Pertanika 15(1), 55-59 (1992)

Calculation of the Effective Stopping Power of Ions Generated by Neutrons in Tissue Constituents

ELIAS SAION
Department of Physics
Faculty of Science and Environmental Studies
Universiti Pertanian Malaysia
43400 UPM Serdang, Selangor Darul Ehsan, Malaysia

D.E. WATT
Director and Safety Advisor
Environmental Health and Safety Services
University of St. Andrews
St. Andrews, Fife, KY16 9TS, United Kingdom

Key words: stopping powers, heavy charged particles, Ziegler's universal screening length.

ABSTRAK

Kertas ini melaporkan pengiraan kuasa penghenti zarah-zarah bercas berat yang tersentak oleh neutron dalam empat-unsur kandungan tisu bagi tenaga zarah daripada 0.1 keV hingga 1.0 MeV. Pada tenaga rendah kurang daripada 30 keV/amu yang mana proses penghenti nukleus lebih berperanan daripada proses penghenti elektron, nilai kuasa penghenti berkesan lebih tinggi daripada nilai pendekatan perlambatan selanjarnya (PPS). Sisihan di antara kedua-dua nilai ini bergantung kepada jisim sasaran dan juga tenaga serta jisim zarah.

ABSTRACT

This paper reports the calculation of stopping powers of heavy charged particles generated by neutrons in four-element tissue constituents for particle energies from 0.1 keV to 1.0 MeV. At low projectile energies of less than 30 keV/amu where the nuclear stopping phenomenon is more dominant than the electronic stopping phenomenon, the effective stopping power values are higher than the continuous slowing-down approximation (CSDA) values, from which the deviation is dependent upon the target mass and the energy and mass of the projectiles.

INTRODUCTION

Knowledge of stopping powers and projected ranges of low-energy secondary charged particles is very important for accurate prediction of energy deposition by intermediate energy neutrons in tissue (Al-Affan *et al.* 1984). Intermediate energy neutrons slow down in tissue matter to generate short-range heavy charged particle recoils which have ranges less than the cellular dimension of most mammalian cells. The radiation quality of these neutrons, however, is not fully defined for radiation protection purposes although charged particles generated by these neutrons are known to be capable of producing biological effects (Jung and Zimmer 1966; Al-Kazwini *et al.* 1988). Some have reported an increase in the radiobiological effectiveness (RBE) of intermediate energy neutrons of energies less than 100 keV (Key 1971; Mill 1986).

The penetration of charged particles through matter is a complex phenomenon which can be measured in terms of stopping power and projected ranges. In the region where projectile velocities, v, are greater than the electronic orbital velocity, v_0 (= $2\pi e^2/ h$ = 25 keV/amu) the path length of ions in matter is a straight line. However, in the low energy region, i.e. $v < v_0$, the pathlength is no longer a straight line but a complex form (Cook *et al.* 1953) due to various interaction processes such as elastic collision with the target atom, inelastic collision with electrons, charge exchange and chemical binding effects. In general, there is competition between the loss of energy of charged particles to electrons and to recoil particles (Lindhard and Scharff 1961). The particles undergo successive small angle scattering known as multiple scattering which may produce recoils deflected in the direction inside the medium, increasing the stopping cross section per atom. The scattering angle becomes larger as the particle energy decreases. The particles travel in a zig-zag path which partly explains the difference between the projected range and path length of ions at low energies. The difference is very significant at energies where quasi-elastic scattering becomes dominant (Watt 1972).

The projected range is an average thickness of material traversed by a number of particles directed perpendicular to the material surface. The effective stopping power is the energy loss per unit length along this projected range. For low energy ions the effective stopping power value is greater than the continuous slowing down approximation (CSDA) value because of the significant importance of elastic scattering collisions with nuclei of the target materials and range of straggling. In the region where nuclear stopping becomes more dominant than electronic stopping, and experimental stopping-power data is lacking, the stopping process of charged particles in matter is not fully understood and here, an attempt is made to include the effective nuclear stopping in the general stopping power formula. However, for ions at high energies, the effective stopping power will be the same as the CSDA stopping power because the loss of energy there is mainly due to collisions with atomic electrons.

