INSTITUTE FOR DATA EVALUATION AND ANALYSIS
TECHNICAL REPORT 2

# Abstracts of Selected Papers Published by Tatsuo Tabata and His Coworkers Volume 1: 1959–1980

Edited with Commentaries by Tatsuo Tabata

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Abstracts of Selected Papers Published by Tatsuo Tabata and His Coworkers
Volume 1: 1959–1980
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*Dedicated to Dr. Shigeru Okabe*

One of the central facts about science is that it pays no attention to East and West and North and South and black and yellow and white. It belongs to everybody who is willing to make effort to learn it.

Freeman Dyson, in *Nature's Imagination*,
ed. J. Cornwell (Oxford U. P., 1995) p. 1

# Contents

Commentary and Erratum, when available, are placed next to the abstract page of a paper. Their availability is indicated by the symbols C (for Commentary) and E (for Erratum) in the parentheses after the titles in the following list.

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## IV Nuclear Physics



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## Appendix I Papers in Japanese

## Appendix II Papers in an Internal Journal

# I The Passage of Fast Electrons through Matter

Because of the complicated nature of the multiple processes of scattering and energy absorption which take place as the electron penetrates the absorber, a complete theoretical treatment of the problem is extremely difficult, . . .

R. D. Birkhoff, in *Handbuch der Physik,* edited by S. Flügge, Vol. 34 (Springer, Berlin, 1958) p. 53

# Paper 1

*Backscattering of electrons from 3.2 to 14 MeV*
*T. Tabata*
*Phys. Rev.* ***162****, 336–47 (1967)*

**Abstract**

Monoenergetic electrons of energies from 3.2 to 14 MeV provided by a linear accelerator have impinged normally on thick targets. Backscattered electrons have been detected by an ionization chamber, the multiplication factor of which was calibrated with a Faraday chamber as a function of average energy per backscattered electron. Angular distributions of backscattered electrons measured for a total of seven targets, effectively semi-infinite and ranging in atomic numbers from 4 to 92, show a trend similar to Dressel's result. However, the backscattering coefficients obtained are lower than his values and are consistent with those reported by other previous authors. Variations of angular distribution and backscattering coefficient with target thickness also have been investigated for Cu, Ag, and Au targets at an incident energy of 6.1 MeV. Some of the angular distributions observed were compared with results of a simple calculation proposed by the author, and an interpretation has been given that the relative contribution of sidescattering compared with that of diffusion increases with increasing energy in the region considered. Backscattering coefficients for the thinnest targets of lower atomic numbers level off toward a nonzero intercept similar to Cohen and Koral's lower-energy result. This tendency is considered to be caused by the contribution of energetic secondary electrons. The backscattering coefficient $\eta(E_0, Z, \infty)$ of electrons incident on the semi-infinite target of atomic number $Z$ with kinetic energy $E_0$ above 1 MeV is expressed by an empirical equation $\eta(E_0, Z, \infty) = 1.28\exp\left[-11.9Z^{-0.65}\left(1+0.103Z^{0.37}E_0^{0.65}\right)\right]$ ($E_0$ in

MeV), appreciable deviations from experimental data occurring only for $Z \leq 6$ and $Z/E_0$ approximately equal to or less than 2 $\text{MeV}^{-1}$.

## Commentary

THIS paper was Tabata's doctoral thesis. He wrote a story related to this work as follows[1]:

> When our experiment was still at a preliminary stage, Harder and Ferbert[2] reported the backscattering coefficients for energies from 8 to 22 MeV. It was lucky that our method of measurement was different from theirs. We were measuring the backscattering coefficients differential in scattering angle using the X-ray compensation type of ionization chamber developed by Van de Graaff et al.[3], and considered it worth to continue our experiment.
>
> At the time our experiment was almost completed, Dressel[4] reported the backscattering coefficients for energies from 0.5 to 10 MeV. His results were appreciably higher than the results obtained by the majority of previous authors, and he discussed that the discrepancy might be attributed to errors in the previous work. On the basis of our results, we were able to report timely that the cause of the discrepancy might be in Dressel's work. This was confirmed by Harder and Metzger[5] and by Ebert et al.[6]
>
> Dressel himself carefully checked his experiment later, and found that his errors had been caused by the peripheral halo of electrons that impinged on the target but was missed by the Faraday cup.7

The reviewer of this paper reported:

> The author is a competent experimentalist, and the work appears to be carefully and painstakingly done.

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[1] Adapted from T. Tabata and R. Ito, *The Passage of Fast Electrons through Matter: The Work at the RCOP and Related Topics*, Radiat. Center Osaka Prefect. Tech. Rep. No. 3 (1983). An abridged version of this report was published: T. Tabata, Acta Radiol. Suppl. 364, 21 (1983).

[2] Ref. 7 of this paper.

[3] Ref. 16 of this paper.

[4] Ref. 8 of this paper.

[5] D. Harder and L. Metzger, Z. Naturforsch. **23a**, 1675 (1968).

[6] P. J. Ebert, A. F. Lauzon and E. M. Lent, Phys. Rev. **183**, 422 (1969).

[7] R. W. Dressel (private communication).

More than 45 publications have cited this paper.[1] The empirical equation for the saturation backscattering coefficient given in this paper was superseded by that of paper 7 in this volume (see also Commentary on paper 7).

**Erratum**

(i) In the 13th line of Appendix B (page 347), $\exp[-x/\lambda \;\; \cos(\pi-\theta)]$ might be understood as $\exp\{-(x/\lambda)\cos(\pi-\theta)\}$. However, what the author meant was

$$\exp\{-x/[\lambda\cos(\pi-\theta)]\}.$$

(ii) Similarly to the above, $\exp[-x/\lambda\times\cos(\pi-\theta)]$ in equation (B1) of Appendix B (page 347) should be replaced by

$$\exp\{-x/[\lambda\times\cos(\pi-\theta)]\}.$$

(iii) In the fifth line from the bottom of Appendix C (page 347), "Eq. (A4)" should read "Eq. (C1)."

[1] The numbers of citation times given in the volumes of the present series do not include the citation by Tabata's own group. The total number of citation times for all the publications of Tabata and his coworkers is more than 640. Detailed data on citation of their papers will be given in Vol. 2 of this series.

# Paper 2

*A simple calculation for mean projected range of fast electrons*

*T. Tabata*

*J. Appl. Phys.* ***39***, *5342–3 (1968)*

**Abstract**

It is shown that the mean projected range of electrons measured by Harder and Poschet can be related by a simple semiempirical relation to the mean range calculated under the continuous slowing-down approximation

## Commentary

THE relation given in this paper between the mean projected range (also called projected range[1] or average penetration depth[2,3]) and the mean range (also called continuous slowing-down approximation range[4]) was superseded by the relations in later papers.[1,5] The result of further study on the same topic is to appear.[6]

Fernández-Varea et al.[3] and Tabata and Andreo[7] reported the usefulness of the average penetration depth for the scaling of depth–dose curves of electrons in medical dosimetry.

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[1] Paper 5 in this volume.

[2] International Commission on Radiation Units and Measurements, *Stopping Powers and Ranges for Protons and Alpha Particles*, ICRU Report 49 (1993).

[3] J. M. Fernández-Varea, P. Andreo and T. Tabata, Phys. Med. Biol. **41**, 1119 (1996).

[4] International Commission on Radiation Units and Measurements, *Stopping Powers for Electrons and Positrons*, ICRU Report 37 (1984).

[5] T. Tabata, P. Andreo, K. Shinoda and R. Ito, Nucl. Instrum. Methods B **108**, 11 (1996).

[6] T. Tabata and P. Andreo, "Semiempirical formulas for the detour factor of 1- to 50-MeV electrons in condensed materials," Radiat. Phys. Chem. (in press).

[7] T. Tabata and P. Andreo, Jpn. J. Med. Phys. **17**, 151 (1997).

# Paper 3

*On the experimental determination of the maximum range of monoenergetic electrons*

*T. Tabata, R. Ito and S. Okabe*

*Jpn. J. Appl. Phys.* ***8****, 393–8 (1969)*

**Abstract**

Tails of the absorption curves of monoenergetic electrons were measured under various measuring geometries for absorbers of Be, Al, Cu, Ag and Au at an energy of 15 MeV. The absorber was placed in air and transmitted electrons were detected with an ionization chamber. The curves observed were analyzed with the *n*th power method to obtain the maximum range. The resulting values were found largely to be affected by the geometry especially in the case of absorbers of high atomic number. It was also found that the tail decays exponentially in the case of the curve observed for Au at the smallest distance between the absorber and the detector. These facts invalidate general use for monoenergetic electrons of the definition of the maximum range given by the nth power method, and a new definition with associated measuring procedure is proposed.

