

*THE ASSESSMENT OF DOSE EQUIVALENT IN STRAY RADIATION FIELDS
AROUND HIGH-ENERGY PROTON ACCELERATORS*

M. Höfert and G.R. Stevenson

The assessment of dose equivalent in stray radiation fields around high-energy proton accelerators is a challenging task both from the theoretical and the practical point of view.

Calculations of the composition of the stray field are possible starting out from the interaction of the primary beam in a target and transporting the subsequent hadron cascade through a bulk shield generally made up of an iron/concrete sandwich.

The measurement techniques so far used to assess dose equivalent in such radiation fields are complicated. Three possible approaches are described. They have also been the basis of intercomparisons made in the past.

The proportional counter technique is considered to be one method allowing an insight into the distribution of radiation qualities. When this is coupled with more detailed particle and energy spectrometry to define the incoming field a better understanding of the whole problem will be reached.

To be presented at the Workshop for
Practical Implementation of Microdosimetric Counters
in Radiation Protection
Homburg/Saar, May 15-17, 1984

THE ASSESSMENT OF DOSE EQUIVALENT IN STRAY RADIATION FIELDS AROUND HIGH-ENERGY PROTON ACCELERATORS

1. INTRODUCTION

The problem of the assessment of dose equivalent in stray radiation fields around high energy proton accelerators has been the subject of several articles in the past of which only two recent ones are quoted for further reference (McC80, Tho83). The emphasis in this paper is focussed on a description of the composition of the stray radiation fields and an understanding of results of previous intercomparisons between different measurement methods in view of this composition and the energy dependence of the various detectors employed.

2. THE STRAY RADIATION FIELD

The most important component of the radiation field outside the shielding of a high-energy proton accelerator, from the radiological point of view, is the neutron component. This comes from the nuclear interactions in the cascade induced in shields, targets, collimators, etc., struck by the high-energy protons. Charged particles such as protons and pions are also produced in these nuclear interactions but except at the highest energies they are preferentially removed from the cascade because of slowing down by Coulomb processes.

Figure 1 shows the results of a theoretical calculation by O'Brien (O'Br71) of the neutron spectrum in the concrete side-shielding of a high-energy proton accelerator. The spectrum has essentially a $1/E$ form from thermal energies up to about 1 MeV. There is a peak, due to evaporation neutrons, in the 1-10 MeV range and a second peak, probably due to intranuclear cascade processes, in the 100 MeV region. This higher energy peak has been confirmed experimentally by Madey et al. (Mad76) and also in calculations reported by Stevenson (Ste83) of the high-energy cascade in iron. These latter calculations are also shown in Fig. 1, arbitrarily normalized to the 100 MeV peak in the O'Brien calculations.

In the forward direction the composition of the radiation field is somewhat different since it contains the higher energy cascade-generating particles instead of the lower energy particles produced at wide angles to the incident particles. Figure 2 shows the forward spectrum of the Stevenson calculations, normalized only for comparison purposes to the O'Brien spectrum. The contribution of protons and pions to the dose equivalent of particles above 20 MeV could be as high as 16 and 34% respectively for thin to moderately thick shieldings.

At very large depths in the forward shielding of proton accelerators only the muon component remains. Muons are produced by the in-flight decay of some pions and other short-lived particles in the nuclear cascade; they can also be produced directly in very high energy (>100 GeV) nuclear interactions. Since muons do not undergo nuclear interactions they can be removed from the cascade only by Coulomb slowing-down and other electromagnetic processes. At proton energies above 30 GeV and behind secondary pion beam endstops, muon considerations dominate shielding requirements; however, from a radiological viewpoint muons are simply minimum ionizing particles much like electrons of energies >10 MeV.

3. CONVENTIONAL ASSESSMENT OF DOSE EQUIVALENT

It is not the aim of this paper to discuss which dose equivalent quantity is relevant or should be considered in radiation protection dosimetry. It should only be mentioned that ICRP now requires the determination of effective dose equivalent while at present fluence to dose equivalent conversion factors published earlier are the basis for neutron measurements. These factors are generally based on broad parallel monoenergetic particle beams impinging on phantoms where the maximum dose equivalent occurring in the body is related to the corresponding fluence.