MATERIALS AND METHODS

Calculation of Effective Stopping Power

The effective stopping power, ${}^{i}S_j^{eff}$ (E), can be determined according to Watt and Sutcliffe (1972) in a manner similar to that adopted by Al-Affan *et al.* (1984).

$$ {}^{i}S_j^{eff}\left(E\right) = \frac{{}^{i}S_j^{n}\left(E\right)}{2\gamma f\left(x\right)} + {}^{i}S_j^{e}\left(E\right) \qquad (1) $$

where E is the energy of the recoil particle, ${}^{i}S_j^{n}$ (E) and ${}^{i}S_j^{e}$ (E) are the nuclear and electronic stopping powers of recoil particle type i in the atom type j respectively. $\gamma^2 = 4\, m_i\, m_j / (m_i + m_j)^2$ with m_i and m_j being masses of particle i and target j respectively. f(x) is the function which converts the effective stopping power of nuclear stopping and is given as

$$ f(x) = 0.021\,[\ln(m_i/m_j)]^2 - 0.1434\,[\ln(m_i/m_j)] + 0.3642 \qquad (2) $$

Ziegler *et al.* (1985) introduced a new universal screening length, $a_z = 0.8854a_0/(Z_i^{0.23} + Z_j^{0.23})$, where Z_i and Z_j are the atomic number of recoil ion type i and target atom type j respectively. The corresponding screening function produces a tight grouping with a standard deviation of 18%, better than the one derived from a well-known Lindhard's screening length, $a_L = 0.8854a_0/(Z_i^{2/3} + Z_j^{2/3})^{1/2}$, which has standard deviation of 40%. They found that their fitting universal screening function is in good agreement with the experimental data within 5% of the standard deviation. The reduced energy, ε_z, for ions of energy E (keV), in terms of Ziegler's screening length is given by

$$ \varepsilon_z = \frac{32.53\, m_j\, E}{Z_i Z_j (m_i + m_j)(Z_i^{0.23} + Z_j^{0.23})} \qquad (3) $$

The total stopping power is the sum of the nuclear and electronic stopping powers expressed in terms of Ziegler's reduced energy by

$$ {}^{i}S_j\,(E) = \frac{8.462\times 10^{-15}\, Z_i Z_j m_i}{(m_i + m_j)(Z_i^{0.23} + Z_j^{0.23})} \times \left[\mathrm{Sn}(\varepsilon_z) + \mathrm{Se}(\varepsilon_z)\right] \qquad (4) $$

where Sn and Se are reduced nuclear and electronic stopping power respectively. The reduced nuclear stopping power is given by Ziegler in equations (5) and (6) for low and high energy ions respectively.

$$ \mathrm{Sn}(\varepsilon_z) = \frac{\ln\left(1 + 1.1383\,\varepsilon_z\right)}{2\left[\varepsilon_z + 0.01321\,\varepsilon_z^{0.21226} + 0.19593^{0.5}\right]} \qquad (5) $$

for $\varepsilon_z \leq 30$ keV/amu

$$ \mathrm{Sn}\left(\varepsilon_z\right) = \frac{\ln\left(\varepsilon_z\right)}{2\,\varepsilon_z} \quad \text{for } \varepsilon_z > 30 \text{ keV/amu} \qquad (6) $$

The corresponding reduced electronic stopping power can be expressed accordingly in terms of Ziegler's screening length by

$$ \mathrm{Se}(\varepsilon_z) = \frac{7.93 \times 10^{-2}\, Z_i^{2/3}\, Z_j^{1/2}\left(m_i + m_j\right)^{3/2} \varepsilon_z^{1/2}}{m_i^{3/2}\, m_j^{2/3}\left(Z_i^{0.23} + Z_j^{0.23}\right)} \qquad (7) $$

(Note the occurrence of $Z^{-0.23}$ replacing $Z^{-1/3}$ in the expression given by Watt and Sutcliffe (1972)).

In the high energy region, however, the contribution from nuclear stopping is very small and can be neglected. Therefore, one needs to consider only the electronic stopping power and this can be calculated according to the Bethe formula or by Ziegler's code (1985). The latter has been adopted in this work.

The effective stopping powers of heavy recoil ions (i.e. protons, C, N, O) in tissue constituents (i.e. hydrogen, carbon, nitrogen and oxygen) have been determined. Except for recoil protons, the CSDA nuclear stopping power for C, N and O ions was calculated according to equations (5), (6) and the first term of equation (4). The electronic stopping powers of energies of less than 30 keV/amu were calculated according to equation (7) and the second term of equation (4). The choice of energy cut off corresponds to the ion velocity of about 2.25 x 10^6 m s^{-1}. The electronic stopping powers for ions in the high energy region were calculated according to Ziegler's code. Normalization was performed to connect smoothly the stopping power values below 30 keV/amu to Ziegler's stopping powers for every ion interacting on each target.

