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^{20}NE INTERACTION IN EXTENDED MATTER

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^{20}Ne INTERACTION IN EXTENDED MATTER

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Abstract

Although heavy ion transport theory is developed to a relatively advanced stage, the present limitation in biomedical and electronic applications is the uncertainty in nuclear fragmentation parameters. Present status on ^{20}Ne beams is discussed and useful formulae are presented for future use in analysis of beam transport experiments.

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Introduction

Considerable progress has been made, in recent years, toward the understanding of the interaction of high charge and energy (HZE) particles with extended matter. A number of theoretical methods have emerged by which estimates of transport quantities can be made from microscopic interaction data.[1-3] Although the microscopic interaction data have been poorly known, improvements in quantity and quality are becoming available so that meaningful calculations could be made in the near future.[3-6]

In the present paper, we develop a simplified theory of HZE transport which is suitable for analysis of ions of modest energies. The main value of the formalism is that a simple framework is provided by which all important transport quantities can be calculated from the basic interaction data using a small desktop computer. We will show that major uncertainties in transport quantities arise due to uncertainties in present-day fragmentation parameters. The present theory may be useful in preliminary data analysis in addition to its importance as a step in developing more detailed and accurate transport models. In the present analyses, ^{20}Ne beams are investigated due to the availability of experimental data.

Transport Theory

With a straightahead approximation, the basic equations are given by[3]

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E}\,\tilde{S}_j(E)+\sigma_j\right]\phi_j(x,E) = \sum m_{jk}\sigma_k\phi_k(x,E) \qquad (1)$$

where the nuclear cross sections are assumed energy independent and approximately given by[7]

$$\sigma j = 58.1(A^{1/3}+2.51-1.11/A^{1/3}-1.11/2.51)^2 \qquad (2)$$

The stopping power $\tilde{S}_j(E)$ is estimated using the approximate range energy relation given by

$$R_j(E) = \delta E^n A_j/Z_j^2 \tag{3}$$

where $\delta = 9.2 \times 10^{-4}$, $n = 1.75$, A_j is the ion mass, Z_j is the ion charge and $R_j(E)$ is the ion range in cm of G5 nuclear emulsion for an assumed emulsion density of 3.815g/cm^3. For a monoenergetic beam of I-type ions of energy E_0 incident on the emulsion stack the HZE fluence is given by[8]

$$\phi_j(x,E) = \frac{\tilde{S}_j[R_j(E)+x]}{\tilde{S}_j(E)} e^{-\sigma_j x}\phi_j\{0,R_j^{-1}[R_j(E)+x]\}$$

$$+ \frac{1}{\tilde{S}_j(E)} \int_E^{R_j^{-1}[x+R_j(E)]} \frac{\exp[-\sigma_j R_j(E'')]}{\exp[-\sigma_j R_j(E)]} \sum m_{jk}\sigma_k\phi_k[x+R_j(E)-R_j(E''),E'']dE'' \tag{4}$$

where

$$\phi_j\{0,R_j^{-1}[R_j(E)+x]\} = \delta\{R_j^{-1}[R_j(E)+x]-E_o\}\delta_{jI} \tag{5}$$

which are solved by an iterative procedure. The first term, found by neglecting the integral term, is

$$\phi_j^{(o)}(x,E) = \frac{e^{-\sigma_j x}}{\tilde{S}_j(E)} \delta_{jI}\delta[x+R_j(E)-R_j(E_o)] \tag{6}$$

