RUTHERFORD BACK SCATTERING OF PROTONS AT MEDIUM ENERGIES*

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In the 3–20 keV energy range for light ions we are on the threshold of validity for the Lindhard–Scharff theory, but the screening is sufficiently small for the screened Coulomb scattering to be approximated by Rutherford scattering. Using the Rutherford scattering cross section, McCracken and Freeman (1969) showed that, for an incident ion of energy E_0 and atomic number Z_1 upon a target of atomic number Z_2,

$$N_E = -1\cdot 42\, f(z)\, I(E/E_0)\, E_0^{-3/2}\,, \tag{1}$$

where N_E is the *total* number of back-scattered ions with energy exceeding E, $I(E/E_0)$ is an integral which McCracken and Freeman plotted numerically in their paper, and the function $f(z)$ is approximated by Z_2^2, for $Z_1 \ll Z_2$. For heavy targets the

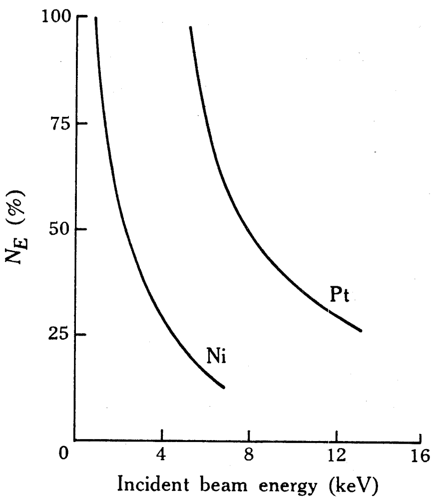

Fig. 1.—Plot of N_E as a function of incident beam energy for protons upon platinum and nickel targets, taking $E/E_0 = 0\cdot 1$ and assuming Rutherford scattering.

screening is not negligible and the expression (1) is only qualitative. However, it does predict the observed changes in N_E with E_0 to considerable accuracy, for energies in the several keV range.

Figure 1 shows a plot of N_E against the incident ion energy, with $E/E_0 = 0\cdot 1$ and the appropriate value of $I(E/E_0)$, for platinum and nickel targets. The trends are clearly the same as those shown by the experimental results in Figure 24 of Cawthron,

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Cotterell, and Oliphant (1969*b*). In order to obtain the total scattering for particles of several keV energy it is thus possible to approximate the exact scattering cross section by the Rutherford cross section.

Considering some numerical values, we see that at 4 keV equation (1) predicts $N_E \simeq 25\%$ for protons incident upon nickel, while from Figure 24 of Cawthron, Cotterell, and Oliphant (1969*b*) the value of α_{n}, the total fraction of the incident beam scattered as neutrals, is $\simeq 40\%$. At 8 keV incident proton energy, the scattering from nickel has decreased too sharply for accurate comparison; however, for platinum, the values for N_E and α_{n} are about 50% and 40% respectively. Thus, considering the approximations made in calculating N_E and α_{n}, the agreement is quite satisfactory. This agreement indicates that, at these energies, the majority of back-scattered particles are without charge.

Cawthron, Cotterell, and Oliphant (1969*b*) showed that when protons are back-scattered from platinum targets (at 90° angle of scattering) the majority of scattered *ions* possess more than 78% of the incident particle energy E_0. In that paper the values for α_{n} were calculated from the expression

$$\alpha_{\mathrm{n}} = \{i_{\mathrm{c}}/i_{+} - (\alpha_{+} - \alpha_{-}) - \gamma(\alpha_{+} + \alpha_{-})\}/\gamma\,, \tag{2}$$

where i_{c} is the measured current to the electron collector, i_{+} is the incident beam current, α_{+} and α_{-} are the fractions of the incident beam scattered as positive and negative ions respectively, and γ is the secondary electron emission coefficient for the collector (nickel in the experiment). The coefficient γ is assumed to be independent of particle charge at a given energy (Cawthron, Cotterell, and Oliphant 1969*a*).

Now, for 5 keV protons incident upon a platinum target, $\alpha_{+} \simeq \alpha_{-}$ (Cawthron, Cotterell, and Oliphant 1969*b*) and so (2) becomes

$$\alpha_{\mathrm{n}} = \{i_{\mathrm{c}}/i_{+} - \gamma(\alpha_{+} + \alpha_{-})\}/\gamma$$

or, as obviously $\alpha_{\mathrm{n}} + \alpha_{+} + \alpha_{-} = 1$,

$$i_{\mathrm{c}}/i_{+} = \gamma\,.$$

The values of i_{c}/i_{+} ($= R$, the apparent total scattering coefficient) were presented in Figure 1 of Cawthron, Cotterell, and Oliphant (1969*b*); for 5 keV protons incident upon a platinum target, $R \simeq 48\%$, and thus $\gamma \simeq 48\%$ for the particles striking the collector. Referring to Figure 2A of Cawthron, Cotterell, and Oliphant (1969*a*),* we see that, for a secondary electron emission coefficient of 48%, the equivalent particle energy is 3·5 keV. Thus the "average energy" of the scattered particles from the target is 3·5 keV, or 70% of the incident energy. Of course this is a very rough calculation, but as most of the scattered particles are neutral, as discussed above, we can infer that the energy spectra of the scattered neutrals are probably considerably broader than those for charged particles.

In the above discussion several sets of experimental data have been used to establish that back-scattering of protons from metal targets, in the 3–10 keV energy range, is approximately Rutherford and that the back-scattered particles are predominantly neutral up to several keV, with an average energy less than that of

* The vertical coordinates of Figure 2A, for proton and deuterium ions on various targets, should read 1, 2, 3, ... in that paper.

the scattered protons alone. This confirms that incident protons penetrating some distance into the target pick up electrons and are scattered as neutrals, the cross section for such scattering increasing sharply with decreasing incident particle energy over this energy range.

References

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