | | | | 1400 | 375 | 2180(5890) | 160 | 0.69 | 1.07 (2.88) |
| 4 | Mean value for three dosim. | | | 1397±125 | 395±26 | 2395±320 | 160±20 | 0.68±0.01 | 1.17±0.03 |
| 5 | 967±49 | 0.35 | 149 | 1170 | 235 | 1925(4040) | 180 | 1.21 | 1.99 (4.18) |
| 5 | | | | 1340 | 240 | 2090(4390) | 160 | 1.39 | 2.16 (4.54) |
| 5 | | | | 1300 | 235 | 2160(4540) | 180 | 1.34 | 2.23 (4.69) |
| 5 | Mean value for three dosim. | | | 1270±89 | 237±3 | 2060±120 | 173±12 | 1.31±0.01 | 2.13±0.03 |
| 6 | 903±47 | 0.0 | 23 | 797 | 79 | 56 | 100 | 0.88 | 0.06 |
| 7 | 2028±106 | 0.0 | 52 | 1805 | 164 | 154 | 240 | 0.89 | 0.08 |
| 8 | 399±21 | 0.02 | 17 | 463 | 34 | 77 | 50 | 1.16 | 0.19 |
| 9 | 797±45 | 0.02 | 32 | 954 | 63 | 112 | 90 | 1.20 | 0.14 |
| 10 | 4205±226 | 0.02 | 175 | 3830 | 321 | 574 | 400 | 0.91 | 0.14 |

* Values in brackets : standard interpretation.

## TABLE 2

Comparison of hadron and gamma doses between Cerberus, fission track dosimeter and CERN film-badge

| | CERBERUS | | | Fission track dosimeter | | | CERN film-badge | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Pos. | $H_h$(mrem) | Contrib. for hadrons > 20 MeV | $H_\gamma$ (mrem) | standard inter-pretation $H_h$(mrem) | TLD $H_\gamma$(mrem) | optimized inter-pretation $H_h$(mrem) | $H_h$(mrem) | $H_\gamma$(mrem) | $\frac{H_h(\text{fission tr.})}{H_h(\text{Cerberus})}$ | $\frac{H_h(\text{film-badge})}{H_h(\text{Cerberus})}$ |
| 11 | 463±24 | 0.09 | 76 | 357±13 | 128 | 568±129 | 830(1000) | 180 | 1.23±0.08 | 1.79±0.08 |
| 12 | 3577±198 | 0.07 | 418 | 1977±164 | 438 | 3267±359 | not eval. | 800 | 0.91±0.01 | - |
| 13 | 675±40 | 0.24 | 96 | 1208±216 | 142 | 882±356 | 1060(1700) | 120 | 1.31±0.28 | 1.57±0.06 |
| 14 | 5302±318 | 0.23 | 731 | 10380±875 | 900 | 5242±385 | not eval. | 920 | 0.99±0.01 | - |
| 15 | 493±25 | 0.0 | 15 | 86±26 | 102 | 170±31 | 0 | 100 | 0.34±0.01 | 0 |
| 16 | 4067±206 | 0.0 | 126 | 324±13 | 341 | 1163±96 | 300 | 600 | 0.29±0.01 | 0.07±0.01 |