The second term is derived by substituting $\phi_j^{(o)}(x,E)$ and evaluating the integral in equation (4) as

$$\phi_j^{(1)}(x,E) = \frac{m_{jI}\sigma_I}{\tilde{S}_j(E)} \int_E^{R_j^{-1}[R_j(E)+x]} \exp\{-\sigma_I x - \sigma_I[R_I(E)-R_I(E'')]-\sigma_j[R_j(E'')-R_j(E)]\}$$

$$\delta[x+R_j(E)-R_j(E'')+R_I(E'')-R_I(E_o)]\frac{dE''}{S_I(E'')} \qquad (7)$$

This is evaluated to yield

$$\phi_j^{(1)}(x,E) = \frac{m_{jI}\sigma_I}{\tilde{S}_j(E)} \quad \frac{\nu_j}{|\nu_I-\nu_j|} \exp\{-\sigma_I x-\sigma_I[R_I(E)-R_I(E'')]$$

$$- \sigma_j[R_j(E'')-R_j(E)]\} \qquad (8)$$

where ν_j is the ratio $Z_j{}^2/A_j$ and $R_j(E'')$ given by

$$R_j(E'') = \frac{\nu_j}{\nu_I-\nu_j} [R_I(E_o)-R_j(E)-x] \qquad (9)$$

is subject to the restriction

$$R_j(E) \leq R_j(E'') \leq x + R_j(E) \ . \qquad (10)$$

Note that equations (9) and (10) result in

$$\frac{\nu_I}{\nu_j} [R_I(E_o)-x] \leq R_j(E) \leq \frac{\nu_I}{\nu_j} R_I(E_o)-x \qquad (11)$$

We now consider evaluation of the dose, the integral fluence, and the integral LET spectra.

The dose of the primary beam is

$$D_I^{(o)}(x) = A_I \int_o^\infty \phi_I^{(o)}(x,E)\, \tilde{S}_I(E)dE$$

$$= A_I \tilde{S}_I\, \{R_I^{-1}[R_I(E_o)-x]\}\exp(-\sigma_I x) \tag{12}$$

and similarly[8]

$$D_j^{(1)}(x) = A_j \int_o^\infty \tilde{S}_j(E)\phi_j^{(1)}(x,E)dE$$

$$= A_j \frac{\nu_j m_{jI}\sigma_I}{|\nu_I-\nu_j|} \int_o^\infty \exp\{-\sigma_I x-\sigma_I[R_I(E)-R_I(E'')]$$

$$- \sigma_j[R_j(E'')-R_j(E)]\}dE \tag{13}$$

where the relations (9) and (10) are yet to be employed. The limits of integration are to be restricted by equation (11). The integrand of equation (13) has the values

$$\left.\begin{array}{ll} \exp(-\sigma_I x) & (E'' = E) \\ \exp(-\sigma_j x) & (E'' = R_j^{-1}[x+R_j(E)]) \end{array}\right\} \tag{14}$$

Approximating the integrand of equation (13) with an exponent which varies linearly between the limits indicated by equation (14) yields

$$D_j^{(1)}(x) = \frac{m_{jI}\sigma_I A_j \nu_j}{|\nu_I-\nu_j|}\ \frac{|E_{u_j}-E_{\ell_j}|}{(\sigma_I-\sigma_j)x}\,[\exp(-\sigma_j x)-\exp(-\sigma_I x)] \tag{15}$$

as given elsewhere.[9] In (15), E_{ℓ_j} and E_{u_j} are the limits of E given by equation (11).

The integral fluence is similarly derived as

$$\Phi_I^{(o)}(x) = \int_0^\infty \phi_I^{(o)}(x,E)dE = e^{-\sigma_I x} \tag{16}$$

with

$$\Phi_j^{(1)}(x) = \frac{\nu_j m_{jI}\sigma_I}{|\nu_I - \nu_j|} \int_{R_{\ell_j}}^{R_{u_j}} \exp\{-\sigma_I x - \frac{(\sigma_j-\sigma_I)x}{R_{u_j}-R_{\ell_j}} (R_j - R_{\ell_j})\} dR_j$$

$$= \frac{\nu_j m_{jI}\sigma_I}{|\nu_I - \nu_j|} \frac{|R_{u_j} - R_{\ell_j}|}{(\sigma_I - \sigma_j)x} [\exp(-\sigma_j x) - \exp(-\sigma_I x)] \tag{17}$$

and where we have made use of equation (14) and the values

$$\left.\begin{aligned} R_{\ell_j} &= \frac{\nu_I}{\nu_j} [R_I(E_o) - x] \\ R_{u_j} &= \frac{\nu_I}{\nu_j} R_I(E_o) - x \end{aligned}\right\} \tag{18}$$

given as the limits of equation (11).

