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ENERGY LOSS OF ALPHA PARTICLES IN TISSUE

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Summary

Stopping powers of alpha particles have been measured for CO_2, O_2, N_2, CH_4 over an energy range from 0.1 to 5.3 MeV. From these measurements atomic stopping cross sections of alpha particles in tissue (H:10.1%, C:12.1%, N:4.0%, O:73.6% by weight) have been evaluated. Around 1 MeV the results are as much as 50% higher than those calculated by Neufeld and Snyder, assuming that the stopping power of an ion is given by the product of the proton specific stopping power and the average of the square of the charge of the ion.

1. Introduction:

Biological damage produced by charged particles in tissue depends on the absorbed dose delivered and on the linear energy transfer (LET). This paper takes into consideration only alpha particles because of their importance in radiological problems, such as in thermal neutron capture therapy, π^- meson capture therapy, and in contamination problems which may arise around nuclear reactors and isotope laboratories. As an aid in the assessment of such dose evaluation problems, the stopping power of α particles in CO_2, O_2, N_2, CH_4, has been measured. Making certain assumptions, the atomic stopping cross-section of α particles in a medium like human soft tissue of composition (H:10.1%, C:12.1%, N:4.0%, 0.73.6% by weight[1]) has been evaluated.

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2. Stopping power of heavy charged particles in tissue:

The energy loss of a heavy charged particle is due mainly to interactions with electrons and with whole atoms of the medium traversed. The first process, electronic collisions, produces ionization and excitation of the atoms of the medium. The second process, atomic collision, produces elastic transfer of momentum and kinetic energy to the struck atom. The latter process becomes appreciable when the velocity of a moving ion is considerably lower than the "unit atomic velocity" ($e^2/\hbar$). This unit corresponds to the velocity of an orbital electron in a hydrogen atom and is $2.187 \cdot 10^8$ cm/sec. Moreover, at low energy an ion passing through matter shows a charge fluctuation due to capture and loss of orbital electrons.

A general method for determining the energy loss of heavy ions in tissue has been outlined by Neufeld and Snyder[2]. This method is based on the assumption used by others[3] that the electronic stopping power dE/dx of an incident ion is represented by

$$\frac{dE}{dx} = \overline{q^2}\, K_s \qquad (1)$$

where $\overline{q^2}$ is the average of the square of the charge of the moving ion and K_s, defined as the specific energy loss, represents the electronic stopping cross section corresponding to a moving ion of unit charge in a medium comprising atoms of type s. The specific energy loss, K_s, for a given medium has been evaluated by dividing the experimental proton stopping power by the average square charge of the proton.

Once K_s is known the stopping power for any ion can be calculated from (1) using experimental information on $\overline{q^2}$ for the ion in consideration. Consequently, the energy loss in tissue is given by

(2) $$\frac{dE}{dx} = \Sigma_s N_s \overline{q^2} K_s$$

where N_s is the number of atoms of type s per cm^3 of tissue.

This procedure as pointed out by the authors is not experimentally vindicated and thus can only be considered as a means of estimating the LET in an approximate way.

3. Experimental procedure and results:

The apparatus, reported in a previous work[4], consists of a variable pressure gas cell in which α particles from a ^{210}Po source lose their energy, and of a semiconductor detector at a fixed distance from the source for measuring the residual α energy. The results of the measurements in various gases are shown in fig. 1, where the curves give the remaining energy of α particles after they have traversed different thicknesses X of a gas at 15°C temperature and 76 cm Hg of pressure. By differentiation of the curves in fig. 1 and by successive path normalization the stopping powers of α particles in CO_2, O_2, N_2, CH_4 have been obtained. The results are given in fig. 2, 3, 4, 5 as function of α particle energy.

4. Stopping of α particles in tissue:

In evaluating the stopping power of α particles in tissue, it is assumed that tissue is a homogeneous mixture of hydrogen, carbon, nitrogen and oxygen with the composition by weight mentioned above. To proceed further, the following assumptions are made: 1) that the stopping power is independent of the state of condensation of the medium, 2) that Bragg's additivity law of stopping power is valid. As far as point 1) is concerned, experimental evidence relating to light elements is not very conclusive[5,6,7]. Regarding point 2), no deviation has been found for α particles of 5 MeV[8]; for energies less than 5 MeV deviations are of the order of a few per cent[9,10,11].

