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CHANGES IN THE FREQUENCY DISTRIBUTION OF ENERGY DEPOSITED IN SHORT PATHLENGTHS AS A FUNCTION OF ENERGY DEGRADATION OF THE PRIMARY BEAM*

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RUNNING HEADING: Statistics of Proton Energy Deposition

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ABSTRACT

The frequency distributions of event size in the deposition of energy over small pathlengths have been measured after penetration of 44.3 MeV protons through various thicknesses of tissue-equivalent material. These distributions have been measured over a range of penetration extending from zero thickness to thicknesses of muscle-equivalent plastic close to that corresponding to the total range of the protons. These distributions are those associated with the passage of the proton through 0.667×10^{-4} g/cm^2 of a tissue-equivalent gas. The transition from the region where statistical fluctuations dominate to that where a significant spread in beam energy has taken place is clearly demonstrated. In no instance does it appear that the concept of dose based upon a value of the stopping power or average energy deposited adequately defines the energy delivered to a structure having the dimensions usually associated with those of biological significance if only a relatively small number of events are required for induction of damage.

KEY WORDS

Ionization - Energy Deposition - Protons - Beam Degradation

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INTRODUCTION

The possible consequences and probable importance of the statistical fluctuations of energy deposition in small volumes have been pointed out by Rossi and Rosenzweig (1) and by Kellerer (2, 3). The theory governing such fluctuations is generally felt to be best treated by the work of Vavilov (4) as corrected by the method of Blunck and Leisegang (5).

The frequency distributions of energy depositions associated with the passage of a monoenergetic 43.7 MeV proton beam through various thicknesses of a tissue-equivalent gas were investigated by Hilbert, Baily, and Lane (6). This work demonstrated, for the case where the energy loss is very much smaller than the particle energy, that first, the full width at half maximum (FWHM) is very large and second, that significant differences between the average energy loss and most probable energy loss exist due to the skewness caused by the large number of events having high energy losses. The spread and the skewness both are functions of the mean energy loss, its relative value with respect to the mean binding energy of the atomic electrons in the material under consideration, and its value relative to the maximum possible energy transfer which the incident particle can make to an electron in a single collision. Good correlation between theory and experiment has been found when comparisons are made based on the full width at half maximum (FWHM) of the distribution functions. Similar distributions for electrons have been reported by Kageyama, Nishimura, and Onai (7).

A comparison of theory and experimental data acquired using 46.4 MeV protons, over most of the range of energy depositions recorded with that energy proton, has been made by Baily, Steigerwalt, and Hilbert (8). Good agreement was again found for the FWHM and for the values of the average and most probable energy losses. However, significant discrepancies were found above and below the most probable value. These discrepancies manifest themselves in a deficiency of low energy loss events and an excess of high energy loss events. Loss of secondaries from the sensitive volume of the proportional counter cannot account for these, since they would produce an excess of small energy losses and would also cause a larger discrepancy to appear in the region of high energy losses than is found.

Some preliminary data on the character of the frequency distributions which occur in small volumes after passage of a homogeneous beam through a large amount of absorber and thus after suffering various energy losses was given by Hilbert and Baily (9). In addition to statistical fluctuations such distributions are subject to perturbations due to the resulting inhomogeneity of the energy distribution of the charged particles (10, 11, 12). These latter authors have shown that the energy spectra of a homogeneous beam of charged particles becomes skewed toward lower energies after passage through thin absorbers. As absorber thickness becomes greater the distribution approaches a gaussian. This change occurs because of statistical fluctuations of the energy loss in the absorber and because the different energy particles lose energy at different average rates. The distribution again becomes non-gaussian after the mean particle energy is reduced to less than 35 per cent of the initial particle energy. This is the point where the fluctuations introduced by statistics are overcome by the spread in stopping powers corresponding to the particle energy spectra. In such a situation, the frequency distribution of energy losses in a small pathlength could be significantly altered by the amount of material traversed by the particle before entering the volume of interest.