The LET spectrum is evaluated in a manner similar to equation (17) as

$$\Phi_j(x,>S) = \int_{E_m}^{E_S} \phi_j(x,E)dE \tag{19}$$

where E_S is the energy at which $S_j(E)$ is numerically equal to S and E_m is the energy at which $S_j(E)$ obtains its maximum value. In terms of equation (3)

$$E_S = [A_j \nu_j / n\delta S]^{\frac{1}{n-1}} \tag{20}$$

Defining $R_{S_j} \equiv R_j(E_S)$ and $R_{m_j} \equiv R_j(E_m)$ we may write equation (19) as

$$\Phi_j^{(1)}(x,>S) = \frac{\nu_j m_{jI} \sigma_I}{\left|\nu_I - \nu_j\right|} \; \frac{\left|R_{u_j} - R_{\ell_j}\right|}{(\sigma_I - \sigma_j)x} \left\{\exp\left[-\sigma_j x - \frac{(\sigma_I - \sigma_j)x}{(R_{u_j} - R_{m_j})}(R_{u_j} - R_{S_j})\right] - \exp(-\sigma_I x)\right\} \tag{21}$$

The maximum stopping power in the present calculation is taken as

$$S_j(Em) = 10^3 Z_j^{1.1} \tag{22}$$

as determined from the results of Zeigler.[10]

Results

The transition of a ^{20}Ne ion beam of 250 MeV/amu in G5 nuclear emulsion has been studied experimentally by Jain and Aggarwal.[7] At each nuclear fragmentation site, the number of fragments of each species were identified by observing the δ-ray density along the track. A set of fragmentation cross sections was compiled. The calculated dose given by equation (15) using Jain's and Aggarwal's fragmentation cross sections are shown in figure 1 in comparison to their experimental values of dose from various secondary components. As can be seen in figure 1, the dose obtained from counting particle tracks in emulsion is reasonably consistent with their fragmentation parameters. Additional fragmentation cross sections are shown in table I. The values labeled TS are the Tsao-Silberberg parameters calculated using their computer programs.[11] The values labeled VR are the velocity renormalized Tsao-Silberberg values which were found to give the best agreement with ^{20}Ne transition experiments performed by Schimmerling and coworkers[3] at the Lawrence Berkeley Laboratory. The values labeled LaRC are recent results from theoretical calculations at the Langley Research Center.[6]

In figure 2, the Jain and Aggarwal dose curves are compared to evaluation of equation (15) using the fragmentation parameters of Tsao and Silberberg. It is seen that the N,O,F group greatly overestimates the corresponding experimental values. The Li,Be,B,C group is only slightly underestimated by the Tsao-Silberberg parameters. The He dose is underestimated by both sets of parameters. It is clear from table I that the VR parameters would make an even larger overestimate of the experimental values for the important NOF group.

In an earlier study of 670 MeV/amu ^{20}Ne ions in water, we found that the Tsao-Silberberg parameters significantly underestimate the dose at a given depth.[3] The velocity renormalized parameters (VR), however, provide good agreement with the LBL experiments as seen in figure 4 of the earlier study. It is clear from comparison of results for the Tsao-Silberberg fragmentation parameters with results for the Jain-Aggarwal parameters that if used to perform the Ne on water calculations the latter values would lead to even further reductions in dose and thus lead to even greater disagreement with the LBL experiments.[3] This is especially clear since the velocity renormalized values in table I are in good agreement with the LBL experiments.

The present situation is most unclear with respect to the fragmentation and transport of 250 MeV/amu ^{20}Ne ion beams in extended materials. The results of Jain and Aggarwal are internally consistent but cannot be reconciled with the experiments of Schimmerling et al.[3] insofar as the transport equation (1) is correct. It does not appear that the simple range formula is responsible for these differences since more accurate values were used in our earlier results.[3] An additional set of experiments on ^{20}Ne at 250 MeV/amu using sophisticated experiments such as those of Schimmerling et al. is likely to settle the issue.