From the curves of fig. 1, 2, 3, 4 the molecular stopping cross sections for CO_2, O_2, N_2 and CH_4 designated respectively as S_{CO_2}, S_{O_2}, S_{N_2}, and S_{CH_4} are obtained by dividing dE/dx by the number of molecules per cubic centimeter. A gram of tissue can be realized adding n_1 molecules of CH_4, n_2 molecules of O_2, n_3 molecules of N_2 and subtracting n_4 molecules of CO_2. Then the atomic stopping cross section for α particles in tissue becomes:

$$(3) \quad S_\alpha = \frac{n_1 \times S_{CH_4} + n_2 \times S_{O_2} + n_3 \times S_{N_2} - n_4 \times S_{CO_2}}{N} \text{ MeV cm}^2$$

where $n_1 = 152 \times 10^{20}$
$n_2 = 230 \times 10^{20}$
$n_3 = 8.6 \times 10^{20}$
$n_4 = 91.3 \times 10^{20}$
$N = n_1 \times 5 + n_2 \times 2 + n_3 \times 2 - n_4 \times 3 = 963 \times 10^{20}$

Fig. 6 (full circles) shows the atomic stopping cross section for α particles in tissue obtained using the formula (3) and given as a function of the particle speed expressed in atomic units (e^2/n). A comparison with values given by Neufeld and Snyder(2) shows that the present results are higher by as much as 50% at 1 MeV.

The open circles in fig. 6 represent the atomic stopping cross sections obtained by inserting into the formula (3) the molecular stopping cross sections as given by Whaling(12) in CO_2, O_2, N_2, CH_4 for α particles > 2 MeV. Over the limited range of comparison good agreement with the present work is shown.

A further examination of the results may also take into consideration the ratio S_α/S_p of the atomic cross sections for an α particle and a proton of the same velocity. Since the present work is limited to α particles, S_p for protons in tissue has been obtained with formula (3) using the experimental molecular stopping cross section for protons in CO_2, O_2, N_2, CH_4 as reported by others[12,13]. These results for protons, shown in fig. 7, are in agreement with those given by Neufeld and Snyder[2], obtained by the general method mentioned in Section 2. Then the ratio S_α/S_p has been calculated using S_α from present work, as well as using S_α from Neufeld and Snyder. The results, given in fig. 8, show that S_α/S_p from present work (full circles) is considerably higher than the one derived from Neufeld and Snyder (dashed line). For comparison, the ratio S_α/S_p (full line) as given in Whaling's review[12] is also shown. The Whaling ratios represent the average experimental values of S_α/S_p averaged over all stopping materials, on the assumption that S_α/S_p is a function of the ion velocity alone. The agreement with present calculations is quite satisfactory.

5. Conclusions:

The atomic stopping cross section for α particles in tissue presented in this paper differs from that previously calculated. The method used for α-particles by Neufeld and Snyder gives lower values in the energy range where difficulties arise in the estimation of capture and loss of electrons and use has to be made of the mean square charge $\overline{q^2}$. This suggests that in addition to the approximation of formula (1), the experimental values of $\overline{q^2}$ used for α particles could have produced the discrepancy of the results.

The formula (1), although not rigorous, is simple and useful, but the results are strictly dependent on the mean square charge of the proton to obtain K_s, and then on the mean square charge of the moving ion to get the corresponding stopping power.

The present measurements on α particles have clarified the difficulties in assessing dose evaluation in human soft tissue. In view of the biological significance of the processes involved, the higher atomic cross sections found here require a change in the estimates of the dose equivalent deposited by α particles in tissue.

6. Acknowledgements:

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FIGURE CAPTIONS:

Fig. 1 Remaining energy of Po^{210} alpha particle beam after traversing a certain path X of gas. The circles represent the experimental points, their error is equal or less than the diameter.

Fig. 2 Energy loss of alpha particles in CO_2.

Fig. 3 Energy loss of alpha particles in O_2.

Fig. 4 Energy loss of alpha particles in N_2.