# Paper 4

*Charge distribution produced by 4- to 24-MeV electrons in elemental materials*
*T. Tabata, R. Ito, S. Okabe and Y. Fujita*
*Phys. Rev. B* ***3****, 572–83 (1971)*

**Abstract**

Charge-deposition distributions of monoenergetic electrons normally incident on thick absorbers of Be, Al, Cu, Ag, and Au have been measured with a thin collector moved through the absorber thickness. The measurements have been made at incident energies of 4.09, 7.79, 11.5, and 14. 9 MeV, and also at 23.5 MeV for absorbers other than Be. Values of the most probable charge deposition depth $x_{\mathrm{m}}$ and the charge-deposition straggling $w$ have been determined from the distributions observed. The ratio of $x_{\mathrm{m}}$ to the theoretical mean range $L$ of the incident electrons decreases with decreasing incident energy $E_0$ and with increasing atomic number $Z$ of the absorber, reflecting the effect of multiple-scattering detours of the primary electrons. The ratio $w/L$ shows an increase with increasing $E_0$ in the region of $E_0$ approximately equal to or greater than 11 MeV for Al and in the entire energy region of the present experiment for Cu, Ag, and Au; this trend is considered mainly due to bremsstrahlung energy-loss straggling. The contribution to the measured distributions of electrons mediated by bremsstrahlung has been found to be less than about $1 \times 10^{-3}$ $\mathrm{cm}^2/\mathrm{g} \cdot$absorbed electron. Some of the distributions are compared with the Monte Carlo results of Berger and Seltzer. Agreement between the experimental and calculated results is rather good except in the case of the Be absorber.

## Commentary

RECEIVING a preprint of this paper, Berger wrote to Tabata[1]:

> I like your paper very much; it is a substantial contribution, and very clearly written; your command of English is really excellent.

For the charge-deposition distribution of electrons of about 10-MeV energy in Be, there was a discrepancy between the experimental result of this work and the ETRAN Monte Carlo result by Berger and Seltzer. Comparing the EGS4 and ETRAN Monte Carlo results for the energy-deposition distribution of electrons in water, Rogers and Bielajew[2,3] rediscovered similar discrepancies, i.e. higher penetrability of electrons in the ETRAN results. This led to the improvement of energy-loss straggling algorithm used in the ETRAN code.[4] Later comparison between the experimental and ITS-3.0 Monte Carlo charge-deposition distributions for Be showed rather good agreement[5,6] (the ITS-3.0 code system[7] used the same improved energy-loss straggling algorithm as ETRAN).

## Erratum

The following typographical errors have been found.

(i) For the two equations in the right column of page 574, equation numbers are missing. The equation, $L = \ldots$, should be numbered (4) and the equation, $w^2 = \ldots$, should be numbered (5).

(ii) In the second line from the bottom of Acknowledgments (page 582), "computor" should read "computer."

(iii) In reference 16 on page 583, "Gkabe" should read "Okabe."

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[1] M. J. Berger (private communication).

[2] D. W. O. Rogers and A. F. Bielajew, Trans. Am. Nucl. Soc. **52**, 380 (1986).

[3] D. W. O. Rogers and A. F. Bielajew, Med. Phys. **13**, 687 ( 1986).

[4] S. M. Seltzer, in *Monte Carlo Transport of Electrons and Photons,* edited by T. M. Jenkins, W. R. Nelson and A. Rindi (Plenum, New York, 1988) p. 153.

[5] T. Tabata, P. Andreo, and R. Ito, Nucl. Instrum. Methods B **94**, 103 (1994).

[6] T. Tabata, P. Andreo, K. Shinoda and R. Ito, Nucl. Instrum. Methods B **95**, 289 (1995).

[7] J. A. Halbleib, R. P. Kensek, G. Valdez, S. M. Seltzer and M. J. Berger, IEEE Trans. Nucl. Sci. **39**, 1025 (1992).

# Paper 5

*Extrapolated and projected ranges of 4- to 24-MeV electrons in elemental materials*

*T. Tabata, R. Ito, S. Okabe and Y. Fujita*

*J. Appl. Phys.* ***42****, 3361–6 (1971)*

**Abstract**

The extrapolated range $R_{ex}$ and the projected range $R_{pr}$ of 4- to 24-MeV electrons in Be, Al, Cu, Ag, and Au have been determined from the experimental data for the charge-deposition distribution produced by the electrons in the effectively semi-infinite absorber. While the results for $R_{ex}$ show no significant difference from the data obtained by Harder and Poschet and by Ebert *et al.* for the absorber configuration of finite slab, the present values of $R_{pr}$ for the absorbers of high atomic number are slightly smaller than the results of Harder and Poschet. In the energy region considered here, $R_{ex}$ has been found to obey an empirical equation of the form $R_{ex} = A(E_0 - B)^C$, where $A$, $B$, and $C$ are expressed by simple functions of atomic number, and $E_0$ is the incident kinetic energy of the electron. A semiempirical relation previously found between $R_{pr}$ and the continuous slowing-down approximation range $R_0$ has been modified so as to show better agreement with the present data.

## Commentary

IN addition to experimental data, this paper presented empirical equations for the extrapolated range and the projected range (also called average penetration depth) of electrons. Both of the equations have been superseded by the results of later work: paper 9 in this volume and the paper by Tabata et al.[1] for the extrapolated range; papers by Tabata et al.[2] and Tabata and Andreo[3] for the projected range.

## Erratum

In the second line from the bottom of Acknowledgments (page 3365), “air” should read “aid.”

[1] T. Tabata, P. Andreo, and K. Shinoda, Nucl. Instrum. Methods B **119**, 463 (1996).

[2] T. Tabata, P. Andreo, K. Shinoda and R. Ito, Nucl. Instrum. Methods B **108**, 11 (1996).

[3] T. Tabata and P. Andreo, “Semiempirical formulas for the detour factor of 1- to 50-MeV electrons in condensed materials,” Radiat. Phys. Chem. (in press).

# Paper 6

*Projected-range straggling of 4- to 24-MeV electrons in elemental materials*

*T. Tabata, R. Ito, S. Okabe and Y. Fujita*

*Jpn. J. Appl. Phys.* ***10****, 1503–8 (1971)*

**Abstract**

By modifying the derivative of the empirical expression of Ebert *et al*. for the transmission curve, an empirical equation is developed which expresses the projected-range straggling (PRS) distribution of electrons in the semi-infinite medium as a function of depth $x$, incident energy $T_0$, and atomic number $Z$ of the absorber. Values of constants in this equation are determined through least-squares fit to the experimental data of the present authors for $4.09\ \text{MeV} \le T_0 \le 23.5\ \text{MeV}$ and $4 \le Z \le 79$. The ratio of the PRS parameter $\Delta R$ (full width at half-maximum of the PRS distribution) to the most probable projected range is found approximately to be expressed by a power function of $Z^2/T_0$. An empirical relation which expresses $\Delta R$ as a linear function of the extrapolated, the projected, and the most-probable projected range is also given.

# Paper 7

*An empirical equation for the backscattering coefficient of electrons*

*T. Tabata, R. Ito and S. Okabe*

*Nucl. Instrum. Methods* ***94****, 509–13 (1971)*

**Abstract**

Backscattering coefficient $\eta$ of monoenergetic electrons impinging normally on the thick target has been found to be expressed by an empirical equation of the form $\eta = a_1/(1 + a_2\tau^{a_3})$, where $\tau$ is the incident kinetic energy in units of the rest energy of the electron, and the parameters $a_i$ ($i = 1$, 2, 3) are given by simple functions of target atomic number $Z$. Values of eight constants to express $a_i$ have been determined by least-squares fit to a total of 615 experimental points in 20 references. This equation is valid for $Z \geq 6$ in the energy region from about 50 keV to the highest energy of the existing experimental data (22 MeV), and the rms deviation of the experimental data from the equation is about 7%.

## Commentary

FOR energies below about l00 keV, the equation given in this paper for the backscattering coefficient $\eta$ can be approximated as

$$\eta = 1.15 \exp\left(-8.35 Z^{-0.525}\right), \quad (1)$$

where Z is the atomic number of the absorber material. Verdier and Arnal[1] derived the following semiempirical formula valid for energies from 10 to 100 keV [equation (A1) of this paper]. It can be rewritten as

$$\eta = \exp\left(-6.8 Z^{-0.5}\right), \quad (2)$$

which is similar to equation (1). At high energies, on the other hand, the equation of Tabata et al. is approximated as

$$\eta = a_1 / a_2 \tau^{a_3}, \quad (3)$$

where $\tau$ is the incident-electron energy in units of the rest energy of the electron, and $a_3$ lies between 0.823 and 1.51 for atomic numbers from 6 to 92. Okabe et al. proposed[2] an equation similar to this for energies above about 10 MeV:

$$\eta = 0.022 (Z/\tau)^{1.2}. \quad (4)$$

Therefore, the equation of Tabata et al. approximately contains both equations (2) and (4) as limiting cases, and can be regarded as the unified equation of these.

Pruitt[3] measured the backscattering loss of electrons from a Faraday cup for energies from 20 to 120 MeV, finding that the dependence of the fractional loss upon energy was well represented by the equation of Tabata et al. This indicates that the equation is possibly valid at least up to about 120 MeV, though the highest energy data used in the formulation was 22 MeV.[4]

This paper has been cited in more than 85 publications. The equation was later modified by Ito et al.[5] to extend the applicable region to lower energies. Kuzminikh et al.[6,1] reported the formula for the backscattering coefficient of

[1] Ref. 30 of this paper.