The calculated LET spectra is shown in figure 3 for the three fragmentation data sets of Jain and Aggarwal, Tsao and Silberberg, and velocity renormalized. Only the high LET components are shown in figure 3 which demonstrate an order-of-magnitude uncertainty in calculated LET spectra due to differences in fragmentation cross sections. Such large uncertainty in LET spectra will not be acceptable in the evaluation of health hazard/benefit as well as estimation of effects on active electronics devices. Clearly, the principal weakness in developing transport models is the lack of consistent fragmentation parameters.

To help define adequate fragmentation cross sections, the Langley Research Center is supporting a theoretical program to evaluate the fragmentation parameters from fundamental nuclear theory.[6] Preliminary results of these calculations are shown in table I for comparison. It is hoped that such physically based models, coupled with the relatively limited experimental data base, will one day allow reliable predictive capability in heavy ion radiation research.

It is hoped that the present formulas will also be helpful in understanding the transport of heavy ions through extended matter. Higher order terms can be added to the series approximation when necessary. The greatest uncertainty, however, in most applications will lie in the inherent uncertainties of the fragmentation parameters rather than in the basic transport formalism presented.

References

1. Curtis, S. B., Doherty, W. R. and Wilkinson, M.: Study of Radiation Hazards to Man on Extended Near Earth Missions. NASA CR-1469, 1969.

2. Letaw, J., Tsao, C. H., and Silberberg, R.: Matrix Methods of Cosmic Ray Propagation, Composition and Origin of Cosmic Rays. Ed. M. M. Shapiro, Reidel Publ. Co., Dordrecht, Holland, 1983.

3. Wilson, J. W., Townsend, L. W., Bidasaria, H. B., Schimmerling, W., Wong, M., and Howard, J.: ^{20}Ne Depth-Dose Relations in Water. Health Physics, vol. 46, no. 5, May 1984, pp. 1011-1111.

4. Townsend, L. W., Wilson, J. W., and Bidasaria, H. B.: Heavy Ion Total and Absorption Cross Sections Above 25 MeV/Nucleon. NASA TP-2138, 1983.

5. Townsend, L. W., Wilson, J. W., and Bidasaria, H. B.: Nucleon and Deuteron Scattering Cross Sections from 25 MeV/Nucleon to 22.5 GeV/Nucleon. NASA TM-84636, 1983.

6. Townsend, L. W., Wilson, J. W., Norbury, John W., and Bidasaria, H. B.: Ion Fragmentation. NASA TP-2305, 1984.

7. Jain, P. L. and Aggarwal, M. M.: Abstract: Nuclear Fragmentation of Clinical Heavy-Ion Beam. Bull. Am. Phys. Soc. vol. 29, no. 4, April 1984, p. 635.

8. Wilson, J. W.: Analysis of the Theory of High-Energy Ion Transport. NASA TN D-8381, 1977.

9. Wilson, J. W.: Heavy Ion Transport in the Straight Ahead Approximation. NASA TP-2178, 1983.

10. Ziegler, J. F.: Stopping Cross-Sections for Energetic Ions in All Materials. Pergamon Press, New York, 1980.

11. Silberberg, R., Tsao, C. H., and Shapiro, M. M.: Semiempirical Cross Sections and Applications to Nuclear Interaction of Cosmic Rays, Spallation Nuclear Reactions and Their Applications (Edited by B. S. P. Shen and M. Merker), Reidel Publ., Boston, 1977, pp. 49-82.