Fig. 5 Energy loss of alpha particles in CH_4.

Fig. 6 Atomic stopping cross section of alpha particles in tissue.

Fig. 7 Atomic stopping cross section of protons in tissue.

Fig. 8 Atomic stopping cross section ratio S_α/S_p for alpha particles and protons of the same velocity.

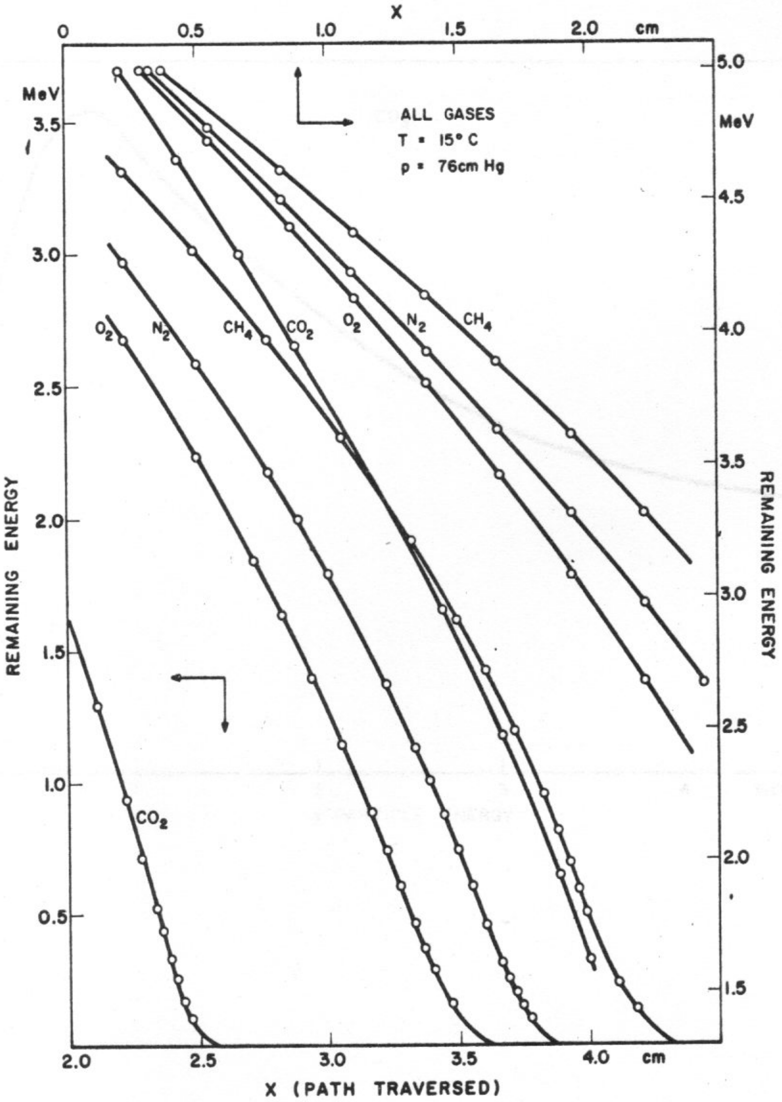

X
0
0.5
1.0
1.5
2.0
cm
MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
REMAINING ENERGY
ALL GASES
T = 15° C
p = 76cm Hg
5.0
MeV
4.5
4.0
3.5
3.0
2.5
2.0
1.5
REMAINING ENERGY
O2
N2
CH4
CO2
O2
N2
CH4
CO2
2.0
2.5
3.0
3.5
4.0
cm
X (PATH TRAVERSED)