[2] Ref. 31 of this paper.

[3] J. S. Pruitt, Nucl. Instrum Methods **100**, 433 (1972).

[4] These comments have been adapted from T. Tabata and R. Ito, *The Passage of Fast Electrons through Matter: The Work at the RCOP and Related Topics*, Radiat. Center Osaka Prefect. Tech. Rep. No. 3 (1983).

[5] R. Ito, P. Andreo and T. Tabata, Bull. Univ. Osaka Prefect. A, **41**, 69 (1993).

[6] V. A. Kuzminikh, I. A. Tsekhanovski and S. A. Vorobiev, Nucl. Instrum. Methods **118**, 269 (1974).

positrons by fitting the function of this paper to the data obtained with the segments-model computation.

## Erratum

The following errors have been found.

(i) In Fig. 1(a) on page 509, the lowest-energy data point for aluminum was placed wrongly. Its value of $\eta$ should read 0.14.

(ii) The same error as in (i) affected the calculation of the relative rms deviation $\delta$ in Table 4 on page 511. The value of 8.3 for Al should be replaced by 7.8. The overall relative rms deviation was not affected.

(iii) In the third line below equation (A1) on page 512, "mass number" is better to be replaced by "atomic weight."

(iv) In the inequality (A2a) on page 512, the coefficient 0.045 should be replaced by $4.5 \times 10^2$.

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[1] V. A. Kuzminikh and S. A. Vorobiev, Nucl. Instrum. Methods **129**, 561 (1975).

# Paper 8

*An empirical equation for the average energy-loss fraction of backscattered electrons*

*T. Tabata, R. Ito and S. Okabe*

*Jpn. J. Appl. Phys.* **11**, 1220 (1972)

**Abstract**

An empirical equation is given to express the average energy-loss fraction $\langle \Delta T \rangle / T_0$ of backscattered electrons as a function of incident energy $T_0$ and absorber atomic number $Z$. Values of eight constants in the equation have been determined by the least squares fit of the equation to the experimental data for $0.005 \le T_0 \le 3$ MeV and $6 \le Z \le 92$. The root-mean-square error of the equation is 11%.

## Commentary

LATER an empirical equation for the fractional energy $f_{BE}$ of backscattered electrons was formulated[1] on the basis of experimental and Monte Carlo results, and it can be used in place of the equation given in this paper [$(1-f_{BE})$ gives the average energy-loss fraction of backscattered electrons].

## Erratum

In Table I, the value of $b_8$ should read 0.12 instead of 0.122.

[1] T. Tabata, P. Andreo and K. Shinoda, "Fractional energies of backscattered electrons and photon yields by electrons," Radiat. Phys. Chem. (in press).

# Paper 9

*Generalized semiempirical equations for the extrapolated range of electrons*
*T. Tabata, R. Ito and S. Okabe*
*Nucl. Instrum. Methods* ***103****, 85–91 (1972)*

**Abstract**

The extrapolated or practical range $R_{ex}$ of monoenergetic electrons in the energy region 0.3 keV–30 MeV for the absorbers of atomic number 6–92 has been found to be expressed by a single semiempirical equation of the form

$$R_{ex} = a_1\left[\left(1/a_2\right)\ln\left(1+a_2\tau\right) - a_3\tau/\left(1+a_4\tau\right)\right],$$

where $\tau$ is the incident kinetic energy in units of the rest energy of the electron, and the parameters $a_i$ ($i = 1, 2, \ldots, 5$) are given by simple functions of atomic number $Z$. Values of nine constants to express $a_i$ have been determined by least-squares fit to a total of 232 experimental points reported in 18 references; the data used have been confined to those obtained from number-transmission measurement. The rms deviation of the equation form the experimental data is 4.5% for energies above 1 MeV and 8.4% for the entire energy region. Although the latter value is rather large, it is mainly due to large fluctuation of the experimental data for energies below 1 MeV. An approximate inverse relation which expresses $\tau$ as a function of $R_{ex}$ is also given.

## Commentary

THE semiempirical equation for the extrapolated range of electrons given in this paper has a unified form of previous equations at low and high energies as described below.[1]

> At low energies the form of our equation approaches the equation developed by Weber[2] to express both the continuous slowing-down approximation range $R_0$ and the extrapolated range in aluminum [see equation (A3) of this paper]. At high energies the form of our equation approaches the following formula for $R_0$ derived by Koch and Wyckoff[3]:
>
> $$R_0 = \left(k_1 A / Z^2\right) \ln\left(1 + k_2 Z\tau\right), \qquad (1)$$
>
> where $k_1$ and $k_2$ are constants for a given absorber material, $\tau$ is the incident electron energy, and $A$ and $Z$ are the atomic weight and the atomic number of the absorber material. Thus our equation has unified the two equations at low and high energies.

This paper has been cited in more than 80 publications including the textbook written by Tsoulfanidis.[4] Tabata et al.[5] have proposed a new semiempirical equation for the extrapolated range, which is more accurate at least in the energy region between 0.1 and 100 MeV.

Batra and Sehgal[6] have given a theoretical interpretation of the dependence of the extrapolated range on energy and material, and compared their calculations with the equation of this paper to find general agreement.

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[1] Adapted from T. Tabata and R. Ito, *The Passage of Fast Electrons through Matter: The Work at the RCOP and Related Topics*, Radiat. Center Osaka Prefect. Tech. Rep. No. 3 (1983).

[2] Ref. 9 of this paper.

[3] H. W. Koch and J. W. Wyckoff, IRE Trans. Nucl. Sci. **NS-5**, No. 3, 127 (1958).

[4] N. Tsoulfanidis, *Measurement and Detection of Radiation* (McGraw-Hill, New York, 1983).

[5] T. Tabata, P. Andreo, and K. Shinoda, Nucl. Instrum. Methods B **119**, 463 (1996).

[6] R. K. Batra and M. L. Sehgal, Phys. Rev. B **23**, 4448 (1981).

# Paper 10

*A fitting function for energy dissipation curves of fast electrons*

*T. Tabata, R. Ito and S. Okabe*

*Nucl. Sci. Eng.* ***49***, *505–6 (1972)*

**Abstract**

A procedure is presented for determining the energy dissipated by fast electrons at different depths in a variety of materials. The method enables interpolation of the calculated depth–dose profile to account for variations in the atomic number.

# Paper 11

*An algorithm for the energy deposition by fast electrons*

*T. Tabata and R. Ito*

*Nucl. Sci. Eng.* ***53****, 226–39 (1974)*

**Abstract**

An algorithm to calculate the energy deposition distribution produced by monoenergetic fast electrons normally incident on the semi-infinite absorber is given. While the algorithm is based on elementary relation that is also a basis of similar work by Kobetich and Katz, higher accuracy has been attained and the region of validity has been extended by using better approximations and new expressions for its evaluation. Empirical equations recently developed for the extrapolated range and the backscattering of electrons have been utilized, and the effect of bremsstrahlung production has been taken into account by the use of a modified Koch–Motz equation. Expressions for three adjustable parameters introduced into the algorithm have been determined by least-squares fit to published experimental and Monte Carlo results of the energy deposition distribution. The algorithm obtained is valid for incident energies from about 0.1 to 20 MeV and for atomic numbers of the absorber from about 5.3 (effective atomic number for a light compound) to 82.

## Commentary

THIS paper has been cited in more than 55 publications. Lathrop and Wienke[1] attached calling and plotting programs to the FORTRAN function subprogram EDEPOS given in this paper to make a stand-alone module.

The EDEPOS code was later used as part of the EDMULT code[2,3] to calculate the energy-deposition distributions of electrons in multilayer slab absorbers, and was modified to attain higher accuracy.[4,5]

Following the method of this paper, Frederickson et al. derived an analytic approximation for the depth profile of charge deposition by 0.1- to 100-MeV electrons in thick slab absorbers.[6]

In his review paper on electron transport studies, Garth[7] enumerated "analytic and semiempirical models" as one of the theoretical approaches for solving the transport problems, and wrote as follows, citing this paper and another[2]:

> Prolific developers of semiempirical models for energies > 100 keV have been Tabata and Ito.

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[1] B. L. Lathrop and B. R. Wienke, Computer Phys. Comm. 38, **389** (1985).

[2] T. Tabata and R. Ito, Jpn. J. Appl. Phys. **20**, 249 (1981).

[3] Radiation Shielding Information Center, *EDMULT 3.11 MICRO: Electron Depth–Dose Distributions in Multilayer Slab Absorbers*, Computer Code Collection CCC-430, RSIC, Oak Ridge Natl. Lab. (1992).

[4] T. Tabata, R. Ito and S. Tsukui, Radiat. Phys. Chem. **35**, 821 (1990).

[5] T. Tabata, P. Andreo and K. Shinoda, "An algorithm for depth–dose curves of electrons fitted to Monte Carlo data," Radiat. Phys. Chem. (in press).

[6] A. R. Frederickson, J. T. Bell and E. A. Beidl, IEEE Trans. Nucl. Sci. **42**, 1910 (1995).

[7] J. C. Garth, Trans. Amer. Nucl. Soc. **52**, 377 (1986).