METHOD

The experimental results discussed in this paper were obtained using the method described in (6) except for the introduction of various thicknesses of tissue-equivalent plastic made of Shonka muscle (13). These absorbers were placed in contact with the entrance window of the proportional counter. The proton beam utilized had an energy of 44.3 ± 0.2 MeV and was generated by the Sector Focusing Cyclotron at the University of California, Los Angeles.

The proportional counter used in this investigation was cylindrical and fabricated from the same tissue-equivalent material which was used for the absorbers. The pathlength of the particles through the counter was accurately defined by the coincidence system described in (6). The filling gas was an equimolar He-CO_2 mixture at a pressure of 20 torr. The electron density of this gas is 3.01×10^{23} electrons/g. The experimental distributions were measured for a pathlength equivalent to 0.590×10^{-4} g/cm^2 of unit density tissue. Exit and entrance windows were fabricated from 0.00025" aluminized mylar. Sufficient events were examined to provide reasonably good statistics over the entire range of energy events recorded. In each case approximately 10^4 events were collected in the channel corresponding to the most probable energy loss.

RESULTS

The experimental data obtained is shown in Figs. 1, 2, and 3. All curves have been normalized so that the total probability for each is equal to unity. Fig. 1 shows the frequency distribution curves of the energy deposited in the sensitive volume after passage through various thicknesses of Shonka muscle varying from zero to 1.54 g/cm^2 (1.40 cm). Curve A represents the data obtained for the undegraded beam and Curves B, C, D, E, and F are after passage through 0.22 g/cm^2, 0.44 g/cm^2, 0.66 g/cm^2, 0.99 g/cm^2, and 1.54 g/cm^2, respectively.

After passage through sufficient material, degradation of the beam (energy spread of the primary protons entering the sensitive volume of the counter), produces a significant change in the energy deposition pattern. This results in a broader distribution function than would have been obtained from a primary proton beam whose energy was equal to that calculated from the residual range of the 44.3 MeV protons. This is illustrated in Figs. 2 and 3. Curve F of Fig. 1 is reproduced as Curve A in Fig. 2 and represents the frequency distribution obtained after passage through 1.54 g/cm^2 of Shonka muscle. Curves B and C of Fig. 2 are the distributions of energy loss after passage through 1.60 g/cm^2 and 1.63 g/cm^2, respectively. In Fig. 3 we have the frequency distributions obtained after passage of the beam through 1.63 g/cm^2, 1.74 g/cm^2, 1.79 g/cm^2, and 1.85 g/cm^2 of Shonka muscle shown as Curves A, B, C, and D.

The FWHM decreases steadily from a maximum for the undegraded beam through that value obtained after passage through 1.63 g/cm^2 (Curve D of Fig. 2 and Curve A of Fig. 3) then starts to increase again. This is a logical consequence of having introduced a significant spread of energies in the proton beam with a low energy tail.

The pertinent quantitative data obtained are given in Table I.

DISCUSSION

It is clear that for absorber thicknesses of less than approximately 1.6 g/cm^2 the statistical fluctuations in energy loss are the dominating factors in determining the character of the frequency distributions of energy loss by 45 MeV protons traversing short pathlengths. As expected, the distribution becomes narrower with decreasing beam energy and the average energy loss increases. This continues until the point where energy straggling of the incident beam becomes important. It appears from our data that a loss in proton energy of about 75 per cent is required to introduce a significant spread in beam energy. At this point the straggling has introduced a sufficient spread in energy, in particular a low energy tail, so that this becomes the dominant factor in determining the character of the energy deposition pattern. These factors are evidenced by the steady decrease in the width of the energy loss functions through the first 1.63 g/cm^2 of absorber thickness and the subsequent broadening of these with further degradation of the beam. Of prime importance is the fact that in no instance do these functions approach the narrow gaussian functions commonly attributed to energy deposition patterns. The observed broadness and character have important implications for concepts of radiation effects and radiobiological models which are based on the pattern of energy deposition in small volumes of biological significance.

A second important aspect of the data is the fact that for all distributions the most probable energy loss is significantly lower than the average energy loss. In a small volume or target and for an effect dependent on a single or small number of traversals, the actual dose delivered will be incorrectly inferred if absorbed dose (macroscopic) is used.