FIG. 1

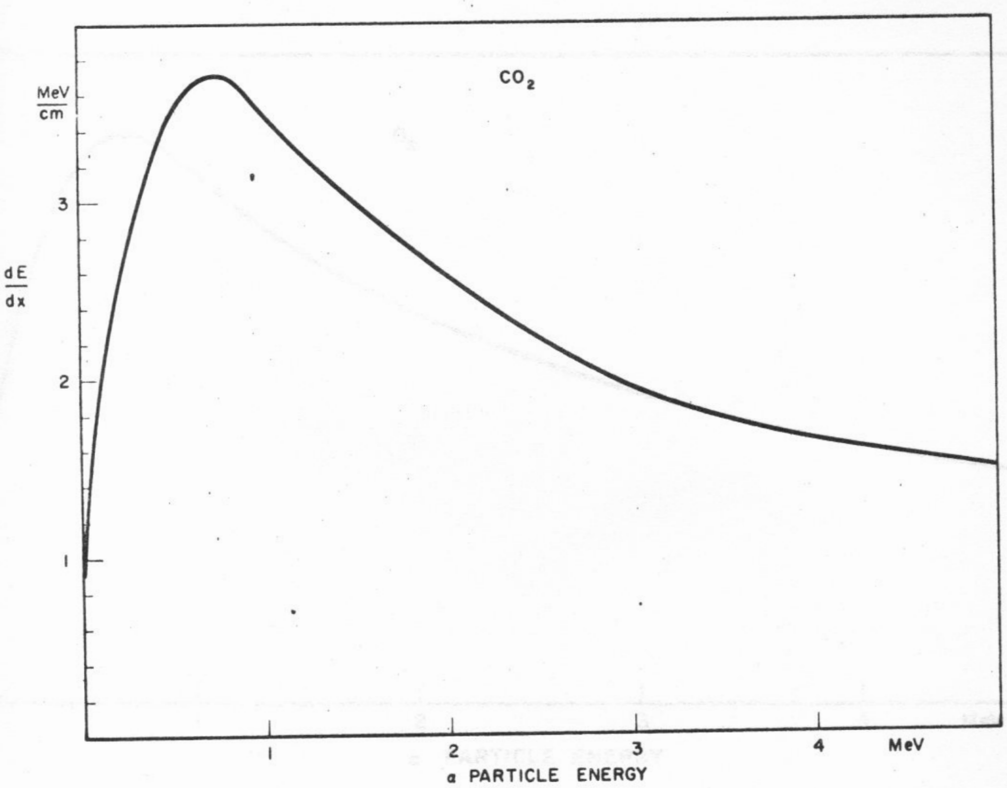


FIG. 2

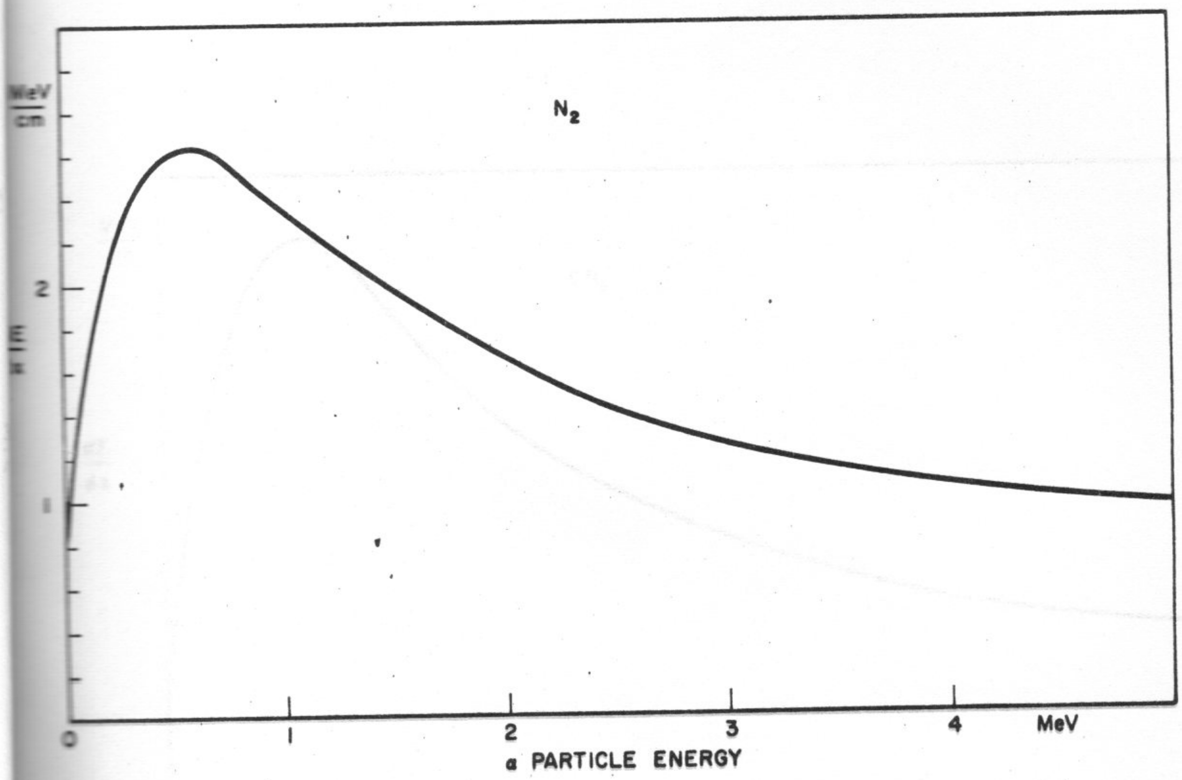


FIG. 4

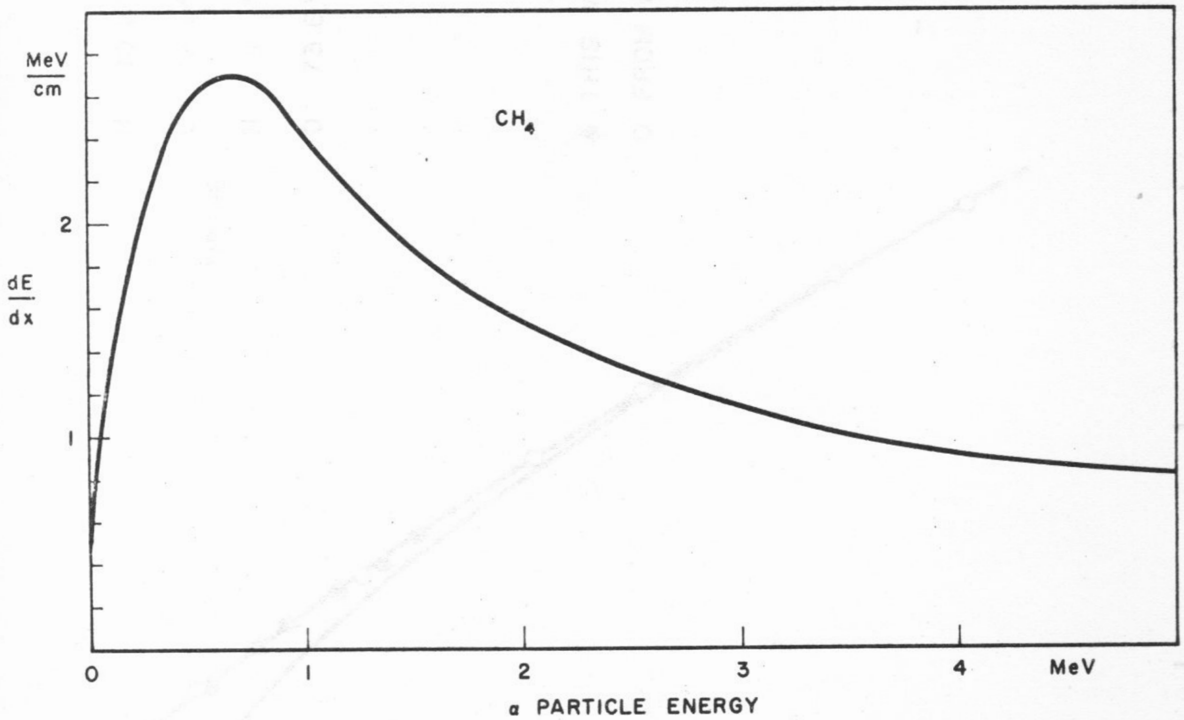