# Paper 12

*Parametric representation of the energy deposition by fast electrons under oblique incidence*

*T. Tabata and R. Ito*

*Int. J. Appl. Radiat. Isot.* ***26****, 411–5 (1975)*

**Abstract**

Application of a series of weighted Laguerre polynomials has been investigated to reproduce energy depositions of fast electrons obliquely incident on the plane surface of a semi-infinite absorber. Details of the representation have been determined by fitting the series to the distributions generated by the Monte Carlo code of Berger and Seltzer. Polynomials up to the fourth order have been used with a scale factor proportional to $\cos\theta$, where $\theta$ is the angle of incidence, and each coefficient of the polynomial has been found to be well expressed by a linear or a quadratic function of $\cos\theta$. Values of twelve parameters required to express the angular-dependent distribution have been determined, and are tabulated for the cases of 0.5–10-MeV electrons incident on aluminum and 2-MeV electrons incident on copper, tin and polystyrene. The r.m.s. relative error, in which the mean is taken with weights proportional to the square of the fitted values, is 4.2 per cent in the worst case.

## Erratum

In equation (3) on page 412, $c_i$ should read $c_{ij}$.

# Paper 13

*A generalized empirical equation for the transmission coefficient of electrons*
*T. Tabata and R. Ito*
*Nucl. Instrum. Methods* ***127****, 429–34 (1975)*

**Abstract**

An empirical equation for the transmission coefficient of monoenergetic electrons normally incident on the absorber has been formulated by modifying the expression proposed by Rao. It utilizes a semiempirical equation recently developed for the extrapolated range of electrons, and the dependence of a single remaining parameter upon the incident energy $T_0$ and the atomic number $Z$ of the absorber has been determined by using a total of 79 experimental transmission curves for $T_0 = 8$ keV – 30 MeV and for $Z = 4 - 82$. The rms absolute error of the equation is about 0.03 in most cases.

## Commentary

USING the equation in this paper, Lazurik[1] et al. derived an analytic expression for the maximum penetration depth of electrons. They also showed that this parameter would be useful as the characteristic depth of energy and charge deposition in a target irradiated by electrons.

Lazurik et al. called the above parameter “average depth of electron penetration.” This terminology is confusing with the “average penetration depth (projected range)” of papers 2 and 5 in this volume, though the two definitions are rather close. Their parameter is the average of the maximum depths electrons reach during its motion in an semi-infinite target. These depths are not necessarily the endpoint of electron’s path, but often lies deeper than the latter because of the backward scattering of electrons in the medium.

## Erratum

Figures 1 and 5 include simple errors. Corrected figures are given below.

(i) For the abscissa of Fig. 1, the label $10^{-2}$ is placed at a wrong position.

(ii) In Fig. 5, ticks for both ordinate and abscissa are missing.

[1] V. Lazurik, V. Moskvin and T. Tabata, IEEE Trans. Nucl. Sci. **45** (3) (in press).

# Paper 14

*An empirical relation for the transmission coefficient of electrons under oblique incidence*

*T. Tabata and R. Ito*

*Nucl. Instrum. Methods* **136**, *533–6 (1976)*

**Abstract**

An empirical relation for the transmission coefficient of electrons impinging on aluminum absorbers is given as a function of absorber thickness $x$, incident energy $T_0$, and angle of incidence $\theta$. It has been formulated by incorporating the dependence upon $\theta$ in the empirical equation for the case of normal incidence reported previously by the present authors. Numerical constants in the relation have been determined through least-squares fit to the data for $T_0 = 0.5-10$ MeV generated by the Monte Carlo code of Berger and Seltzer. The rms deviation, evaluated over $\theta = 0-75$ deg, of the relation from the Monte Carlo data is about 0.03 in the entire energy region considered.

# Paper 15

*An improved interpolation formula for the parameter B in Molière's theory of multiple scattering*

*T. Tabata and R. Ito*

*Jpn. J. Appl. Phys.* ***15****, 1583–4 (1976)*

**Abstract**

An improved interpolation formula is given for the parameter B that appears in Molière's theory of multiple scattering and is defined by a transcendental equation. The error of the formula is less than 0.1% in the region of the values commonly used of the parameter $\log_{10}\Omega$.

# Paper 16

*Interpolation formulas for quantities related to radiative energy-loss of electrons*
*T. Tabata and R. Ito*
*Nucl. Instrum. Methods* ***146****, 435–8 (1977)*

**Abstract**

An interpolation formula is given for the quantity $\phi_{\mathrm{rad}}/\bar{\phi}$ that is proportional to the radiative energy-loss divided by the total energy of the incident electron. Errors caused by the formula have been checked for three sets of values of $\phi_{\mathrm{rad}}/\bar{\phi}$, which have been computed by Berger and Seltzer with different empirical corrections to reduce Born-approximation errors. Incident energies from 1 keV to 1000 MeV and atomic numbers of material from 1 to 92 have been considered. Values of six parameters in the formula have been determined by using Tchebyschev's criterion of approximation, and the maximum error has been found to be less than 1.9% for the intermediate set with Aiginger–Rester correction as well as for the no-correction set. A table of parameters in the case of the Aiginger–Rester set is provided for 59 elements. An interpolation formula for the Aiginger–Rester correction factor is also given.

# Paper 17

*Approximation to cos$\gamma$ appearing in the formula for the Coulomb scattering of relativistic electrons*

*T. Tabata and R. Ito, Nucl. Sci. Eng.* ***65****, 414–5 (1978)*

**Abstract**

An approximate expression for the function $\cos\gamma$, defined by the use of the gamma function of a complex argument, has been developed to economize the computations pertaining to the single- or the multiple-Coulomb scattering of relativistic electrons. The maximum absolute error of the expression is $2.2\times10^{-6}$.

# Paper 18

*Approximations to Landau's distribution functions for the ionization energy loss of fast electrons*
*T. Tabata and R. Ito*
*Nucl. Instrum. Methods **158**, 521–3 (1979)*

**Abstract**

Approximations are given for the universal function $\phi(\lambda)$ appearing in Landau's theory on the energy loss distribution of fast electrons by ionization and also for the function $P^{-1}(r)$ inverse to the integral of $\phi(\lambda)$. Values of parameters have been determined with the criterion of the best approximation in the Tchebyschev sense. Two results are presented for $\phi(\lambda)$; the simpler one is accurate within an absolute error to 1.0% of the peak value of $\phi(\lambda)$ over the interval $-2.9 \le \lambda < \infty$, and the other, within a relative error of $1.4\times10^{-3}$ over $-3.275 \le \lambda < 100$. The approximation to $P^{-1}(r)$ is accurate within a relative error of $9\times10^{-4}$ over $0.001 \le r \le 0.999$.

## Erratum

IN Table 1 on page 522, the last three values of $P^{-1}(r)$ should be corrected as follows:

At $r = 0.8$ $P^{-1}(r) = 5.7666$

At $r = 0.9$ $P^{-1}(r) = 1.1644\text{E}+1$

At $r = 0.999$ $P^{-1}(r) = 9.8498\text{E}+2$.

# II The Measurement and Use of Radiation

As in Mathematicks, so in Natural Philosophy, the Investigation of difficult Things by the Method of Analysis, ought ever to precede the Method of Composition. This Analysis consists in making Experiments and Observations, . . .

Sir Isaac Newton, *Opticks* (Dover, New York, 1952)

# Paper 19

*Nonobstructive low energy electron beam monitor*

*S. Okabe, T. Tabata and R. Ito*

*Rev. Sci. Instrum.* ***32****, 1347–8 (1961)*

**Abstract**

A modified type of secondary electron monitor useful for the monitoring of low energy electron beams during irradiation is described. Using the window foil at the end of the accelerator as a part of the detector, it is designed to have minimum disturbance on the primary beam. The monitor output is independent of the primary beam energy and proportional to the primary beam current in the range over which the monitor was tested (1.0–1.7 Mev and up to 120 μa).

## Commentary

IN 1960s and the early 1970s, the secondary emission monitors (SEM) were used at many accelerator facilities, and ICRU Report 21 included[1] a description on the SEM. However, no mention about the SEM is given in its updated version[2], ICRU Report 35. At the World Congress on Medical Physics and Biomedical Engineering held in Kyoto in 1991, Tabata saw Planskoy, the author of one of the most important papers on the SEM[3], and asked her about the reason for the disappearance of the SEM from the ICRU Report. It took a little while for her to remember that she had once worked on the SEM. Then she answered that fashion for the instruments might have changed like that for women's dresses.

## Erratum

In Fig. 3 on page 1348, the data point at the second lowest bias voltage used was actually measured at 0 volt. Thus the secondary electron current rises sharply in the region of the lowest bias voltages. This was found by checking the voltage source later.

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[1] International Commission on Radiation Units and Measurements, *Radiation Dosimetry: Electrons with Initial Energies Between 1 and 50 MeV,* ICRU Report 21 (1972).

[2] International Commission on Radiation Units and Measurements, *Radiation Dosimetry: Electron Beams with Energies between 1 and 50 MeV,* ICRU Report 35 (1984).

[3] B. Planskoy, Nucl. Instrum. Methods **24**, 172 (1963).

