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Update of Neutron Dose Yields as a Function of Energy for Protons and Deuterons Incident on Beryllium Targets.

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INTRODUCTION

A large fraction of the world's cancer neutron therapy experience has been gained utilizing neutrons produced from low energy deuterons bombarding tritium targets,[1,2] or from accelerator produced deuterons impinging upon beryllium targets.[3] The neutron beams thus produced have generally exhibited low penetration and poor skin sparing. The present trend for cyclotron based facilities is toward the use of higher energy proton beams on beryllium targets.[4] Since cyclotrons accelerate hydrogen isotopes to approximately the same momentum, protons with maximum energies nearly twice that of deuterons may be obtained from the same machine. Moreover, a greater fraction of the neutrons from p+Be have energies close to the kinematic limit than do neutrons from d+Be.[5,6] Thus, higher incident proton energies lead to neutron beams with higher average energy and greater penetration in tissue.

Neutron absorbed dose yields (absorbed dose rates per unit incident current on targets at a given SAD or SSD) increase with incident charged particle energy for both protons and deuterons.[5] Analyses of neutron dose yield versus incident particle energy have been performed for both deuterons[7-9], and protons.[5] It is the purpose of this report to update those analyses by pooling all of the more recent published results [10-16] and to reanalyse the trend of yield, Y, versus incident energy, E, which in the past has been described by an expression of the form[8,9]

$$Y = aE^b, \quad (1)$$

where a and b are empirical constants. From the reanalysed trend it is concluded that for a given size cyclotron ($E_p=2E_d$), the dose yields using protons are higher than those using deuterons up to a proton energy E_p of 64 MeV.

DATA COLLECTION

All dose yields were obtained from published results of measurements with collimated neutron beams. All values are for either protons or deuterons incident on thick beryllium targets (the p[66 MeV] point is for a 49 MeV thick target).

Most of the deuteron points were measured at 125 cm SAD with a 5x5 cm^2 field. Some older deuteron data[7,17-20] were not included in an earlier analysis by Smathers et al.[9] due to their understanding that at least some of the data[7,18] were obtained under poor experimental conditions. The same data[7,17-20] were not included here. The p+Be neutron dose yields were measured at many SSD's, both in air and at d_{max} in a phantom, for various field sizes, 10x10 cm^2 being most common. All data were corrected to 125 cm SAD by $1/R^2$ and plotted as representing tissue dose rate per unit charged particle current at the incident energy indicated, although variations due to beam size and measurement techniques surely exist.

RESULTS

Yield values for SAD = 125 cm are listed in Table 1 (d+Be), Table 2 (p+Be) and plotted in Fig. 1. The keys to the symbols used in Fig. 1 are found in Tables 1 and 2. Since some published data were only presented in graphical form some of the tabulated values represent the authors' best estimates of yields.

ANALYSIS AND DISCUSSION

The natural logarithms of both the yield (Gy min^{-1} μA^{-1}) and energy (MeV) values were fitted by linear regression to a version of Eq. 1,

$$\ell n\,(Y) = b\,\ell n\,(E) + \ell n\,(a)\ . \qquad (2)$$

The yield equations thus obtained are:

$$Y_d = 1.28 \times 10^{-6}\ E_d^{\,2.99} \quad \text{, for deuterons} \qquad (3)$$

and

$$Y_p = 2.15 \times 10^{-6}\ E_p^{\,2.37} \quad \text{, for protons} \qquad (4)$$

These yields are plotted as straight lines in Fig. 1. The correlation coefficients for the two fits are .998 and .992, respectively.

As mentioned earlier, the data used in the fits have unquoted uncertainties and were measured under widely varying conditions. Therefore, expressions (3) and (4) should be used with caution. The deuteron parameters compare very well with those previously reported by Smathers _et al._[9] ($a_d = 1.356 \times 10^{-6}$, $b_d = 2.97$) and August _et al._[8] ($a_d = 1.24 \times 10^{-6}$, $b_d = 2.99$).

Table 1

d+Be Dose Yield Data

Reference	First Author	Incident Energy (MeV)	Yield at 125cm ($Gy\ min^{-1}\ \mu A^{-1}$)	Figure 1 Symbol
9	Smathers (TAMVEC II)	50	.146	○
		35	.0566	
		31	.0352	
		20	.0103	
		16	.0054	
9	Smathers (Barshall)	20	.0089	△
		17	.0058	
		14	.0034	
		11	.00175	
8	August	40	.0741	□
		38	.0680	
		34	.0493	
		31	.0351	
		25	.0195	
		20	.0102	
		14.75	.0038	
10	Waterman	28	.0291	▲
		16	.0055	
11	Quam	35	.0602	■
5	Amols	35	.0624	●
12	Wambersie	50	.157	⬢