Table I.- Fragmentation parameters for 250 MeV/amu ^{20}Ne on G5 emulsion nuclei

	Fragmentation Cross Section, mb		
Z_j	Tsao-Silberberg	Velocity Renormalized	LaRC
9	112	195	155
8	147	267	103
7	56	106	165
6	63	121	99
5	40	61	26
4	46	50	-
3	50	46	-
2	413	525	-

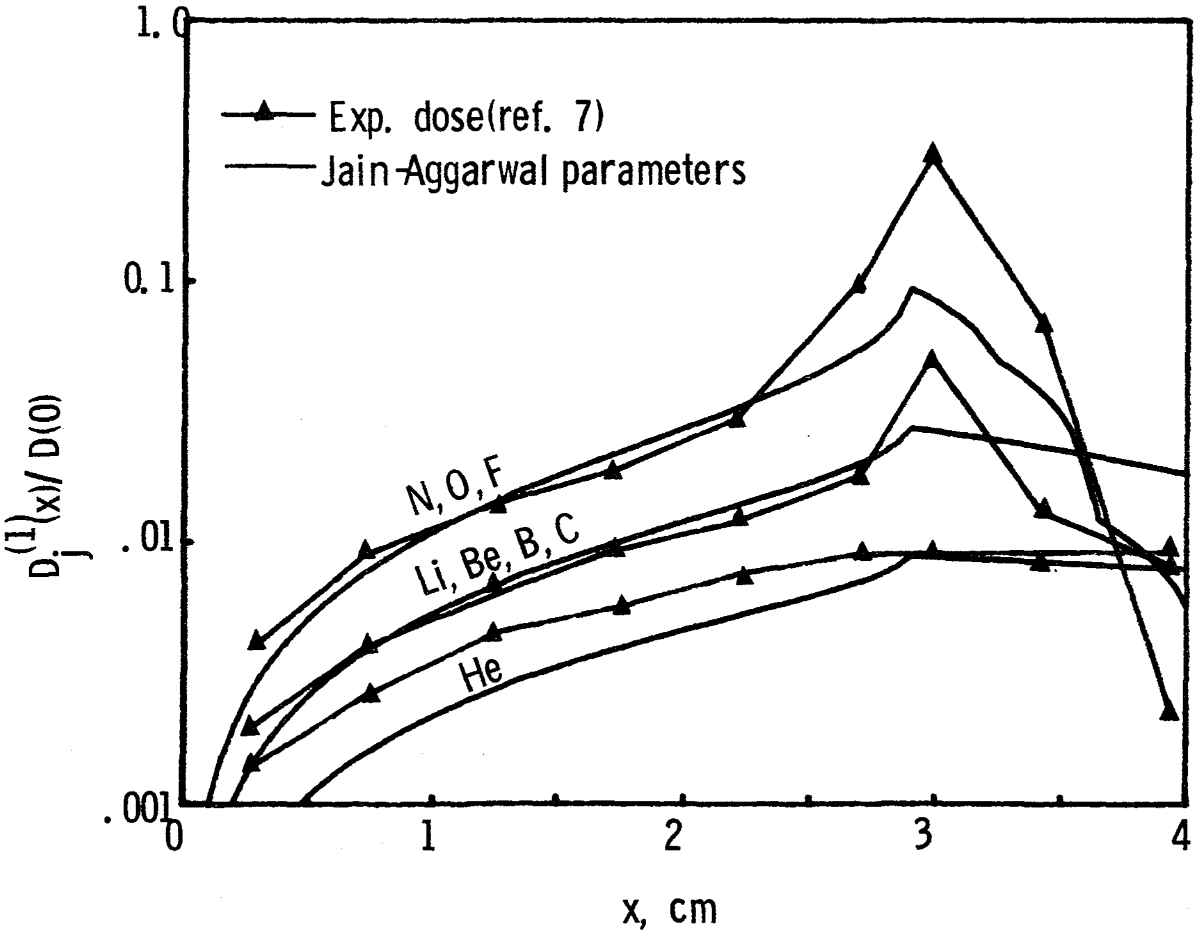

Figure 1.- Experimental dose of Jain and Aggarwal compared to theoretical dose using the Jain-Aggarwal fragmentation parameters.

