AN APPLICATION OF IPM POTENTIAL IN CALCULATING THE ENERGY STRAGGLING FOR FAST PROTON BEAMS*

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ABSTRACT

Energy straggling for fast proton beams in Ni, Al, Ti, Cu, In and Sb solids and N, O, F, B, S, Cl and air gases were calculated using an effective IPM potential which contains an adjustable parameter. The energy and Z_2 (target atomic number) dependence of the energy straggling for proton in materials are obtained when Bonderup and Hvelplund's formulation is used. The results are compared with some experiments in detail, and show in good agreement with them.

Keywords: IPM potential Energy straggling Light ions

I. INTRODUCTION

When a beam of charged particles penetrates matter, the slowing-down is accompanied by a spreading of the beam energy due to statistical fluctuations in a number of successive collision processes. In many cases of practical interest, the distribution in energy loss is sufficiently close to a Gaussian that the spreading around the average value is completely characterized by the average square fluctuation in energy loss, i.e. energy straggling. Since energy straggling is one of the main factors limiting depth resolution of near-surface region microanalysis techniques such as RBS, NRA, PIXE, ERD, SIMS, *etc.*, the accurate information on straggling is important for the application of various ion beams probing methods. In addition the behaviors of light ion in matter are essential elements for those heavy charged particles in material. In this paper, the previous works[1-4] are carried forward with an useful IPM (Independent Particle Model) potential and still effective Bonderup-Hvelplund's formulation, the results calculated are partly compared with recent experiments.

II. THEORY

For light ions of high velocity limit, where all the target electrons are considered free, the energy loss is completely dominated by electronic excitations, the full width

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at half maximum (fwhm) of the energy loss distribution assumed to be Gaussian was given by Bohr's formula

$$\Gamma_B^2 = (8\ln2) \cdot 4\pi Z_1^2 e^4 \cdot Z_2 \cdot N\triangle R. \quad (1)$$

where e is the electronic charge, Z_1 and Z_2 are the atomic number of the projectile and the target atoms respectively, and $N\triangle R$ is the target thickness (atoms/cm^2).

Lindhard and Scharff[1] improved Bohr's treatment, they introduced a quantity of the local energy straggling $\bar{\Gamma}^2(n(r),v)$ which corresponds to the contribution from various parts of the electron cloud. The reduced energy straggling is given by

$$\Gamma^2(Z_2, v)/\Gamma_B^2 = \int_0^\infty 4\pi r^2 n(r) [\Gamma^2 (n(r),v)/\Gamma_B^2]dr \quad (2)$$

where v and $n(r)$ denote the charged particles velocity and the electron density of the target atoms, respectively. Within the Lindhard- Scharff model the collisions are assumed to lead to the same basic, statistically independent excitations in the atoms as in the electron gases by means of which the electronic clouds are described.

Bonderup and Hvelplund[2] have refined this description by using a more accurate expression for the straggling contribution from the various parts of the electron cloud and by applying the realistic Lenz- Jensen model for $n(r)$. The localized contribution is given by

$$\bar{\Gamma}^2(n(r),v)/\Gamma_B^2 = 1 + \{1/5 + [e^2/3\pi \hbar v_f(r)]^{1/2}\}[v_f(r)/v]^2 \cdot \ln[v/v_f(r)]^2 \quad \text{where } v \geqslant v_f$$

$$\Gamma^2(n(r),v)/\Gamma_B^2 = 1/[1+13e^2/\pi \hbar v_f(r)]^{1/2} \cdot [v/v_f(r)]^2, \quad \text{where } v \leqslant v_f \quad (3)$$

Here $v_f(r)$ is the local Fermi velocity defined by

$$v_f(r) = (\hbar/m) \cdot [3\pi^2 \cdot n(r)]^{1/3} \quad (4)$$

where m is the electron mass, $\hbar$ is the Plank constant. Similar calqulations based on the Hartree–Fock–Slater (HFS) electron densities have been performed by Chu[3]. However, the values calculated by all four of these theories are lower than experimental data measured before. Here the IPM electronic density function $n(r)$ with BH's formulation was used to calculate the energy straggling of protons in part solids and gases target. The results reveal a Z_2 oscillatory structure and energy dependence in energy straggling, and also lead to an accuracy of Hartree–Fock (HF) model.

III. THE CALCULATED RESULTS AND COMPARISON WITH EXPERIMENTS

From Eqs.2 and 3, to calculate the energy straggling for light ions in matter by using of BH's theory, the electron densities function $n(r)$ of light ion–atom system must be well–known when any model of potential was employed. As a first series for calculating the energy straggling under IPM potential, an effective charge distribution function of light ion–atom system has been given in our provious work[5], the electron density function $n(r)$ is

$$n(r) = Z_2/d^2a_0^3 \cdot H/4\pi R \cdot e^{\eta}/[H\delta(\eta)+1]^2 \cdot [1+2(H-1)/(H\delta(\eta)+1)] \quad (5)$$

where a_0 is Bohr radius ($a_0=\hbar^2/me^2$); the parameters $H=dZ_2^{0.4}$ and d were fitted by HF eigenvalues in Ref.[6] for each element; η, $\delta(\eta)$ and R are complex functions denoted as $\eta = r/a_0d$, $\delta(\eta)=e^{\eta}-1$ and $R=r/a_0$. Then one can make a numerical integration of Eq.(2) with Eqs.(3–5). In this way the reduced straggling value Γ_s^2/Γ_B^2 is calculated for a given target and a known projectile velocity.