The rationale of conventional radiation protection dosimetry is then as follows: a) calibrate instruments in known fluences for which the broad parallel beam condition is as far as possible realized, b) use these instruments in stray radiation fields where the energy spectrum should be similar to the one of calibration although the

angular distribution of the actual field is generally far from being plane parallel. This approach should lead to a discussion on the influence of geometric effects on the actual dose equivalent to a person moving around in such fields but this problem will not be treated here. Likewise, the angular dependence of the detectors plays an important role in this context but is generally neglected in routine measurements.

Another problem arises if the instrument is used in an energy range much different from the one for which it had been calibrated for. In Fig. 3 measured response curves for three of the detectors used in intercomparison studies are shown (Hoe80, Har83). As can be seen their energy dependence with respect to dose equivalent is considerable. These curves should help in understanding differences found in intercomparisons of dose equivalent measurements in stray fields around high energy proton accelerators. Intercomparisons, although they will not help to give the correct value, nevertheless permit a better understanding of discrepancies considering the qualitative information on the composition of the radiation field.

A special feature of the high energy field is its small variation throughout the body or phantom. Measurements with tissue equivalent ionisation chambers actually revealed that under stray field conditions absorbed dose measurements show a negligible dependence on wall thicknesses up to several centimetres. This fact is assumed to hold also for quality factors, which are an important parameter in the description of measured fields.

4. DESCRIPTION OF MEASUREMENT METHODS

Three different techniques for the assessment of dose equivalent around high energy accelerators will be described in this chapter.

The oldest method makes use of multiple detectors each covering a particular component and energy range. In this category are the activation detectors, which can only be employed in strong radiation fields because of their lack of sensitivity, unless large detectors involving special calibrations are used. In addition the answer is not

available immediately as detectors first have to be evaluated "off-line".

The method used at CERN known as CERBERUS therefore makes use of live detectors except in the case of hadrons above 20 MeV for which the activation of ^{11}C from ^{12}C in a 1 litre scintillation crystal is used. This activation method has good sensitivity (down to 1 hadron per cm^2 and second) and can conveniently be activated and evaluated due to its short half-life of 20 minutes. The other components of the CERN detector set consist of an Andersson and Braun moderator in which the BF_3 -tube is operated in an ionization mode in order to cope with the pulsed structure of the radiation field. The use of the RIC (acronym for rem ion chamber) requires a correction for the ionization current from non-neutronic radiation. This is accomplished by the use of two additional ionization chambers: the already mentioned TE ionization chamber and an air filled aluminium chamber. This detector pair allows to separate in the known way the photonic/charged particle and neutronic components of absorbed dose. In order to arrive at an answer on dose equivalent with the help of the results of the four detectors a rather complicated algorithm is evaluated by the computer giving at the same time the quality factor as well as the percentages in dose equivalent of three apparent components: fast and intermediate energy neutrons, photons and charged particles and finally hadrons above 20 MeV. For the latter contribution, a fluence to dose equivalent conversion of 28 fSv m^2 is used.

Another way of evaluating dose equivalent in mixed radiation fields is the use of a (commercially available) recombination chamber (Zie64). It has been shown that the current in an ionization chamber depends on the LET of the radiation when the collecting voltage has been chosen so low that recombination of ions created along the particle track becomes important. A system of two parallel-plate tissue-equivalent chambers, one operated in the recombination, the other in the saturation mode, makes it possible, with two parameters (voltage and gas pressure) properly adjusted, to determine both dose equivalent rate and quality factor in the stray field around a proton accelerator (Sul84).

Finally an instrument described and built at Brookhaven National Lab. and based on the use of a tissue equivalent proportional counter was employed in measurements at CERN (Kue73). Since the charge of a pulse in a proportional counter is both a function of LET and the track length of the radiation interacting, the total charge for a spherical counter should be directly proportional to the absorbed dose in a corresponding mass of tissue. By multiplying the pulses corresponding to specific LET's with the related quality factors, dose and dose equivalent can be determined simultaneously.