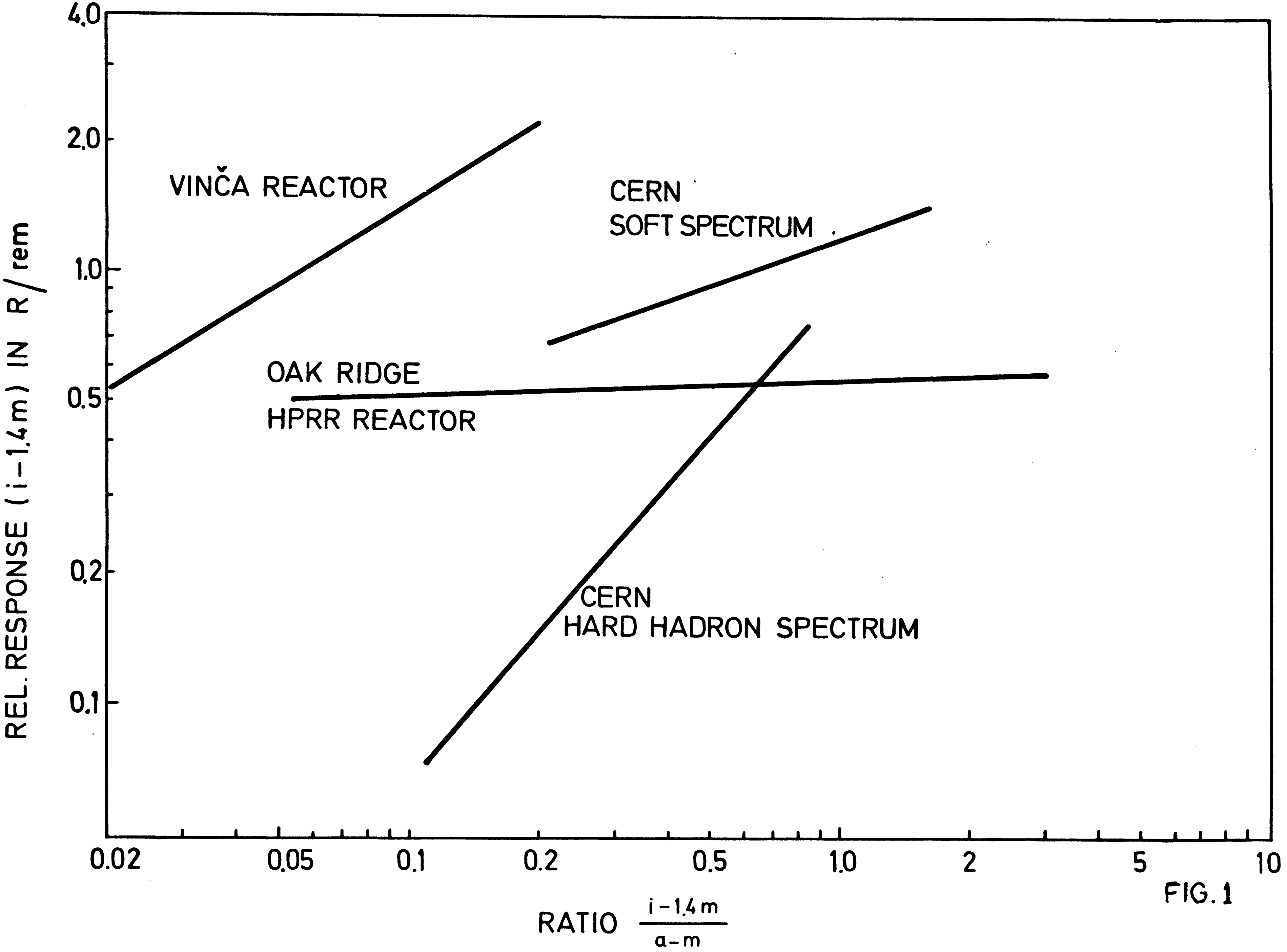
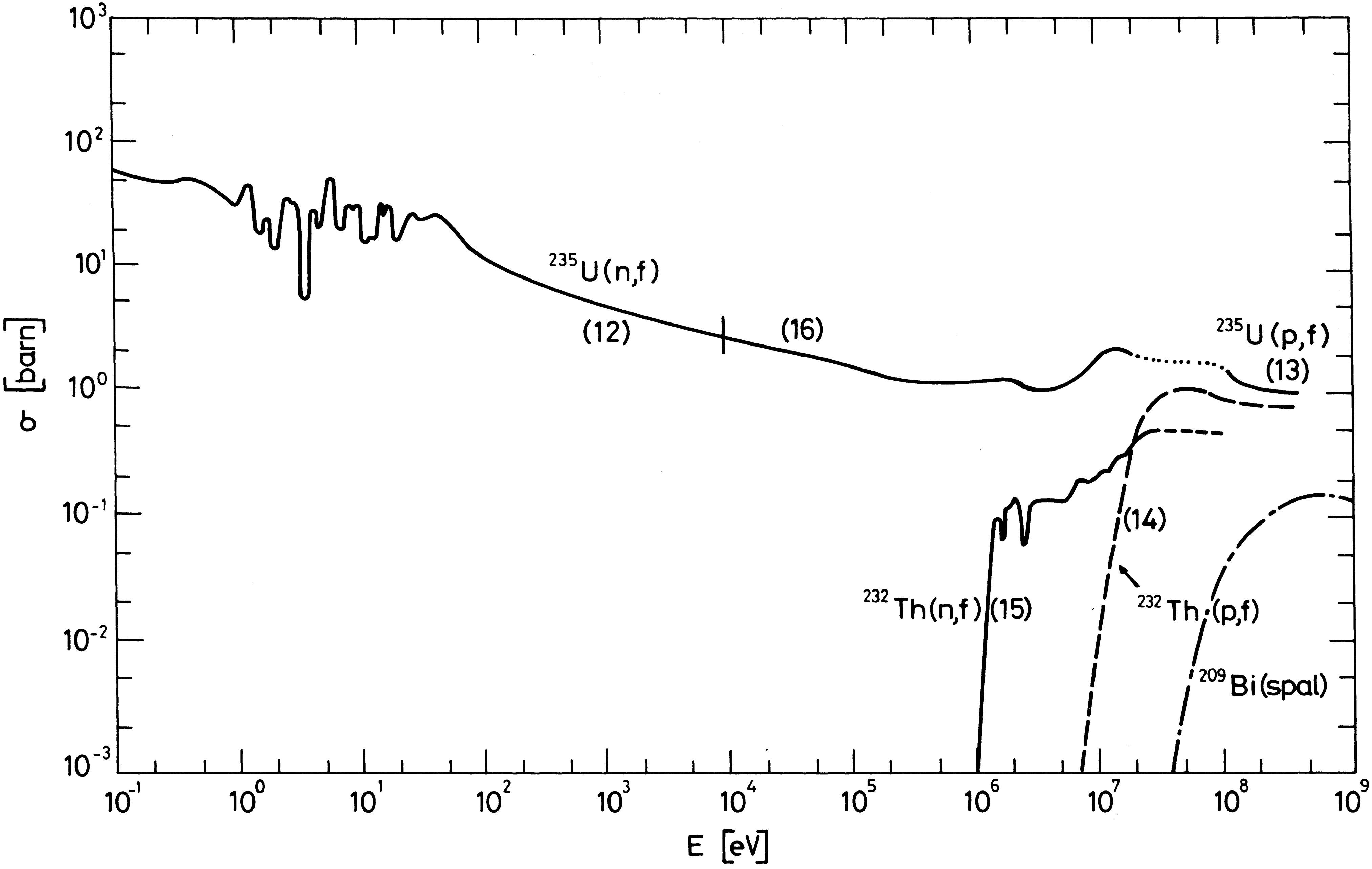

4.0
2.0
1.0
0.5
0.2
0.1
REL. RESPONSE (i−1.4m) IN R/rem
VINČA REACTOR
CERN
SOFT SPECTRUM
OAK RIDGE
HPRR REACTOR
CERN
HARD HADRON SPECTRUM
0.02
0.05
0.1
0.2
0.5
1.0
2
5
10
RATIO i−1.4m / a−m

FIG. 1



$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
σ [barn]
$^{235}$U(n,f)
(12)
(16)
$^{235}$U(p,f)
(13)
(14)
$^{232}$Th(n,f) (15)
$^{232}$Th (p,f)
$^{209}$Bi(spal)
$10^{-1}$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$
$10^9$
E [eV]

FIG. 2