As previously pointed out by Baily, et al. (8), when the logarithm of the number of events in each channel or energy interval is plotted against energy the high energy tail portion is very well approximated by a straight line. In all cases investigated in this set of experiments (Table I), slope of this line is constant in the region governed by statistical fluctuations occurring in the amount of energy deposited in the counter gas. In the region where the behavior of the distribution functions is influenced by energy straggling of the beam this slope tends to decrease. Since this is a negative slope it means a relative increase in the number of high energy events which are due to the low energy tails of the primary distributions, and we therefore remain with rather broad distributions. There are indications that for high energy losses there is a sharp decrease in events, probably due to the loss of low energy primary protons which have suffered larger than average energy losses as a consequence of the straggling phenomenon.

We are not able to readily assess the influence of the loss of high energy delta rays on our experimental curves. As previously pointed out (8), such losses would cause a greater broadening of our distribution functions than presently observed and would therefore cause even greater discrepancies between theory and experiment than are now found. We are intending to investigate the distribution of energy losses by high energy secondaries through the use of a multiwire proportional counter. While both the spatial distribution and the energy deposited in various geometric volumes of these particles are of interest and possible importance to the understanding of the relationship between radiobiological effect and energy absorbed by specific biological targets, including these effects in the calculation is not expected to significantly alter the distribution functions presented in this paper.

CONCLUSIONS

1. Particle energy straggling of an initially monoenergetic proton beam after passage through an absorber causes the frequency distributions of energy deposited in short pathlengths of low atomic number materials to remain broad, even near the end of the particle range and in the region of the Bragg peak.

2. In all cases investigated the ratio of the most probable to the average energy losses has been significantly less than unity.

3. The slopes of the high energy tail portions of the frequency distribution functions are constant for all distribution functions whose shapes are governed by statistical fluctuations.