For protons in four-element tissue constituents, the CSDA stopping powers were obtained by fitting data of the International Committee on Radiation Units and Measurements (ICRU) (Berger 1986), for energies from 1 keV to 20 MeV. The fitting results produced deviation of less than 1%. Consequently, the effective stopping power of ions in four-element tissue constituents was calculated according to equation (1).

RESULTS AND DISCUSSION

The effective and CSDA stopping power values calculated for recoil ions of energy from 0.1 keV to 1 MeV in hydrogen, carbon, nitrogen and oxygen are shown in *Figs. 1, 2, 3 and 4* respectively. The effective and CSDA stopping power values are indicated by S_{eff} (solid lines) and S_{csda} (broken lines) respectively. For nitrogen and oxygen ions, the values have been multiplied by factors of 10 and 100 respectively for graphic purposes only. The results are compared with published experimental data as indicated on each figure. The theoretical calculations of Oldenburg and Booz (1972) are also shown.

The effective stopping power values, as expected, are higher than the CSDA stopping power values. As we can see from the figures, the deviation at the low energy region for a given recoil increases with the target mass and decreases as the projectile energy increases. Also, the deviation for a given target decreases with the mass of the projectile. The deviation is largest for protons

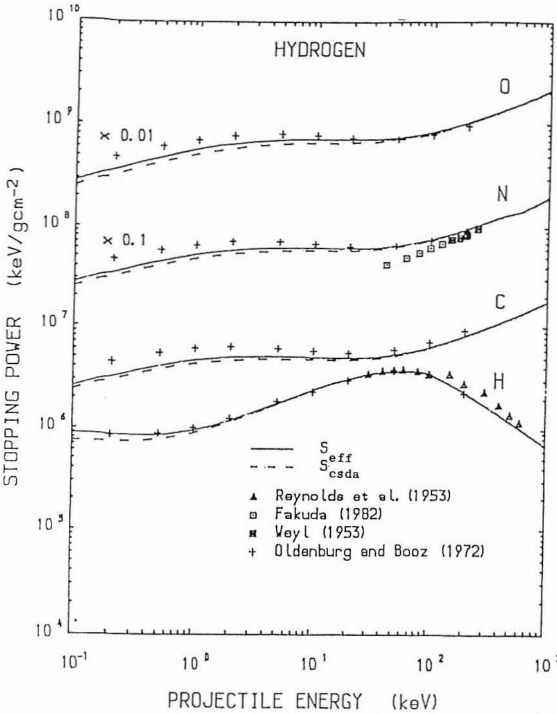

Fig. 1: The calculated effective and CSDA values of stopping powers for heavy ions (proton, C, N and O) in hydrogen

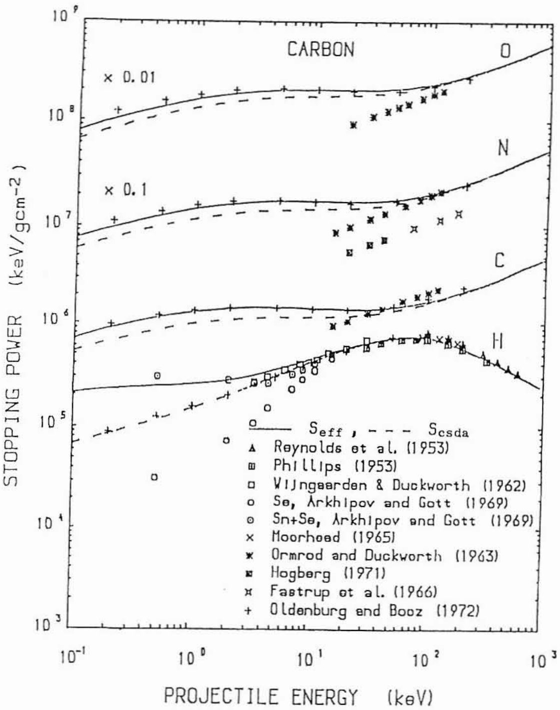

Fig. 2: The calculated effective and CSDA values of stopping powers for heavy ions (proton, C, N and O) in carbon