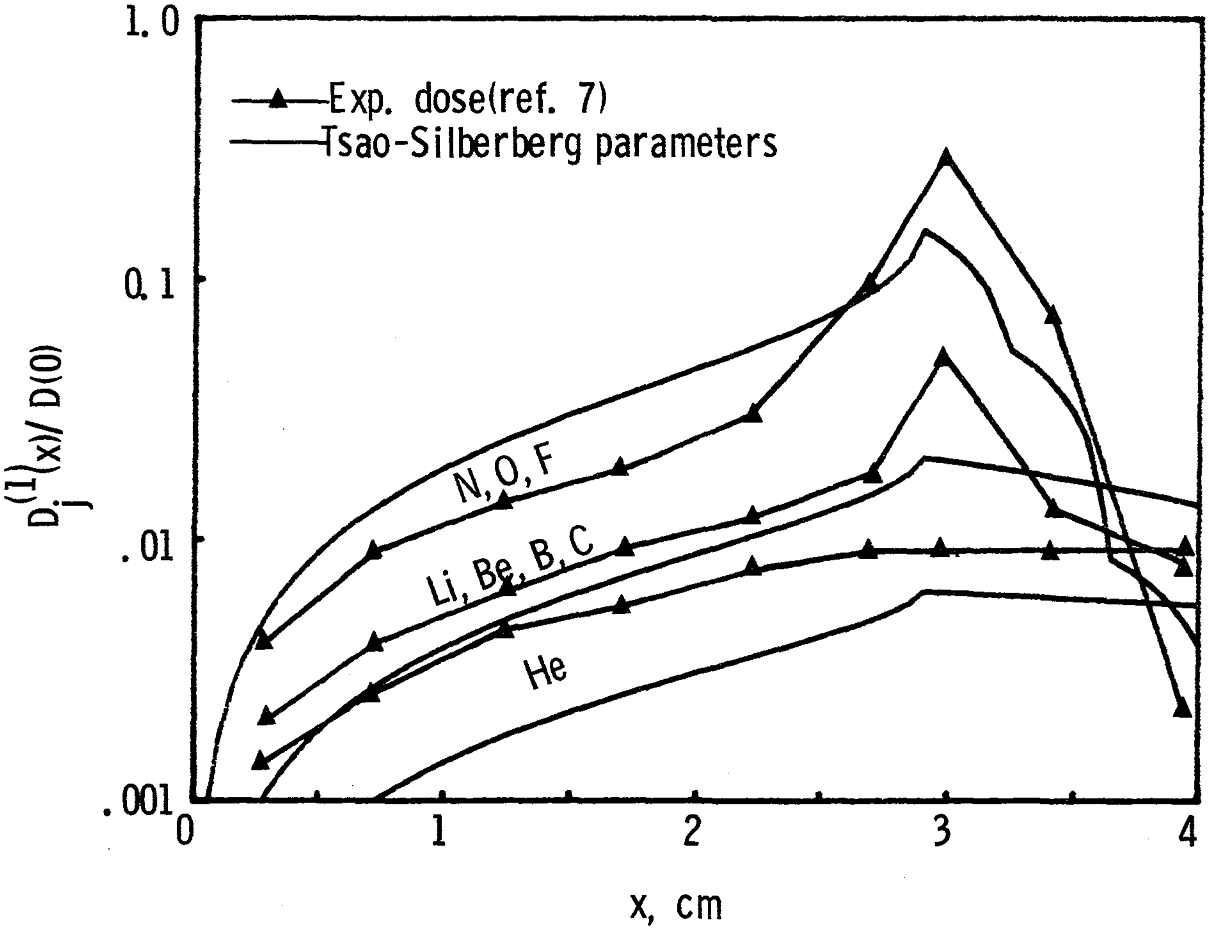

Figure 2.- Experimental data of Jain and Aggarwal compared to theoretical dose using the Tsao-Silberberg fragmentation parameters.