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TABLE I

$E_{proton} = 44.3 \pm 0.2$ MeV

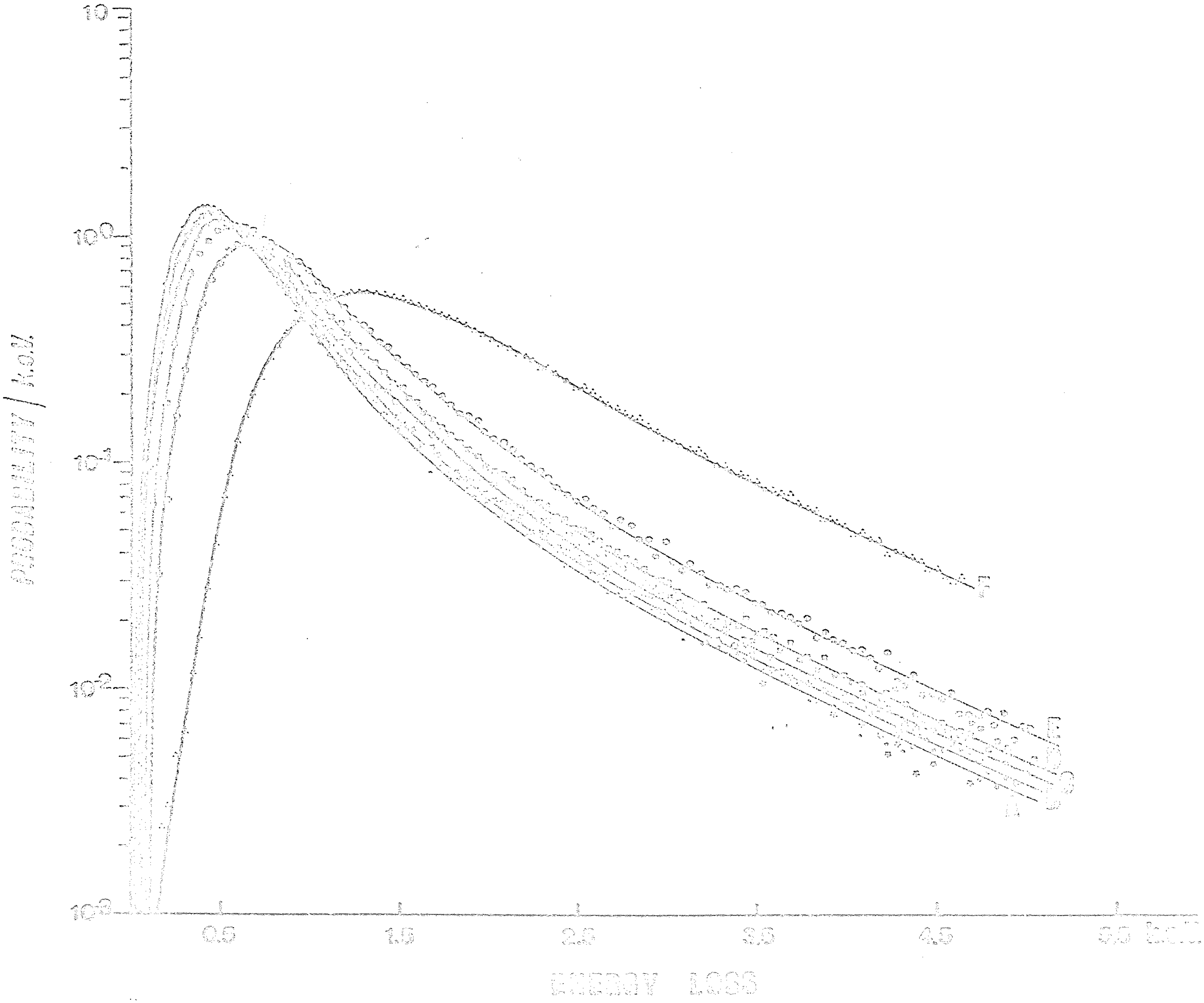
Absorber Thickness - Shonka Muscle (g/cm^2)	Average Energy Loss, $\overline{\Delta}$ (keV)	Most Probable Energy Loss, Δ_{mp} (keV)	$\Delta_{mp} / \overline{\Delta}$	Slope of High-Energy Tail (Prob./keV)/keV	FWHM %
0	0.809	0.43	0.53	0.86	133
0.22	0.856	0.46	0.54	0.85	130
0.44	0.919	0.53	0.58	0.86	126
0.66	0.997	0.61	0.61	0.87	118
0.99	1.17	0.72	0.62	0.84	114
1.54	1.95	1.30	0.67	0.86	111
1.60	2.20	1.50	0.68	0.88	109
1.63	2.94	2.15	0.73	0.55	100
1.74	4.13	3.00	0.73	0.55	113
1.79	5.67	3.90	0.69	0.47	129
1.85	8.49	6.10	0.72	0.41	136

FIGURE CAPTIONS

Fig. 1: Frequency distributions of energy loss in a pathlength of 0.667 x 10^{-4} g/cm^2 of He-CO$_2$ by 44.3 MeV protons after passage through various thicknesses of Shonka muscle. Curve A is for the undegraded beam. Curves B, C, D, E, and F are after passage through 0.22 g/cm^2, 0.44 g/cm^2, 0.66 g/cm^2, 0.99 g/cm^2, and 1.54 g/cm^2, respectively.

Fig. 2: Pathlength, proton energy, and absorbing material are the same as given for Fig. 1. Curves A, B, and C were obtained after passage of the beam through 1.54 g/cm^2, 1.60 g/cm^2, and 1.63 g/cm^2 of Shonka muscle, respectively.

Fig. 3: Pathlength, proton energy, and absorbing material are the same as given for Fig. 1. Curves A, B, C, and D were obtained after passage of the protons through 1.63 g/cm^2, 1.74 g/cm^2, 1.79 g/cm^2, and 1.85 g/cm^2 respectively of Shonka muscle.