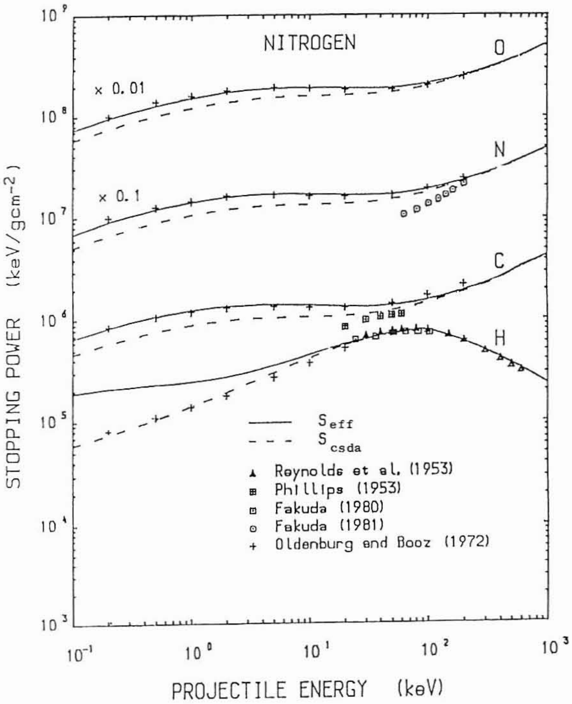

Fig. 3: The calculated effective and CSDA values of stopping powers for heavy ions (proton, C, N and O) in nitrogen

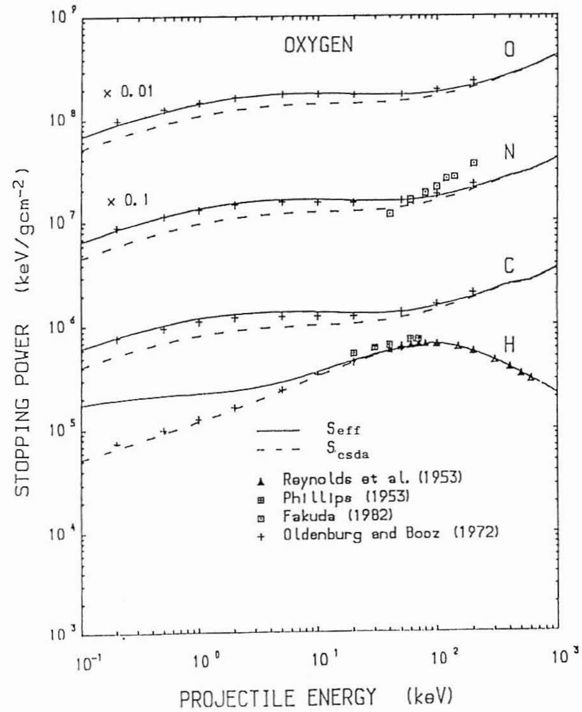

Fig. 4: The calculated effective and CSDA values of stopping powers for heavy ions (proton, C, N and O) in oxygen

in all the targets. In the high energy region, however, the deviation is negligible because the nuclear stopping power component is very small in comparison with the electronic stopping power component.

The experimental stopping power data for recoil ions of low energies are generally lower than the present calculations due to the fact that the measurements were performed for electronic stopping powers. In one case when the calculated nuclear components were added to the experimental data of Arkhipov and Gott (1969), the results were consistent with the present calculation as shown in *Fig. 2,* for proton in carbon. Nevertheless, experimental data for most heavy ions in the low-energy region are scarce and are not sufficient to test the theoretical calculations. The present calculations consider the contribution from the effective nuclear stopping power which is otherwise not included in the experiments. Our results suggest the need to study the contribution of effective nuclear elastic scattering in the penetration of charged particles in hydrogen, carbon, nitrogen and oxygen, from which the effective stopping powers and projected ranges can be calculated. Accordingly, the effective stopping power and projected ranges in tissue and tissue equivalent (TE) materials can then be extracted in the recommended manner. Both quantities are important in the determination of microdose spectra and quality of intermediate energy neutrons in the simulated tissue volume of Tissue Equivalent Proportional Counter (TEPC).

CONCLUSION

The effective stopping power is higher than the CSDA stopping power for low energy ions due to interaction of particles through nuclear elastic scattering. The deviation for a given particle increases with the target mass and decreases with an increase in the projectile energy. For a given target, it decreases with the mass of the particle. The results can be used to predict the quality of intermediate energy neutrons which could show the possibility that elastic nuclear collisions play a significant role in determining an increase in RBE for these neutrons.

REFERENCES

AL-AFFAN, I. A. M., P. COLAUTTI, G. TALPO and D. E. WATT. 1984. Calculated Microdose Spectra for Intermediate Energy Neutrons (1 to 100 KeV). *Radiat. Prot. Dosi.* **5(3)**: 151-157.

AL-KAZWINI, A. T., J. W. CANNINGHAM and D. E. WATT. 1988. Damage by Nuclear Elastic Scattering (NES) - Forty Years On. *Int. J. Radiat. Biol.* **53(4)**: 683-685.