5. RESULTS OF INTERCOMPARISONS

Two intercomparisons were performed using the techniques described above. The results are given in Tables 1 and 2 (Hoe75, Ant79). In both experiments three typical classes of radiation fields were selected, viz. where the high-energy hadron component is important, fast and intermediate neutrons are predominant, and muon beams or muons behind endstops prevail. The results of the CERN measurements will be analyzed with respect to the response curves given in Fig. 3 and the field composition as determined with the CERBERUS.

In cases where the high energy hadron component gives an important contribution to the dose equivalent both CERBERUS and REM2 give quite consistent results where the higher values of the component method are explained by the overlapping and added response of the various detectors used. The higher figures obtained with the proportional counter could be related to its increase in sensitivity above 10 MeV. Quality factors for this kind of stray field are around 4.5 except in the case of the recombination chamber which gives the highest QF's for all radiation fields. This effect could be explained by a relative underestimation of absorbed dose by this instrument.

Positions 3 to 5 are those where fast or intermediate neutrons predominated. Point 3 actually was measured in the Linac area, point 4 perpendicular to a thick lateral concrete shielding and point 5 in front of a labyrinth where an important stray contribution from intermediate energy neutrons is expected. In all these fields the RIC as part of the CERBERUS should greatly overestimate and indeed all dose

equivalent values reported are much higher than those attained by the REM2 or the proportional counter. The two latter instruments actually show a remarkable consistency in the results under such field conditions. The quality factors decrease with decreasing energy of the neutron component as would be expected although those determined with the proportional chamber are lower than those measured with the other two methods. Finally in radiation fields primarily composed of muons all three methods give rather similar results.

The second experiment was made together with the Institute of High Energy Physics around the 70 GeV proton accelerator at Serpukhov. In these measurements the CERBERUS shows a consistent behaviour with the CERN results in three typical radiation environments. Note that the radiation field in the muon channel was practically free of other components. The various combination methods employed at Serpukhov are similar to the one used at CERN and give different answers. The recombination chamber Sukhona-2 shows about the same behaviour as the REM2 detector, while the results reported for the LET-spectrometer are probably too low as one would judge from the rather modest quality factors.

The overall conclusion which can be drawn from these measurements is that all intercomparisons lead to values of dose equivalent agreeing within better than a factor of two and that quality factors obtained at least for the CERN measurements are reasonable within the qualitative understanding of the radiation field composition.

6. CONCLUSIONS

The fact of reasonable agreement between various methods to determine dose equivalent should however not be overemphasised since a better understanding of the various radiation fields encountered outside the shielding of a high energy proton accelerator is needed. One way to enlarge the knowledge about the relevant composition of the former with respect to radiation protection at present available is the use of proportional counters with their possibility to analyse event sizes. The combination of absorbed dose measurements and information of local energy deposition within the geometry of a body phantom will

allow making statements about dose equivalent distributions in the body and their relevance to radiation protection. This knowledge has to be coupled with more detailed particle and energy spectroscopy of the incoming fields in order to fully understand the problem of assessment of dose equivalent around high energy proton accelerators.

REFERENCES;