# Paper 20

*Anomalous emission in secondary emission beam monitors*

*S. Okabe, T. Tabata and R. Ito*

*Nucl. Instrum. Methods* ***26****, 349–50 (1964)*

**Abstract**

The secondary emission monitor has been found to show a peculiar dependence on applied voltage between foils after many hours of use. The characteristics of this anomalous emission of secondary electrons are reported to notify its serious effect on the performance of the monitor.

## Commentary

BURLIN cited this paper together with Fig. 1 in his review article[1], and commented:

> No other authors have reported such bizarre effects, . . . Thus while these results must present a salutary warning to check the performance of any monitor, they should perhaps be received with a little caution, . . .

In retrospect, the anomalous emission described in this paper was found possibly because of rather poor vacuum in the monitor chamber. It was attached directly to the extension tube of the accelerator, but the foil system packed tightly inside the chamber hindered good evacuation around foils, causing much contamination at foil surfaces with deposited carbon layers and adsorbed gases.

The results of later studies cited by Tabata et al.[2] is to be noted:

> The appearance of a peak on the current–voltage curve of the secondary emission monitor does not necessarily indicate the presence of the anomalous emission. Brinkmann and Hellwig[3] observed a slow decrease in the voltage region from 20 to 1000 eV. They explained this by carbon contamination and the energy dependence of two effects: the backscattering of secondary electrons from the collector foils and the emission of tertiary electrons from the emitter foils by the backscattered secondaries. Ohkuma and Kawanishi[4] found a peak on the current–voltage curve when the accelerator was operated with a short-pulse (20-ns width), high-current (6-A peak) mode. They reported that the secondary-electron current at the peak was stable in contrast to our anomalous emission, and suggested an effect due to strong electric field produced by the primary beam.

## Erratum

In Fig. 2 on page 350, “(a)” should be attached to the middle one of oscilloscope traces, and “(b)” to the lowermost one.

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[1] T. E. Burlin, in *Topics in Radiation Dosimetry: Radiation Dosimetry Supplement 1,* edited by F. H. Attix (Academic, New York, 1972) p. 143.

[2] T. Tabata, K. Fukuda, K. Kawabata, et al., Bull. Univ. Osaka Prefect. A **42**, 193 (1993).

[3] E. Brinkmann and G. Hellwig, Nucl. Instrum. and Methods **48**, 163 (1967).

[4] J. Ohkuma and M. Kawanishi, Nucl. Instrum. Methods **211**, 547 (1983).

# Paper 21

*Beam position monitor for accelerators*
*S. Okabe and T. Tabata*
*Rev. Sci. Instrum.* ***36****, 97–8 (1965)*

**Abstract**

A beam position monitor for accelerators has been developed. It uses secondary emission from emitter pieces made of aluminum foil thick enough to stand by themselves. The advantage of the monitor consists in its simplicity, inexpensive construction, and applicability to both pulsed and continuous-beam accelerators. A displacement of about 0.5 mm has been found to be easily detectable for the position of the beam of about 15 mm in diameter.

## Commentary

A more detailed account of this work was given in a paper[1] in an internal journal. A footnote to that paper contradictorily stated that a *detailed* description of the work would be given *briefly* in Rev. Sci. Instr. This is considered to have happened because of the following. The authors initially submitted a detailed version of the manuscript to Rev. Sci. Instr., but they were advised by the reviewer to make it shorter. Thus the final paper became shorter than the preliminary account, and the authors inserted “briefly” in the footnote of the preliminary paper in proof, missing to delete “detailed.”

[1] S. Okabe, T. Tabata and R. Ito, Ann. Rep. Radiat. Center Osaka Prefect., **5**, 56 (1964).

# Paper 22

*Beam profile measurements for electron accelerators*
*S. Okabe, T. Tabata and K. Tsumori*
*Jpn. J. Appl. Phys.* ***5****, 68–73 (1966)*

**Abstract**

New methods have been developed for monitoring the beam profile of electron accelerators. For electron energies above and below 3 MeV, the monitor utilizes the secondary emission from the probe and the partial absorption of the primary beam in it, respectively, and the probe consists of copper wire or thin aluminum plate. The performance of the monitor was investigated with electron beams of a 15 MeV linear accelerator and a 2 MeV resonance transformer. The advantage of these methods are their simplicity and utility for high power accelerators.

## Commentary

THE beam profile of Fig. 7(c) in this paper was explained in the text as caused by occasional matching of the repetition rate of beam pulses to an integer- or a half-integer-multiple of the scanning frequency. Concerning this, the following is to be noted[1]:

> Such matching is expected to be destroyed easily by a slight change of pulse-repetition rate. Strangely, however, the occurrence of profiles with several peaks was rather common at low pulse-repetition rates. It was found later that the noise caused by the ignition of the pulse-forming network of the accelerator was retriggering the wave-form generator for the scanner-coil current to repeat the same relative phase between the scanning and beam pulses. We then modified the wave-form generator not to be triggered by the noise.

[1] Adapted from T. Tabata, K. Fukuda, K. Kawabata, et al., Bull. Univ. Osaka Prefect. A **42**, 193 (1993).

# Paper 23

*Energy monitor for electron beams*
*S. Okabe, T. Tabata and K. Tsumori*
*Rev. Sci. Instrum.* ***37****, 309–10 (1966)*

**Abstract**

An energy monitor for electron beams has been developed which makes use of the elastic scattering of electrons caused by a foil placed in the beam path. The scattered electrons are magnetically analyzed and detected by measuring the direct current from a plastic scintillator. During use of the beam the sweep of the magnetic field is repeated automatically, and the energy spectrum is displayed on a storage oscilloscope. Performance of the monitor constructed for a 15 MeV linear electron accelerator is presented.

## Commentary

THE authors looked at the electron-nuclear elastic peak and the electron-electron scattering peak simply on an *oscilloscope* as seen in Fig. 2 of this paper. Considering that 15 years ago such peaks were observed[1,2] only by painstaking measurements with a coincidence Geiger counter system, the authors felt it exciting.

## Erratum

In the fifth line from the bottom of the right column on page 309, "cps" should read "cpm."

[1] E. M. Lyman, A. O. Hanson and M. B. Scott, Phys. Rev. **84**, 626 (1951).

[2] The reference in footnote 4 of this paper.

# Paper 24

*Contribution of obliquely scattered electrons to the irradiation under the scanner window*

*S. Okabe, T. Tabata, K. Tsumori and R. Ito*

*Jpn. J. Appl. Phys.* ***8***, *1331–4 (1969)*

**Abstract**

Directional distribution of electrons has been investigated for the case where they impinge on the sample after passing through the scanner window. A simple theoretical treatment to estimate the fractions of oblique electron flux is given. An experiment has also been made by using electrons of energies 1.5–8 MeV from a Van de Graaff and a linear accelerator. The calculated and the observed results have shown a moderately good agreement. It is to be noted that the contribution of the oblique flux with angle of incidence greater than 5 deg is about 15–65% under a typical geometric condition for irradiation.

# Paper 25

*Current profile monitor for use in scanning electron beam irradiations*

*S. Okabe, K. Tsumori and T. Tabata*

*Rev. Sci. Instrum.* **41**, *1537–9 (1970)*

**Abstract**

A current profile monitor for the scanning electron beam from the accelerator is described. It utilizes the fact that the electrons scattered through large angles by the exit window of the scanner show a profile similar to that of the main beam at the irradiation site. The scattered electrons are collected by small probes arranged in a linear array parallel to the scanning direction, and the beam profile in this direction is displayed by a storage oscilloscope or an X-Y recorder. This device has been used for electrons of energies 4–16 MeV from a linear accelerator and proved to be useful for continual monitoring with negligible disturbance to the irradiation in progress.

# Paper 26

*Transient electron current observed in gas ionization chambers*
*S. Okabe, K. Tsumori and T. Tabata*
*Nucl. Instrum. Methods* ***104****, 109–16 (1972)*

**Abstract**

The gas-filled ionization chambers, irradiated with pulsed electrons or X-rays from a linear accelerator, have been found to show a transient electron current (TEC) after the after the applied voltage being cut off. This phenomenon has been observed in all the four types of the ionization chambers tested. Building-up and decay characteristics of the TEC, effects on the TEC of temperature, intensity of incident radiation, kind and pressure of filling gas, electrode material have been investigated. From these results, the TEC is considered to be caused by gas molecules and ions adsorbed on the walls and the electrodes of the chamber. One component of the TEC is considered to affect the accuracy of ionization chamber current observed with the applied voltage.

# Paper 27

*Simplification of the water bath method for calibrating a Ra-Be neutron source*

*M. Fujishiro, T. Tabata and J. Furuta*

*Nucl. Instrum. Methods* ***131****, 259–61 (1975)*

**Abstract**

The water bath method for calibrating a Ra–Be neutron source was simplified by introducing a fitting function for the thermal neutron distribution in water. The simplified method requires only measurement of neutrons at a single position in a comparatively small water bath.