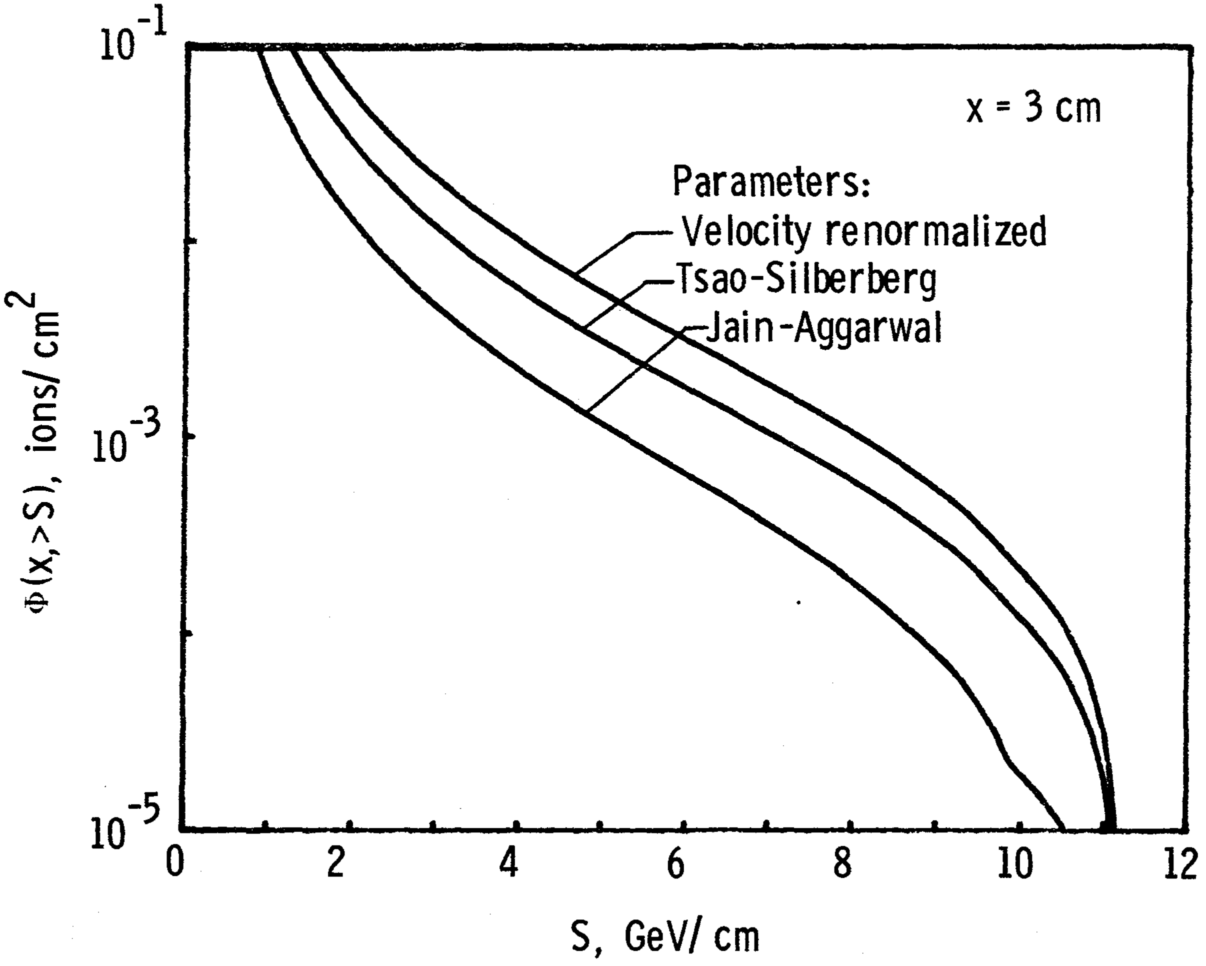

Figure 3.- Integral LET spectra for three sets of fragmentation parameters for 250 MeV/amu ^{20}Ne used in G5 nuclear emulsion.

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16. Abstract

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