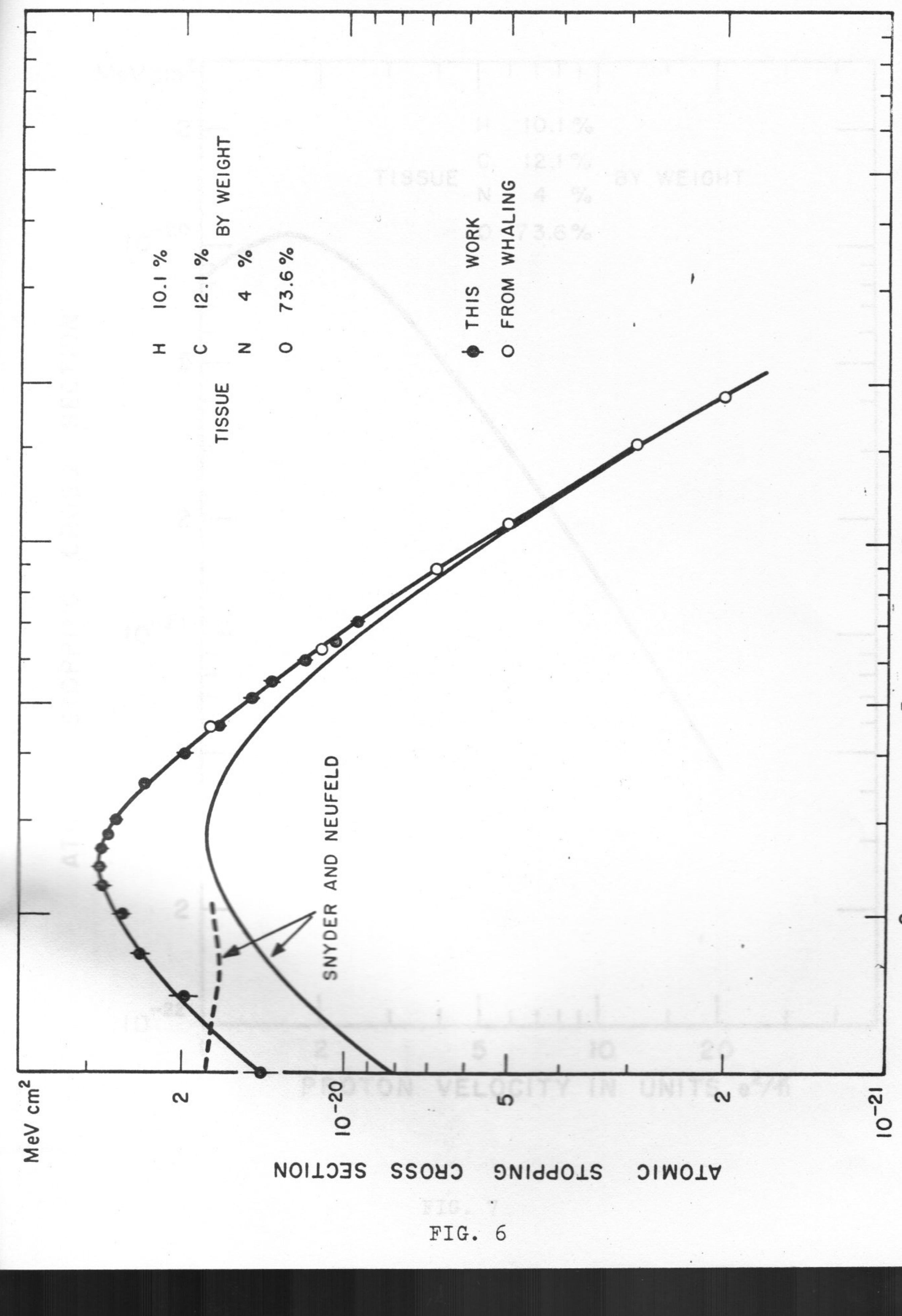


FIG. 5



ATOMIC STOPPING CROSS SECTION
MeV cm²
2
10⁻²⁰
5
2
10⁻²¹
TISSUE
H 10.1 %
C 12.1 %
N 4 %
O 73.6 %
BY WEIGHT
THIS WORK
O FROM WHALING
SNYDER AND NEUFELD
α PARTICLE VELOCITY IN UNITS e²/ħ
2
5
10
20
50