## Commentary

THIS work was done as part of the study on the measurement of $^{9}$Be(γ, n) reaction cross sections mainly carried out by Fujishiro.[1] In a booklet[2] on the recollection of his research life, we find the following anecdote:

> When I visited the Cyclotron Laboratory of the University of Oslo, a researcher by the name of Björnstad said to me regrettingly, "We thought of a similar method, but you were quicker to publish!"

The behavior of the fitting function proposed in this paper was not good at the smallest radii, and a revised function was given soon later (paper 28 in this volume).

[1] M. Fujishiro, T. Tabata, K. Okamoto and T. Tsujimoto, Can. J. Phys. **60**, 1672 (1982).

[2] M. Fujishiro, *25 Years with Beryllium: At a Nook of Radiation Paradigm* (private printing, 1995) in Japanese. The passage cited has been translated into English by T. Tabata.

# Paper 28

*Fitting function for the thermal neutron distribution in water due to a Ra-Be source*

*M. Fujishiro, T. Tabata and J. Furuta*

*Nucl. Instrum. Methods* ***137****, 201–2 (1976)*

**Abstract**

We propose an improved fitting function for the thermal neutron distribution in water due to a Ra–Be source. A correction for estimating the neutron yields from a Ra–Be source is also alluded to.

# Paper 29

*Utilization of natural mica for visualization of electron isodose curves in medium*

*K. Fukuda, S. Nakamura, Y. Satoh, T. Tabata and S. Okamoto*

*Nucl. Instrum. Methods* ***172****, 487–9 (1980)*

**Abstract**

Experimental isodose and depth–dose curves were obtained for 15 MeV electrons incident on an aluminum cylinder. Natural mica sheets were used as dosimeters. The experiment proved the usefulness of natural mica as a dosimeter for visualizing isodose curves.

## Commentary

THE depth–dose distribution in Fig. 5 of this paper shows a minimum at a small depth (correspondingly a neck is seen on the isodose curves of Fig. 4). This led to the study of streaming effects of electron beams on film dosimetry.[1]

[1] S. Okuda, K. Fukuda, T. Tabata and S. Okabe, Nucl. Instrum. Methods **200**, 443 (1982).

# III The Effects of Radiation on Materials

High energy radiation, whether in the form of charged ions, electrons, neutrons, or electromagnetic radiation, can have permanent damaging effects on materials . . .

J. C. Slater, *J. Appl. Phys.* **22**, 237 (1951)

# Paper 30

*Pulsed-radiation-induced current in crystalline fused quartz*

*S. Okabe, K. Tsumori and T. Tabata*

*J. Appl. Phys.* ***40****, 2894–8 (1969)*

**Abstract**

Pulsed-radiation-induced current in crystalline and fused quartz was studied by using 5-μsec pulses of electrons with an energy of 13 MeV and a current density of about 100 mA/cm$^2$ peak and a few μA/cm$^2$ average. The pulse shape of the induced current varied remarkably with time within a few minutes of irradiation and also with the temperature of the sample. The variation in shape showed a dependence on crystal orientation of the sample. The effect of the field of the internal space charge was found to be negligible in the observed phenomena. A qualitative explanation is applied to part of the results in terms of an interaction between excited carriers and traps.

# Paper 31

*Effect of electric field direction on pulsed radiation-induced current in crystalline quartz*

*S. Okabe, K. Tsumori, T. Tabata, K. Kawabata and T. Yoshida*

*J. Appl. Phys.* ***42***, *3545–7 (1971)*

**Abstract**

Dependence upon sample orientation of the pulsed radiation-induced current (RIC) in crystalline quartz has been studied by using 5-μsec pulses of electrons with an energy of 13 MeV. The variation with time of the RIC has been found to depend on the direction of the applied electric field with respect to the *c* axis of the crystal, but not appreciably on the direction of the incident electron beam. Detailed dependence of the pulsed RIC on the angle $\theta$ between the applied electric field and the *c* axis has been measured also for $\theta$ from 0 deg to 90 deg at intervals of 15 deg, and the variation with time of the RIC has been found to be large for $\theta < 60$ deg. The dependence on $\theta$ was confirmed by measuring the average RIC with a picoammeter.

# IV Nuclear Physics

In the atomic realm there is a heavy nucleus and light electrons. This situation is almost characterizable as an authoritarian regime. The heavy, highly charged nucleus decides what happens. By the same analogy, the nucleus can be characterized as a democratic regime. The proton and the neutron are practically the same weight, and exert the same nuclear force.

Victor F. Weisskopf, in *The Physical Universe: 1976 Nobel Conference,* edited by D. Huff and O. Prewett (John Wiley, New York, 1979) p. 1

# Paper 32

*Angular distribution of protons from the reaction $^{12}C(\alpha, p)^{13}N$*

*I. Nonaka, H. Yamaguchi, T. Mikumo, I. Umeda, T. Tabata and S. Hitaka*

*J. Phys. Soc. Jpn.* ***14****, 1260–8 (1959)*

**Abstract**

Angular distributions of protons corresponding to the ground state transition from the reaction $^{12}C(\alpha, p)^{15}N$ have been measured at twelve energies of alpha particles between 25 and 39 MeV. Each angular distribution shows pronounced diffraction-like patterns, but there exists apparently a systematic shift in the shape and magnitude of angular distributions as the energy changes. At lower energies a sharp rise in the backward angles is observed, while at higher energies it is not observed.

Angular distributions of protons corresponding to some excited state transitions have also been measured at 34.6 MeV.

# Paper 33

*Gamma-rays from the 7.56 MeV level in $O^{15}$*

*T. Tabata and K. Okano*

*J. Phys. Soc. Jpn.* ***15****, 1552–5 (1960)*

**Abstract**

The gamma-rays from the $N^{14}(p,\gamma)O^{15}$ reaction at the $E_p = 278$ kev resonance, corresponding to the 7.56 MeV level in $O^{15}$, were studied with a large crystal scintillation spectrometer. The direct ground state transition gamma-ray of about 3% in intensity of the total decay was found to exist in addition to the three known cascade lines. Angular distributions of these gamma-rays are all isotropic, supporting the $J_\pi = \frac{1}{2}+$ assignment to the resonance state. The transition strength (radiation width in units of Weisskopf single particle width) of the direct ground state transition $E1$ gamma-ray is calculated to be $|M|^2 = 4.15 \times 10^{-6}$, which is by a factor of $10^{-4}$ smaller than the normal $E1$ transition strength found in light nuclei. Other transitions in $O^{15}$ are estimated to be of normal strength compared with Wilkinson's estimation.

# Paper 34

*Lower excited states in $P^{29}$ from the $Si^{28}(p, \gamma)P^{29}$ reaction*

*K. Okano, T. Tabata, K. Fukuda and J. Muto*

*J. Phys. Soc. Jpn.* ***15***, *1556–64 (1960)*

**Abstract**

The gamma-rays from the $Si^{28}(p,\gamma)P^{29}$ reaction at the $E_p = 369$ kev resonance were studied with a large NaI(Tl) crystal scintillation spectrometer. The resonance state, corresponding to the 3.116±0.012 Mev fourth excited state in $P^{29}$, was found to decay by (74±4)% to the first excited state at 1.384±0.008 Mev and by (26±4)% to the second excited state at 1.961±0.013 Mev which decays predominantly to the ground state.

From the angular distribution measurements of each gamma-ray line, spins and parities of these lower levels in $P^{29}$ were unambiguously assigned as follows: 1.38 Mev (1st), $J = 3/2+$; 1.96 Mev (2nd), $J = 5/2+$; 3.12 Mev (4th), $J = 5/2+$. These assignments are all consistent with the known character of the corresponding levels in the mirror nucleus $Si^{29}$, and are also in agreement with the theoretical predictions.

From the precise gamma-ray energy measurements, the $Q$-value of this reaction was estimated as 2.760±0.013 Mev, which is by about 36 kev larger than the published value based on the $\beta$-ray end-point energy measurement. The resonance strength $(2J+1)\Gamma_p\Gamma_\gamma / (\Gamma_p + \Gamma_\gamma)$ was found to be $(4.7 \pm 0.8) \times 10^{-3}$ ev.

# V Miscellaneous

Man has at least two sides to his nature: his physical needs and his intellectual life. Part of the latter consists of acquiring as deep an understanding as he can of the nature of the physical world in which he lives. This activity . . . largely falls today.

Robert Geroch, *General Relativity from A to B* (University of Chicago Press, Chicago, 1978)

# Paper 35

*Effective treatment of the interpolation factor in Marquardt's nonlinear least-squares fit algorithm*

*T. Tabata and R. Ito*

*Computer J.* ***18**, 250–1 (1975)*

**Abstract**

A modification of Marquardt's nonlinear least-squares fit strategy is proposed. The performances of the modified and original strategies have been compared for six test problems. The results show that execution times for difficult problems are much reduced by the modification.

## Commentary

THIS paper has been cited in more than 30 publications. The algorithm proposed was implemented, for example, on a Tektronix Graphic System. A FORTRAN code based on this algorithm is given by Tabata and Ito.[1]

[1] T. Tabata and R. Ito, *ALESQ, a Nonlinear Least-Squares Fit Code, and TSOLVE, a Nonlinear Best-Approximation Code*, 2nd revised edition, RIAST Osaka Prefect. Univ. Tech. Rep. No. 2 (1997).