Fig.1 shows the energy dependence of the reduced straggling for proton beams

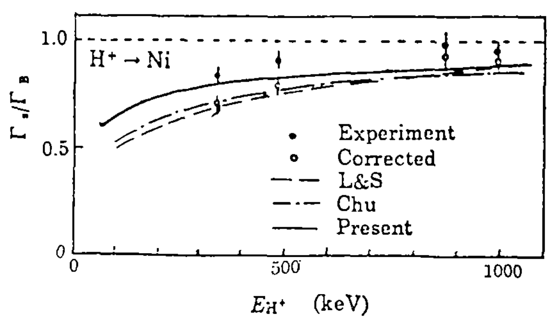

Fig.1 Reduced straggling values for the Ni film plotted as a function of incident energy of proton beams
The solid circles denote the raw data of the experiment by Y.Kido[7], the open circles denote the data corrected for film nonuniformity. the dashed, long–dashed dot–dashed and solid curves are the theoretical predictions of Bohr, Lindhard Scharff, Chu and of present, respectively.

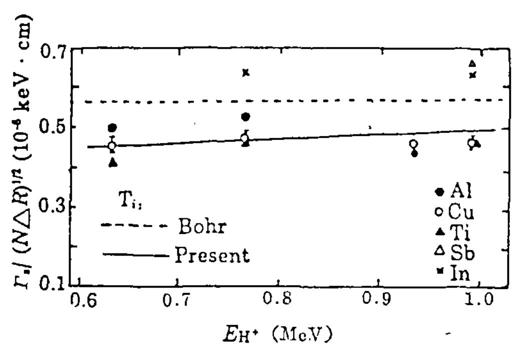

Fig.2 Normalized straggling widths vs H^+ energy
For Al, Cu, Ti, Sb and In films the experimental data by Y.Kido[8] are given as solid–circles, open–circles, solid–triangles, open–triangles and cross marks, respectively. The theoretical predictions shown by the dashed (Bohr) and solid (present) curves are only given for Ti target.

passing through Ni film. In Fig.2, the normalized straggling widths $\Gamma_s/(N\Delta R)^{1/2}$ for Al, Cu, Ti, In and Sb are plotted as a function of hydrogen ion energies. It is clear seen that the theoretical model utilized in this paper was more close to the experimental results, and a small energy dependence of the normalized straggling widths is shown in the energy region from 0.6 to 1.0 MeV.

In Fig.3 the materials Z_2 and energy dependence of normalized straggling $\Gamma_s^2/(N\triangle R)$ for proton beams in some of the gaseous target such as O, F, B, S, Cl, N and air are plotted as a function of H^+energies. The straggling values of air is close to that of nitrogen because air has an effective atomic number of 7.3 and an adjustable parameter of 0.763. The present calculations show a weak energy dependence of the normalized stragling widths, the fact that the crossover of several gaseous elements in low energies predicts the oscillatory structure of energy straggling in Z_2. On the other hand, at low velocity for light ion in matter the possibility of the core–shell electrons excitation of an atom is smaller than that of outer–shell electrons of an atom due to screening effect. Further information on the comparison between here predictions and other recent experiments will be given in future.

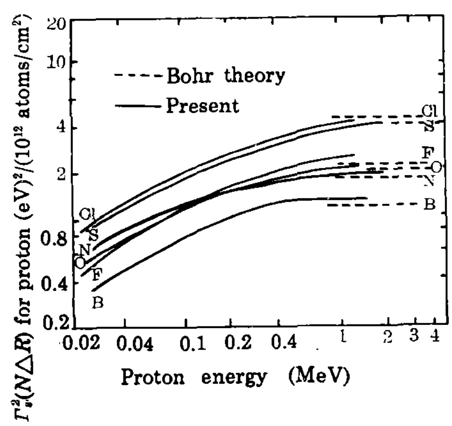

Fig.3 Normalized straggling widths of protons in some gases

IV. CONCLUSIONS

Because the experiments of measuring the energy straggling for protons in solids have been made by Y.Kido with the advantages for smooth target films and good energy resolution of nuclear resonance reaction method, the good agreement between present calculations and the data measured makes that the IPM is more possible to calculate the energy straggling for light ions in solids. The energy straggling for proton beams in gaseous elements is of Z_2 and energy dependences which relate to outer electron distribution and core electeron screening of an atom. Moreover, this theoretical method not only supports recent experiments but also is simpler and more explicit.

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