- Ant79: A.V. Antipov, I.S. Bajshev, V.T. Golovachik, G.I. Krupnyi, V.N. Kustarev, V.N. Lebedev and M. Höfert, Comparison of dose equivalent measurements behind the IHEP accelerator shielding using different methods, Atomic Energy 46, 105 (1979), CERN Trans 78-01, Geneva 1978.
- Har83: H. Hartmann, Arbeiten zur Anwendung eines gewebesäquivalenten Proportionalzählers zur Äquivalentdosismessung in gemischten Neutron-Photonenfeldern: Vortrag 19. Sitzung des Arbeitskreises "Dosismessung externer Strahlung", April 1983, CERN, Geneva.
- Hoe80: M. Höfert and R.C. Raffensøe, Measurement of absolute absorbed dose and dose-equivalent response for instruments used around high-energy proton accelerators, Nucl. Instr. Meth. 176, 443 (1980).
- Hoe75: M. Höfert, A comparison of dose equivalent measurements around a GeV proton accelerator, DI/HP/187, July 1975.
- Kue73: A.V. Kuehner, J.D. Chester and J.W. Baum, Portable mixed radiation dose-equivalent meter, Proc. Symp. on Neutron Monitoring, Vienna 1973, p. 233.
- Mad76: R. Madey, A.R. Baldwin and F.M. Waterman, Neutron spectrum from 20 to about 600 MeV above the Brookhaven National Laboratory AGS Shielding, Trans. Am. Nucl. Soc. 23, 612 (1976).
- McC80: J.B. McCaslin and R.H. Thomas, Practical neutron dosimetry at high energies, Proc. European Seminar on Radiation Protection Quantities for External Exposure, Braunschweig 1980, p. 137.
- O'Br71: K. O'Brien, Neutron spectra in the side-shielding of a large particle accelerator, USAEC Health and Safety Laboratory Report HASL-240 (1971)
- Ste83: G.R. Stevenson, The estimation of dose equivalent from the activation of plastic scintillators, CERN Report TIS-RP/107/PP (1983), to be published in Health Physics.
- Sul84: A.H. Sullivan, The use of detectors based on ionization recombination in radiation protection, CERN Report TIS-RP/130/CF (1984).
- Tho83: R.H. Thomas and G.R. Stevenson, Radiation protection around high-energy accelerators, Div. Report CERN TIS-RP/109/PP, Submitted to Radiation Protection Dosimetry.
- Zie64: M. Zielczynski, V.N. Lebedev and M.I. Salatskaya, Prib. Tekh. Eksp. 6, 73 (1964).

TABLE 1

Results of intercomparative dose equivalent measurements performed around the CERN high-energy proton accelerators

* Positions 1 and 2 : high energy component important, 3-5 fast and intermediate neutrons dominant
6 and 7 : muons behind endstops

Position	Field characteristics in % of			CERBERUS		REM2		Proportional counter	
	Fast neutrons	HEP	Photons	$\mu\text{Sv/h}$	Q	$\mu\text{Sv/h}$	Q	$\mu\text{Sv/h}$	Q
1	45	45	10	175	4.6	124	5.1	222	4.6
2	54	35	11	380	4.0	300	5.6	470	4.5
3	95	< 1	5	452	8.6	332	9.7	349	7.6
4	85	9	6	317	6.1	219	7.5	242	4.2
5	75	6	19	228	3.4	145	3.4	153	2.2
6	58	< 1	42	16.5	1.7	14.1	2.1	16.8	1.7
7	34	11	55	29.9	1.5	22.0	1.5	31.0	1.4

TABLE 2

Results of comparative measurements behind the shielding
of the Serpukhov proton synchrotron

* Combination methods used all the $^{12}\text{C}(h,nh) \ ^{11}\text{C}$ reaction and an Al-chamber filled with air. Method 1: BF_3 -counter in 30 cm moderator. Method 1': BF_3 counter in 25.4 cm \emptyset moderator. Method 2: As 1' but correction with response matrix. Methods 1'' and 2'' as 1' and 2 but GM-counter with ^{103}Rh converter in 25.4 cm \emptyset moderator.

Position	Field composition	Method*	Dose equivalent per accelerator pulse in 10^{-8} Sv		Q	
1	high energy component important	CERBERUS	26.9	1.6	4.2	0.3
		Sukhona-2	28.6	3.0	4.2	0.4
		LET Spectrom.	19.6	2.0	2.8	0.3
		Comb. Method 1	33.6	2.0	3.2	0.6
		Comb. Method 1'	29.5	1.8	3.0	0.3
		Comb. Method 2	24.0	2.0	3.4	0.4
2	fast neutrons dominant	CERBERUS	29.3	1.5	6.1	0.5
		Sukhona-2	18.0	2.3	3.6	0.4
		LET Spectrom.	10.8	1.1	2.0	0.2
		Comb. Method 1	38.7	3.1	3.9	0.3
		Comb. Method 1'	21.1	1.2	2.8	0.3
		Comb. Method 2	19.1	1.4	3.5	0.4
3	muon beam	CERBERUS	5.30	0.33	1.02	0.1
		LET Spectrom.	6.5	0.6	1.2	0.1
		Comb. Method 1''	6.7	0.6	1.1	0.2
		Comb. Method 2''	6.6	0.9	1.2	0.2