# Paper 36

*Varietal differences in the repair of gamma-radiation-induced lesions in barley*

*M. Inoue, R. Ito, T. Tabata and H. Hasegawa*

*Env. Exp. Bot.* ***20***, *161–8 (1980)*

**Abstract**

Dormant seeds of 18 barley varieties were treated with caffeine, immediately after $^{60}Co$ gamma-irradiation. Damage, expressed a reduction in 7 days old seedling height, increased more than the fourth power of dose after irradiation alone and in combination with caffeine post-treatment. Sensitivity coefficients ($a_1$) and $D_{50}$ for each of the varieties, obtained from standard function $F(D) = (1 - a_0)\left[1 - \left(1 - e^{-a_1 D}\right)^5\right] + a_0$ [ $F(D)$ = ratio to control in seedling height, $D$ = radiation dose and $a_0$ = constant] by the computer-assisted method of least squares, corresponded exactly to gamma-sensitivity. After caffeine treatment, $a_1$ values consistently increased and $D_{50}$ decreased in inverse proportion to the extent of gamma-sensitivity.

The dose–response curve, taking all the varieties and treatments together, could be expressed by one general equation, $F(D) = (1 - 0.0923) \times\left[1 - \left(1 - e^{-2.1850 D/D_{50}}\right)^5\right] + 0.0923$.

From the results, it may be concluded that gamma-sensitivity of barley varieties depends on their capacity to repair induced lesions, as controlled by genetic composition.

## Commentary

THE contribution of Ito and Tabata to this work was the analysis of dose–response curves by the use of a model based on the multiple target theory (Figs. 2 and 5).

## Erratum

In Abstract, “expressed a reduction” should read “expressed as a reduction.”

# Appendix I Papers in Japanese

The Japanese physicists, who could all read English, found to their dismay that they could not understand the spoken word. Nevertheless they turned up in their hundreds to hear us. I remember in one place they asked me to give the same lecture that I had given elsewhere. I asked why and they said, ‘Because a translation into Japanese has been published in the newspapers’.

Sir Nevill Mott, *A Life in Science* (Taylor & Francis, London, 1986)

# Paper 37

*The effect of backscattering on the target current of electron accelerators*
*S. Okabe, T. Tabata and R. Ito*
*Oyo Buturi* ***34****, 419–24 (1965)*

**Abstract**

The ratio of target current to incident electron beam current is studied for thick targets of Al, Fe, Sn, Pb and U in the energy range 4–14 MeV. In consideration of practical use, the target is placed in air at about 10 cm from the output window of an electron linear accelerator. The effect of ion current on target current and other errors expected under this experimental condition are verified to be negligible. Therefore, the difference of the observed ratio from unity can be interpreted as the backscattering coefficient of electrons. The backscattering coefficient for a target placed perpendicularly to the beam is found to decrease exponentially with increasing energy in this region. While it increases with the atomic number $Z$ of the target also in the present energy region, the curve of the relation between them does not show such a large change of gradient as observable at $Z \approx 30$ in keV region.

## Commentary

THIS paper describes preliminary results of the work that finally bore fruit in the form of paper 1 in this volume. Before carrying out final measurements, the authors had to construct an experimental room and a scattering-chamber system, into which an analyzed beam from the linear accelerator was to be directed. However, one important set of measurements described in this paper, i. e. the measurements of the dependence of the backscattering coefficient on the angle of incidence of the beam, was not repeated by the use of the scattering chamber.

A preliminary account of the results in this paper was given in English[1], and some results of the dependence on the angle of incidence (6-MeV electrons for aluminum) were cited by Berger and Seltzer[2,3] to compare them with ETRAN Monte Carlo results. The experimental and the Monte Carlo results showed good agreement.

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[1] S. Okabe, T. Tabata and R. Ito, Ann. Rep. Radiat. Center Osaka Prefect. **4**, 50 (1963).

[2] M. J. Berger and S. M. Seltzer, *Review and Updating of Information on Transmission and Reflection of Electrons by Aluminum Shields,* NASA Contract Report NASA-CR-112838 (U. S. Nat. Aeronautics and Space Administration 1970).

[3] M. J. Berger, in *Monte Carlo Transport of Electrons and Photons,* edited by T. M. Jenkins, W. R. Nelson and A. Rindi (Plenum, New York, 1988) p. 183.

# Paper 38

*Penetration of fast electrons through matter (A short review)*

*T. Tabata*

*Oyo Buturi **41**, 268–73 (1972)*

**Abstract**

Recent experimental results on transmission and scattering of fast electrons (mainly in the energy region of MeV) impinging on thick layers of matter are reviewed in comparison with the results of Monte Carlo calculations. Empirical equations universally to describe those experimental data are also reviewed. The description is restricted to the most fundamental geometrical configuration in which the pencil beam is perpendicularly incident on the flat surface of matter.

# Paper 39

*Estimating and measuring methods for the absorbed dose of electrons: Case of 300 keV accelerators*

*S. Okabe, K. Tsumori, T. Tabata, T. Yoshida, A. Nagai, S. Hiro, K. Ishida, I. Sakamoto, T. Kawai, K. Arakawa, T. Inoue and T. Murakami*

*Oyo Buturi* ***43****, 909–18 (1974)*

**Abstract**

Establishment of accurate and reliable methods for estimation and measurement of the absorbed dose is an urgent need in using low-energy electron accelerators. For the purpose of giving a firm basis for the estimation of the absorbed dose, experimental investigations on transmission and backscattering have been made for electrons of energies most utilized in industrial applications, i.e. 200–400 keV. By using the results obtained, an empirical formula expressing the absorbed dose under a practical condition of irradiation parameters has been developed for the case of 300 keV electrons. In order to find a practical and reliable method of dosimetry, characteristics of various film dosimeters have been studied; the characteristics considered are linearity of response, accuracy, and fading effect. Inaccuracy of optical measuring devices for films has also been revealed in this study. Preparation of a manual describing standardized treatments in film dosimetry and centralized supply of films are considered to be necessary for the advance of irradiation engineering.

## Commentary

TABATA'S engagement in this work motivated the commitment of many years by his group to the study of depth–dose algorithms[1–4] for electron beams and the application of them.[5]

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[1] Paper 11 in this volume.

[2] T. Tabata and R. Ito, Jpn. J. Appl. Phys. **20**, 249 (1981).

[3] T. Tabata, R. Ito and S. Tsukui, Radiat. Phys. Chem. **35**, 821 (1990).

[4] T. Tabata, P. Andreo and K. Shinoda, "An algorithm for depth–dose curves of electrons fitted to Monte Carlo data," Radiat. Phys. Chem. (in press).

[5] T. Tabata, R. Ito, I. Kuriyama and Y. Moriuchi, Radiat. Phys. Chem. **33**, 411 (1989).

# Paper 40

*Interaction of electrons with matter in the energy region from 10 eV to several tens MeV (A review)*
*S. Okabe, T. Tabata and Y. Nakai*
*Oyo Buturi **45**, 2–17 (1976)*

**Abstract**

Recent states of researches on various interactions of electrons with matter are reviewed from a unifying viewpoint for the energy region between 10 eV and several tens MeV. In the first half, elementary processes such as ionization, excitation, Auger effect, plasma excitation, collision with free electrons, nuclear scattering and bremsstrahlung, are considered. In the latter half, multiple processes and penetration through thick layers of matter are treated. Problems remaining to be solved are also suggested.

# Paper 41

*Recent trends in radiation physics*

*S. Okabe and T. Tabata*

*J. Atm. Energ. Jpn.* ***18****, 474–8 (1976)*

**Abstract**

Recent studies in the field of radiation physics are reviewed and their relation to nuclear energy research is explained. The studies considered are the interactions of radiation with matter, measurements of radiation and application of them.

# Paper 42

*The gamma-ray dose-rate effect on the sprout inhibition of onion bulbs*

*J. Furuta, E. Hiraoka, S. Okamoto, M. Fujishiro, T. Kanazawa, T. Ohnishi, Y. Tsujii, T. Tabata, S. Hori and T. Ojima*

*Food Irradiat. Jpn.* ***12****, 1–14 (1977)*

**Abstract**

The authors performed the observations of the gamma-ray dose-rate effects to inhibit the sprouting of onion bulbs in the dose-rate range from $2\times10^{2}$ R/h to $3.6\times10^{5}$ R/h, with the doses from 500 R to 20 kR in 1975 and 1976. The onion bulbs used for the experiments were “sensyu-kohdaka” yielded in the middle of June, and were irradiated with a rod type $^{60}$Co-source of about 8000 Ci (1.4 cm $\times$ 30 cm) at the end of July. The irradiated onion bulbs were stored for 8 months in natural condition, and their sprouting was observed every 10 to 20 days.

The time of sprouting of the onions irradiated to lower doses was the faster, and the germination rate increased with days, whereas it decreased when irradiated under higher dose rates. The necessary and sufficient dose for the sprout inhibition was estimated to be about 2000 R under the dose rate of $1\times10^{3}$ R/h, and it increased rapidly for lower dose rates, while it decreased slowly for the higher dose rates.