FIG. 6

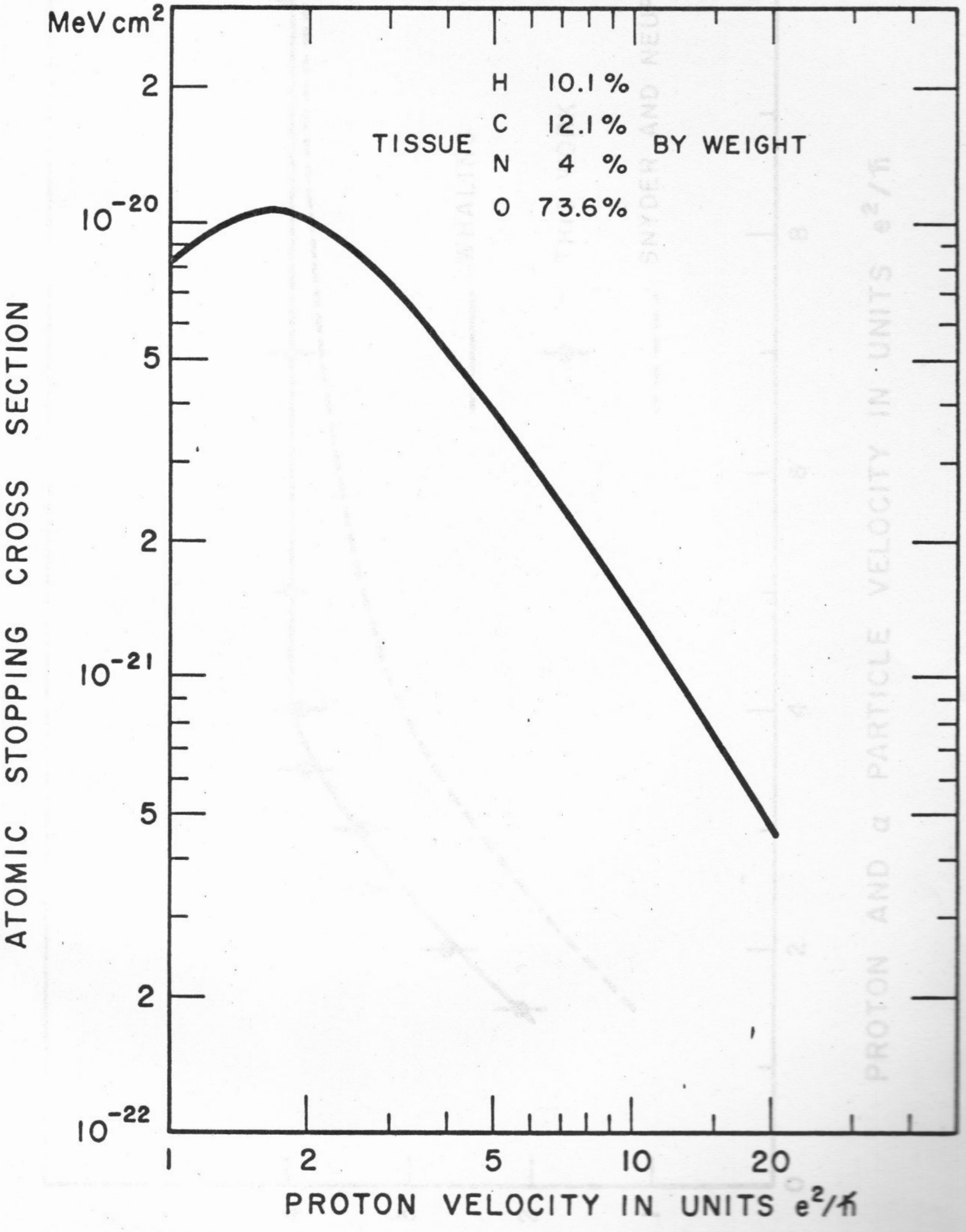
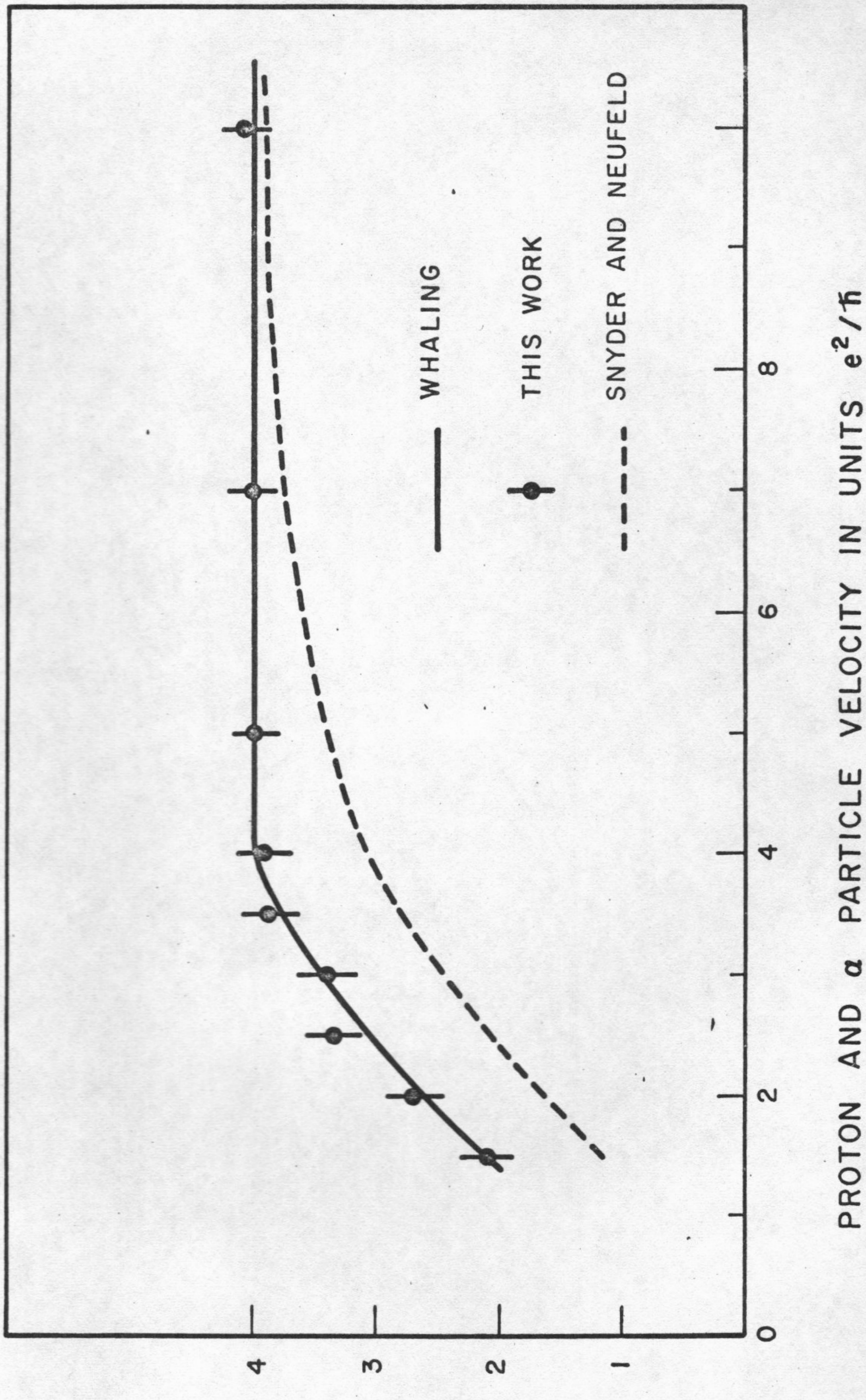

MeV cm²
2
10⁻²⁰
5
2
10⁻²¹
5
2
10⁻²²
ATOMIC STOPPING CROSS SECTION
H 10.1 %
C 12.1 %
N 4 %
O 73.6 %
TISSUE
BY WEIGHT
1
2
5
10
20
PROTON VELOCITY IN UNITS e²/ħ

FIG. 7



$\frac{S\alpha}{Sp}$
1
2
3
4
0
2
4
6
8
WHALING
THIS WORK
SNYDER AND NEUFELD
PROTON AND α PARTICLE VELOCITY IN UNITS $e^2/\hbar$

FIG. 8