Table 2

p+Be Dose Yield Data

Reference	First Author	Incident Energy (MeV)	Yield at 125cm Gy min^{-1} μA^{-1}	Figure 1 Symbol
5	Amols	35 65 66	.0096 .0342 .0433	O
11	Quam	26 35 45	.00446 .0111 .0208	■
10	Waterman	35 46	.0094 .0206	Δ
13	Bewley	45 75	.0208 .0601	+
14	Goodhead	26	.0045	X
15	Johnson	26	.0048	⬢
16	Awschalom	42	.0167	≡

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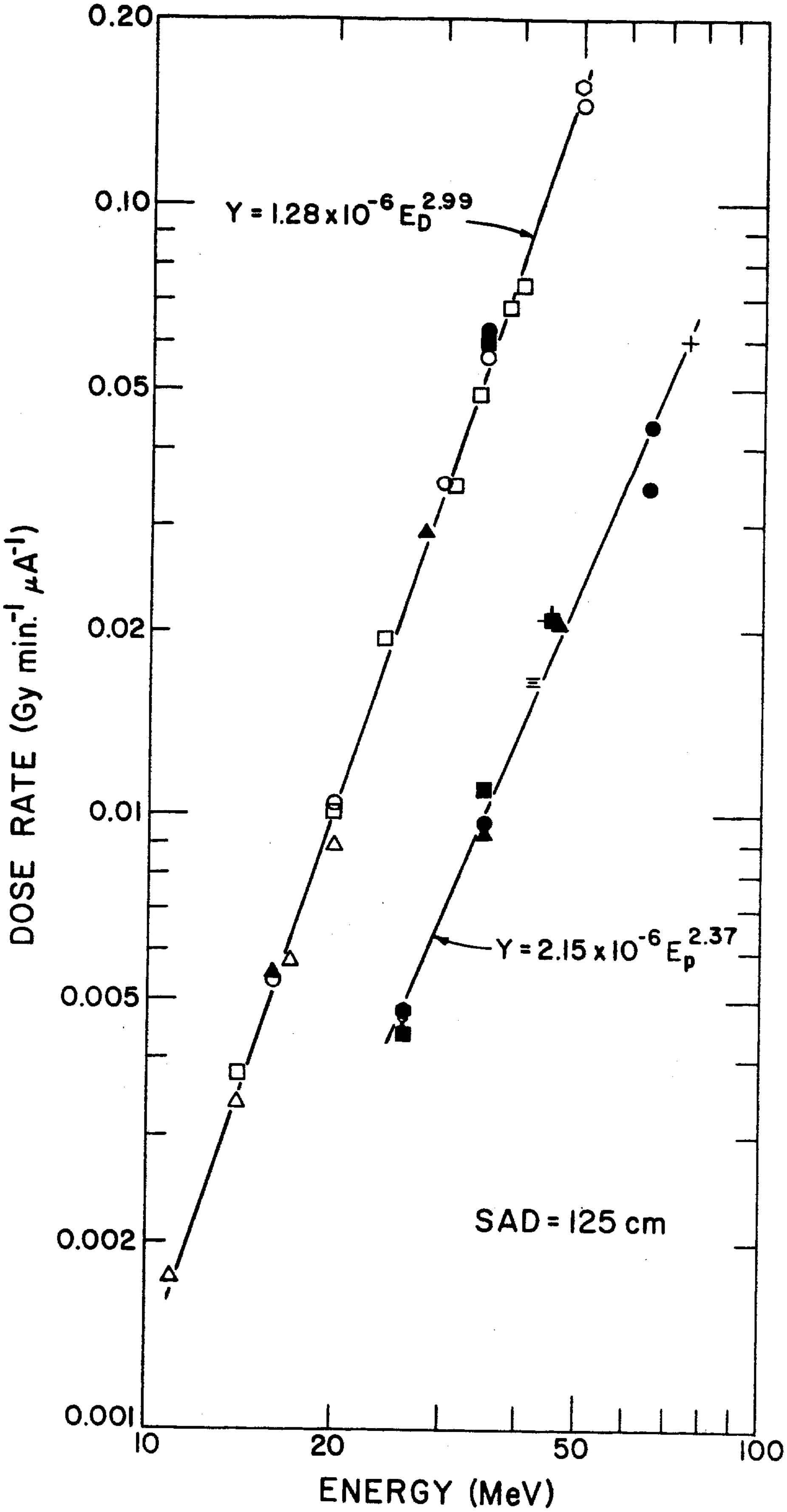
FIGURE CAPTIONS

Figure 1. Dose yield (maximum dose to tissue per incident charged particle current) versus incident charged particle energy for collimated neutron beams generated by deuterons and protons incident on thick beryllium targets. The symbols are referenced in Tables 1 and 2.


0.20
0.10
0.05
0.02
0.01
0.005
0.002
0.001
10
20
50
100
ENERGY (MeV)
DOSE RATE (Gy min.$^{-1}$ μA^{-1})
Y = 1.28 x 10^{-6} $E_D^{2.99}$
Y = 2.15 x 10^{-6} $E_p^{2.37}$
SAD = 125 cm