FIGURE CAPTIONS

- Fig. 1 Neutron spectrum lateral to a concrete shielding as calculated in O'Br71 (o) and Ste73 (●).
- Fig. 2 Hadron spectra in an endstop in forward direction as calculated by Ste83. The lateral neutron spectrum calculated by O'Br71 (o) from Fig. 1 is shown for comparison.
- Fig. 3 Relative dose equivalent response curves for the Rem ion chamber (RIC), the recombination chamber (REM2) and the proportional counter (PC). The response was normalized to one at 1 MeV.

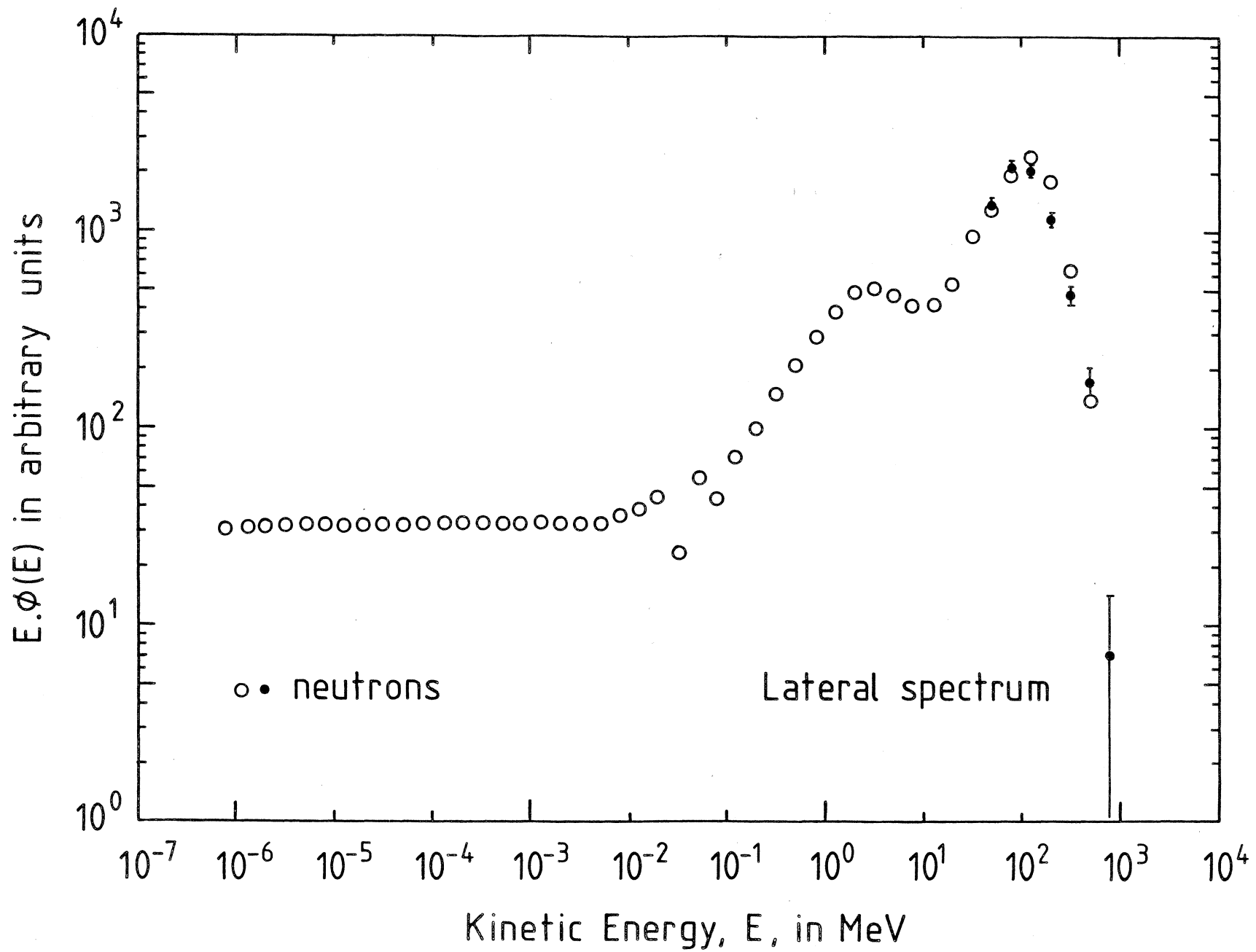


FIG. 1

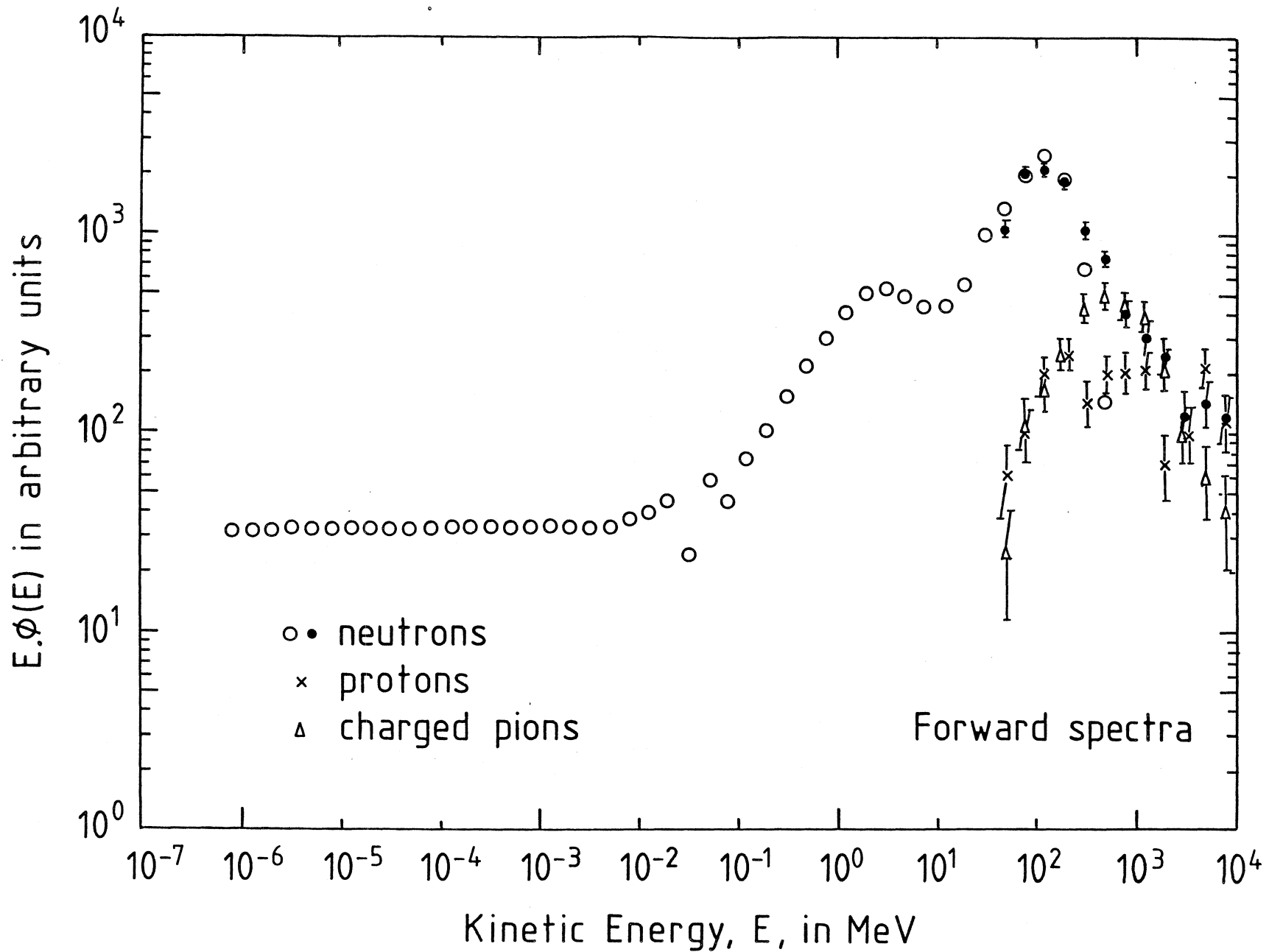


FIG. 2

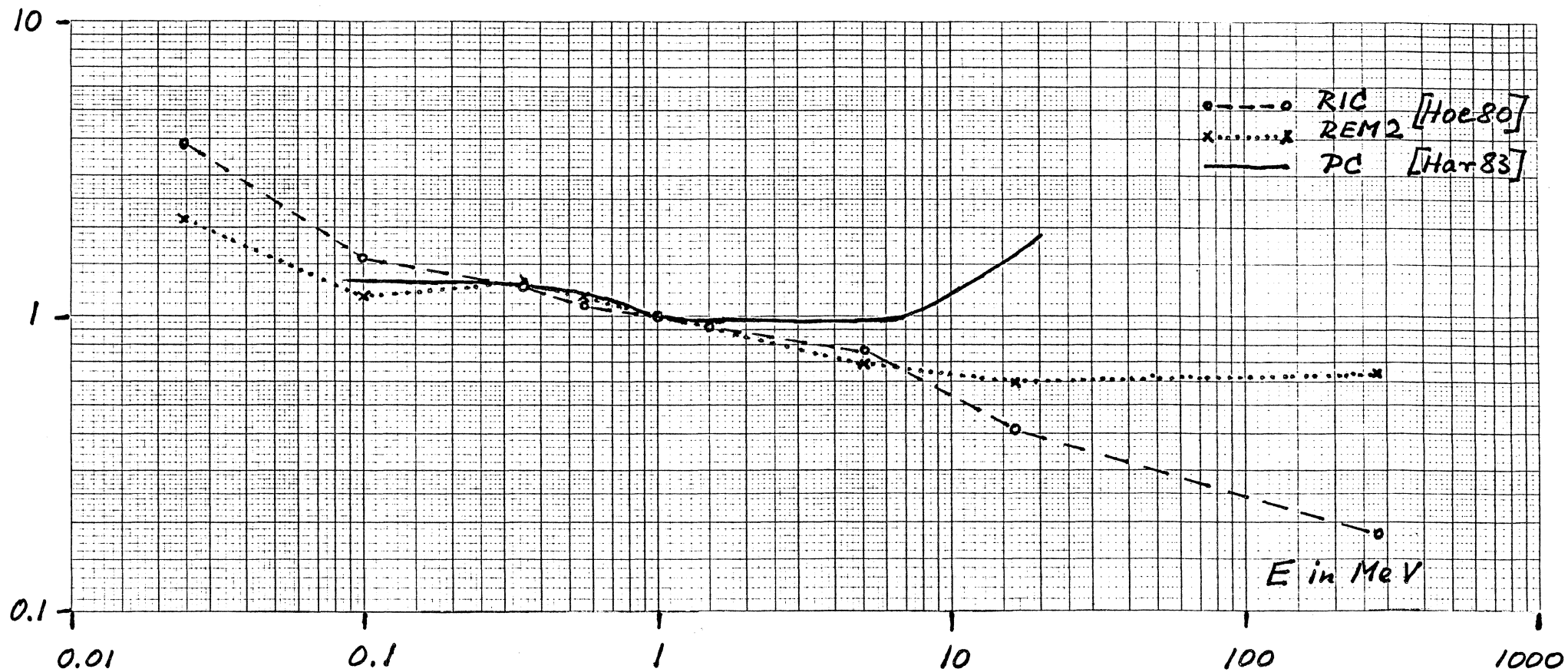


FIG. 3