ARKHIPOV, E. P. and YU. V. GOTT. 1969. Slowing Down of 0.5-30 keV Protons in Some Materials. *Sov. Phys. JETP* **29(4)**: 1146-1151.

BERGER, M. J. 1986. *Proton Stopping-Power and Range Tables.* ICRU Stopping Power Committee.

COOK, C. J., E. JONES and T. JORGENSEN. 1953. Range-Energy Relations of 10-250 keV Protons and Helium Ions in Various Gases. *Phys. Rev.* **91(6)**: 1417-1422.

FAKUDA, A. 1980. Stopping Powers of a Tissue-equivalent Gas for 40-200 keV Protons. *Phys. Med. Biol.* **25(5)**: 877-886.

FAKUDA, A. 1981. Stopping Powers of a Tissue-equivalent Gas for 40-200 keV He^+ and N^+. *Phys. Med. Biol.* **26(4)**: 623-632.

FAKUDA, A. 1982. Stopping Powers of H_2, O_2, C_2H_4 for 40-200 keV Protons. *Phys. Med. Biol.* **27(1)**: 73-79.

FASTRUP, B., P. HVELPLUND and C. A. SAUTTER. 1966. Stopping Cross Section of Carbon of 0.1-9 MeV atoms with Z<20. *Kgl. Danske. Videskab. Selskab. Mat.-Fys. Medd.*, **35, No. 10.**

HOGBERG, G. 1971. Electronic and Nuclear Stopping Cross Sections in Carbon for Light Mass Ions of 4.5 to 46 keV Energy. *Phys. Stat. Sol. B.* **48**: 829-841.

JUNG, H. and K. G. ZIMMER. 1966. Some Chemical and Biological Effects of Elastic Nuclear Collisions. *Curr. Top. Radiat. Res.* **2**: 69-127.

KEY, M. 1971. Comparative Effects of Neutrons and X-rays on Chinese Hamster Cells. In *Proc. Symp. Biological Aspects on Radiation Quality,* p. 431-444. IAEA, Vienna.

LINDHARD, J. and M. SCHRAFF, 1961. Energy Deposition by Ions in the keV Region. *Phys. Rev.* **124(1)**: 128-130.

MILL, A. J. 1986. Filtered Neutron Beams for Cancer Therapy. *CEGB,* No. 19, p. 26-39.

MOORHEAD. R. D. 1965. Stopping Cross Section of Low Atomic Number Materials for He^+, 65-180 keV. *J. Appl. Phys.* **36(2)**: 391-395.

OLDENBURG, U. and J. BOOZ. 1972. Mass Stoping Power and Pathlength of Neutrons Produced Recoils in Tissue and Tissue Equivalent Materials I. Neutron Energy < 6MeV. Report No. EUR 4876E (CEC).

ORMROD, J. H. and H. E. DUCKWORTH. 1963. Stopping Cross Sections in Carbon for Low-Energy Atoms with Z<12. *Can. J. Phys.* **41**: 1424-1442.

PHILLIPS, J. A. 1953. The Energy Loss of Low Energy Protons in Some Gases. *Phys. Rev.* **90(4)**: 532-536.

REYNOLDS, H. K., D. N. F. DUNBAR, W.A. WENZEL and W. WHALING. 1953. The Stopping Cross Sections of Gases for Protons of 30-60 keV. *Phys. Rev.* **92(3)**: 742-748.

WATT, D. E. 1972. Quasi-Elastic Nuclear Interaction in Tissue-Like Media. *Phys. Med. Biol.* **17**: 409-415.

WATT, D. E. and J. F. SUTCLIFFE. 1972. Calculated Stopping Powers, Pathlengths and Projected Ranges of Low Energy Heavy Particles in Soft Tissue and RNA. In *Proc. 3rd. Symp. Microdosimetry,* Report No. EUR 4810, p. 187-198. CEC, Luxembourg.

WEYL, P. K. 1953. The Energy of Hydrogen, Helium, Nitrogen, Neon Ions in Gases. *Phys. Rev.* **91**: 289-296.

WIJNGAARDEN, A. V. and H. E. DUCKWORTH. 1962. Energy Loss in Condensed Matter of 1H and 4H in the Energy Range 4<E<30 keV. *Can. J. Phys.* **40**: 1749-1764.

ZIEGLER, J. F., J. P. BIERSACK, and U. LITTMARK. 1985. The Stopping and Ranges of Ions in Solids. *In* The Stopping and Ranges of Ions in Matter. Vol. 1, p. 1-321. ed. J. F., Ziegler, Pergamon Press.

(Received 18 January 1991)