10
10^0
10^{-1}
10^{-2}
10^{-3}
PROBABILITY / keV
0.5
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2.5
3.5
4.5
5.5 keV
ENERGY LOSS
F
E
D
C
B
A

Fig. 1

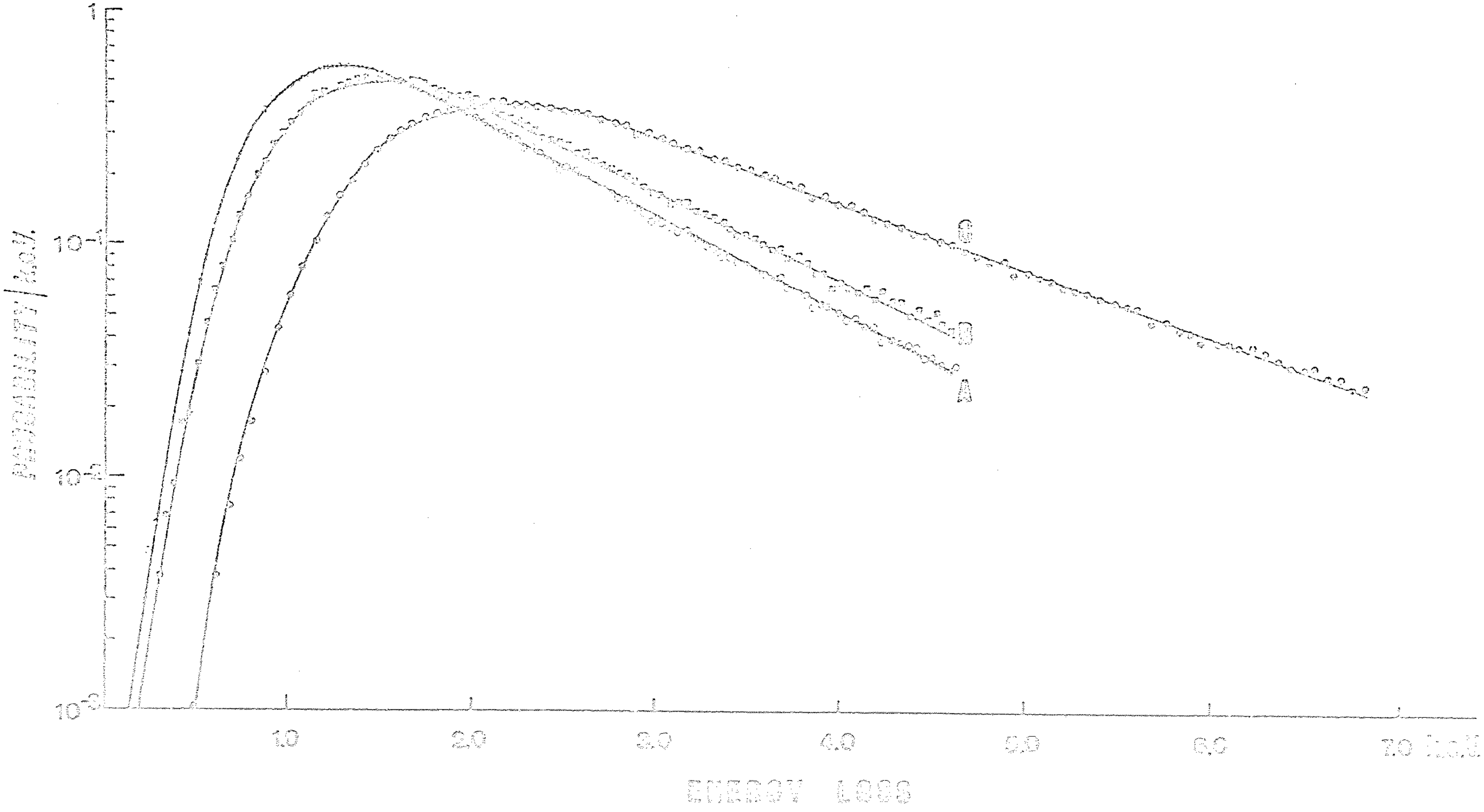
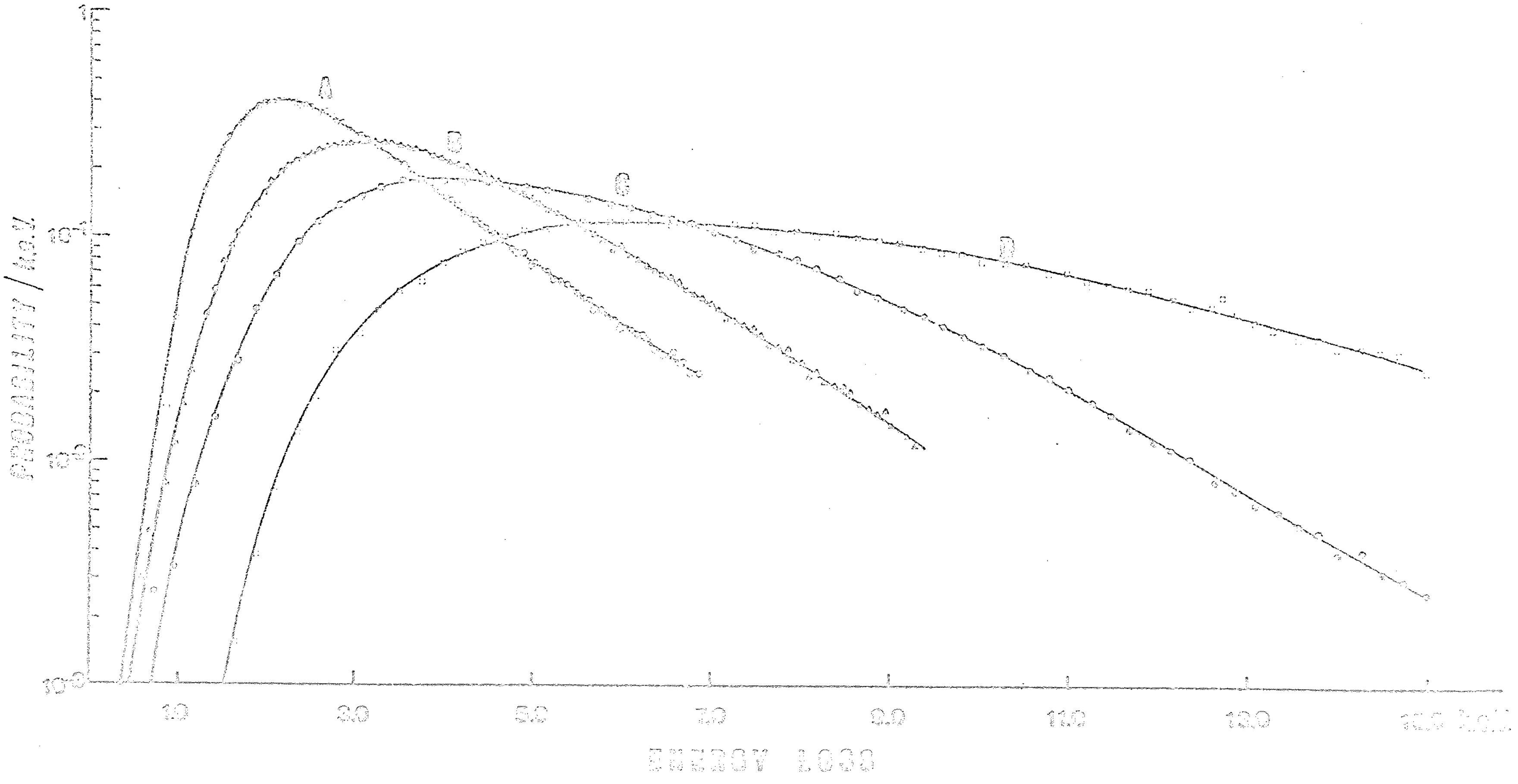

1
10^{-1}
10^{-2}
10^{-3}
PROBABILITY / keV
C
B
A
1.0
2.0
3.0
4.0
5.0
6.0
7.0 keV
ENERGY LOSS

Fig. 2


1
10^{-1}
10^{-2}
10^{-3}
PROBABILITY / keV
A
B
C
D
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3.0
5.0
7.0
9.0
11.0
13.0
15.0 keV
ENERGY LOSS

FIG. 3