After observation of germination rates (eight months after irradiation), the sprout inhibited onion bulbs were cut vertically in order to observe browning of the inner bud, and distribution of lengths of the browned inner bud was measured. The results show that the length of browned inner bud is dependent on the irradiation dose rate; the bulbs irradiated to low doses under low dose rates show the long and rather heavy browning, whereas the ones irradiated to high dose under high dose rates show the short and light browning.

## Commentary

TABATA contributed to this work by analyzing observed frequency distributions of the length of browned part of onions by the use of Gaussian functions in a transformed coordinate system (see equations on page 5 and Fig. 8).

# Appendix II Papers in an Internal Journal

Details that could throw doubt on your interpretation must be given, if you know them. You must do the best you can—if you know anything at all wrong, or possibly wrong—to explain it, or put it out, as well as those that agree with it.

Richard P. Feynman, *Surely You're Joking, Mr. Feynman!* (Norton, New York, 1985)

# Paper 43

*ORC electron linear accelerator. I*

*S. Okabe, K. Tsumori, T. Tabata,*
*K. Kawabata, K. Fukuda, R. Ito,*
*S. Nakamura, T. Azuma and K. Kimura*

*Ann. Rep. Radiat. Center Osaka Prefect.*
***3**, 47–53 (1962)*

**Abstract**

This paper describes the outline of the electron linear accelerator of the Radiation Center of Osaka Prefecture and the preliminary test of its characteristics. The energy spectra of electron beams were measured with the analyzer magnet to study the effects of microwave frequency and the phase shifter on the spectra as well as the relation between the microwave power and the electron beam energy. The results of measurement of the characteristics of the electron gun and the stability of microwave frequency are also reported.

## Commentary

THE acronym of Radiation Center of Osaka Prefecture should be RCOP or RCO. During its manufacturing, however, they called the linear accelerator for RCOP "ORC (Osaka Radiation Center) Linac" at the maker, and the authors stuck with the name in writing this and the next paper. Azuma, the first Head of Physics Department of RCOP, said to his staff later, "Don't call our institute ORC. It is the acronym of Osaka Rehabilitation Center."

In 1990, RCOP was united with University of Osaka Prefecture[1], and was renamed Research Institute for Advanced Science and Technology, University of Osaka Prefecture. Thus ORC Linac became UOP Linac. The results obtained with ORC-UOP Linac through early 1990 were summarized.[2] The number of research papers published in relation to the work with the linac amounted to 291.

[1] In 1996 the university changed its English name to Osaka Prefecture University.

[2] K. Fukuda and T. Tabata ed., "Present Status and Results of the UOP Linear Electron Accelerator," Res. Inst. Adv. Sci. Tech., Univ. Osaka Prefect. (in Japanese).

# Paper 44

*ORC electron linear accelerator. II*

*S. Okabe, K. Tsumori, K. Fukuda,*
*T. Tabata, K. Kawabata, R. Ito,*
*S. Nakamura, T. Azuma and K. Kimura*

*Ann. Rep. Radiat. Center Osaka Prefect.*
***3**, 54–57 (1962)*

**Abstract**

This paper describes intensities and characteristics of electron beams, X-rays and neutrons available from the linear electron accelerator of the Radiation Center of Osaka Prefecture. The maximum electron beam current is obtained at energies from 6.5 to 9 MeV, and is 400 mA peak and 1 mA average. The intensity of X-rays observed is $1.4\times10^4$ r/m at 1 m ahead of the target with the electron energy of 8 MeV. The maximum flux of neutrons obtainable is $8\times10^{11}$ n/s at the electron energy of 13.5 MeV.

# Paper 45

*Neutron yield by ORC Linac*

*S. Okabe, K. Fukuda, T. Tabata,*
*K. Tsumori, S. Nakamura and T. Azuma*

*Ann. Rep. Radiat. Center Osaka Prefect.*
***3**, 65–67, 1962*

**Abstract**

Neutron yields from the linear electron accelerator of the Radiation Center of Osaka Prefecture have been measured for the targets of U, Pb, Bi, Hg and brass. The results show good agreement with those reported by others at electron energies above 10 MeV.

# Paper 46

*Energy distribution of backscattered electrons. I. Instrumentation*

*T. Tabata, S. Okabe and R. Ito*

*Ann. Rep. Radiat. Center Osaka Prefect.* **5**, *60–62 (1964)*

**Abstract**

The experimental arrangement to study the energy distribution of backscattered electrons is described. Primary electrons are provided by a 15 MeV linear accelerator. The scattering chamber, to which an analyzer magnet for scattered electrons is connected, permits a continuous variation of the angle of observation under vacuum. After passing through the analyzer magnet, scattered electrons are detected by measuring the dc current from a plastic scintillator. The energy resolution attainable of the total arrangement is about 3%.

# Paper 47

*Energy distribution of backscattered electrons. II*

*T. Tabata, S. Okabe and R. Ito*

*Ann. Rep. Radiat. Center Osaka Prefect.* ***6****, 56–59 (1965)*

**Abstract**

The energy spectrum of backscattered electrons was measured for monoenergetic electrons of energies 3.2–14.1 MeV impinging normally or obliquely on the thick Au target. The ratio of the most probable energy loss of backscattered electrons to the incident electron energy, observed at the scattering angle of 160 deg in the case of normal incidence, was found to increase from about 27% to 65% with increasing energy in this region. The ratio observed near the reflection angle in the case of 60 deg oblique incidence varied with energy only a little around 10%. The variation of energy spectrum with target atomic number was also studied by using Ag and Cu targets.

# Paper 48

*Angular distribution of transmitted electrons with incident energies 3.2-14.1 MeV. (I)*
*T. Tabata, R. Ito and S. Okabe*
*Ann. Rep. Radiat. Center Osaka Prefect.* ***8****, 60–65 (1967)*

**Abstract**

Angular distributions of transmitted electrons have been measured for monoenergetic electrons of energies 3.2–14.1 MeV normally incident on thick targets of Al, Cu, Ag, and Au. The thickness of the target used ranged 8–80% of the practical range $R$ of incident electrons in each element. The half-value angles of angular distributions observed have been compared with Molière's multiple scattering theory including energy-loss correction, and agreement has been found for thicknesses less than about $0.15R$ in most cases. A simple modification of Molière's theory has been made to explain the trend of the experimental result in the region of target thickness where it fails to hold.

## Commentary

ROOS et al.[1] published the results of a similar experiment, and referred to the effectiveness of the approximate correction proposed in this paper for Molière's theory of multiple scattering when applied to thick targets.

The authors attached the number (I) to the title of this paper, but have not written a continuation.

[1] H. Roos, P. Drepper and D. Harder, in *4th Symp. Microdosimetry, Verbania, Italy, 1973* (EUR-5122), edited by J. Booz, H. G. Ebert, R. Eickel and A. Walker, Vol. 2 (Commission of the European Communities, Luxembourg 1974) p. 779.

# Paper 49

*Measurement of absorbed dose of electrons with a differential calorimeter*

*S. Okabe, T. Tabata and K. Tsumori*

*Ann. Rep. Radiat. Center Osaka Prefect.*, ***10***, *45–49 (1969)*

**Abstract**

A differential calorimeter has been designed for measuring absorbed dose of electrons of energies below 8 MeV. Its performance characteristics have been investigated with electrons of energies 1–6 MeV. The smallest thickness of the sample for which the measurement was possible with this device were a few percent of the practical range of incident electrons, and the response was linear over the region of irradiation current tested (up to 2 mA).

## Commentary

AMONG more than 750 publications mentioned in a series of his review articles on calorimetric applications and instrumentation in nuclear science and technology[1–3], Gunn cited this paper as follows[3]:

> Okabe et al. described a twin semiadiabatic calorimeter used to measure the energy absorbed in aluminum specimens of various thicknesses placed in front of one of the receivers.

This is a very concise and rather accurate summary. The measurement of energies absorbed in aluminum specimens was actually made to test the calorimeter, and was not the purpose of this work as Gunn's summary implies.

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[1] S. R. Gunn, Nucl. Instrum. Methods **29**, 1(1964).
[2] S. R. Gunn, Nucl. Instrum. Methods **85**, 285 (1970).
[3] S. R. Gunn, Nucl. Instrum. Methods **135**, 252 (1976).

# Paper 50

*Empirical and approximate expressions related to back- and multiple scatterings of fast electrons*

*T. Tabata and R. Ito*

*Ann. Rep. Radiat. Center Osaka Prefect.*
***20***, *87–90 (1979)*

**Abstract**

Empirical equations are given for (1) parameters in the saturation function for backscattering proposed by Koral and Cohen, (2) the number backscattering coefficient of electrons incident diffusely on the target of semi-infinite thickness, and (3) the reduced diffusion depth. In formulating expressions for the quantities depending on the incident energy, a procedure based on the scaling law of electron penetration proposed by Harder has been utilized. An approximate expression is also given for the parameter B appearing in Molière's theory of multiple scattering; the functional form being the same as reported previously by the present authors, new values of constants has been determined so as to satisfy the criterion of the best approximation.