APPLICATION OF HIGH ENERGY CHARGE TRANSFER TO BEAM DIAGNOSTICS

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Charge transfer atomic reaction induced by high energy beams on solid materials is shown to be applicable to the beam diagnostics. The yield of the reaction is discussed in some detail.

The atomic collisions of fast heavy particles in solid materials are known with their very small deflection angles and the presence of charge transformation probability (charge transfer rection). There is an interesting calculation1) on the angular distribution of neutralized protons in the P+H → H+P reactions at energies of larger than 10 MeV, in which a local maximum peak is predicted at 1.6 minutes. This means that the momentum transfer in the reaction is of the order of 10^{-4}. For heavier projectiles, it is evident that the larger mass difference between electrons and projectiles works as a further reduction factor for the angular spread of the scattered particles. It is to be noted that these perturbations caused by the reaction are small compared to the moemtnum widths and emittances of the beams from the usual accelerators.

This feature of the atomic collision is of great interest since it provides us a new tool for the beam diagnostics. An idea of its application has been suggested in ref.2) and an example of the use in the calibration of a magnetic spectrograph is seen in ref.3). In this short note we will briefly discuss how large yield we can expect for charge transfer reaction, which is of considerable importance from the practical view point.

It has been shown that the charge exchange collision in solid targets at high energy can well be explained as a sequential process of electron capture and electron stripping as usually seen in gas targets4). Let us take the case of ${}^3He^{2+} \rightarrow {}^3He^{1+}$ reaction in solid as an exapmle. The yield of the ${}^3He^{1+}$ ions is given by the following expression;

$$Y = N_0\ \sigma_c/\sigma_s\ [1- \exp(-\sigma_s t)], \qquad (1)$$

where N_0 is the intensity of the primary beam, t the target thickness and σ_s and σ_c, respectively, are electron capture (${}^3He^{2+} \rightarrow {}^3He^{1+}$) and electron stripping (${}^3He^{1+} \rightarrow {}^3He^{2+}$) cross sections in the target. For large $\sigma_s t$ values, it is clear that the yield takes a constant value at $N_0\sigma_c/\sigma_s$. This state is called charge equilibrium. Fig.1 is our experimental data2) showing the dependence of the yield on the target thickness for the 130 MeV ${}^3He^{2+}$ ions on carbon targets. The σ_c/σ_s is seen to be of the order of 10^{-8} for the present case. The figure also shows that the yield is reasonably large to allow the use of the conventional nuclear radiation detectors for measuring the 'charge transformed particles'. Fig.2 shows the dependence of the yield on the atomic number of target materials, which was measured in the same experiment2). It may be seen that the yield can be controlled within the range of an order of magnitude by selecting the materials for the target.

In the yield estimation for the arbitrary projectiles on the arbitrary materials, one has to rely on the theoretical predictions. Born calculation explains σ_s quite well. The theory by Gillespie5) shows the σ_s can be written in the form $\sigma_s = 8\pi a_0{}^2/V_1{}^2(I_1 + I_2/V_1{}^2)$, where a_0 is Bohr radius, V_1 the projectile velocity in atomic unit and I's are functions of the atomic numbers of the projectile (Z_p) and target (Z_t). The σ_s has a moderate dependence on V_1 and takes values around $10^{-17} \sim 10^{-18}$ cm^2/atom for the cases shown in fig.2.

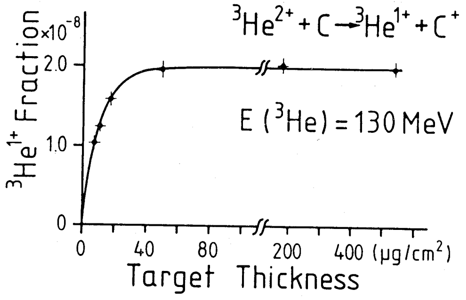

Fig. 1.
Thickness dependence of $^3He^{1+}$ yield from carbon. The solid curve is a least square fitting result using eq.(1).

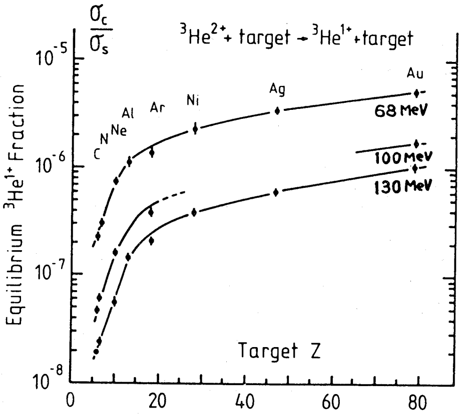

Fig. 2.
Equilibrium charge fraction of $^3He^{1+}$ as a function of target atomic number Z_t at 68, 100 and 130 MeV. The solid lines are to guide the eye.

The correct estimation of σ_c is still a challenging problem for theoreticians6). A convenient way to estimate it is to use the first order Born calculation7,8). Nikolaev8) introduced a semiempirical correction factor for the calculation to explain experimental data. The more sophisticated theory including the higher order Born terms9) have been developed only for the restricted cases of special electron transitions. For the projectile velocities much larger than the target K-electron velocity, σ_c behaves6) as $\sigma_c \propto Z_p{}^5 Z_t{}^5 V_I{}^{-12}$, which is of the order of nuclear cross section for the cases shown in fig.2. For heavier ions, a semiempirical scaling law of σ_c is helpful10).

The above estimations result in σ_s and σ_c of the order of 10^{-17} and 10^{-25} cm^2/atom, respectively, for the 130 MeV ^{3}He ions on the carbon target. The mean free path of the $^3He^{1+}$ ions in carbon, therefore, becomes so small that all the $^3He^{1+}$ ions emerging from the target may well be considered to be produced at the exit face of the target. This means that the effects of energy straggling and multiple scattering are common for all the outgoing particles irrespective of their charge states, which also supports the applicability of charge transfer to the beam diagnostics.

References

1) R. Shakeshaft and L. Spruch, J. Phys. 11 (1978) L457.
2) I. Katayama, G.P.A. Berg, W. Hurlimann, S. Martin, J. Meissburger, W. Oelert, M. Rogge, J.G.M. Romer, J. Tain and B. Styczen, to be published in Phys. Lett. A; Contribution to 8th International Conf. on Atomic Physics (Goteburg 1982) B57.
3) I. Katayama, S. Morinobu, Y. Fujita, M. Fujiwara, T. Yamazaki and H. Ikegami Nucl. Instr. Meth. 171 (1980) 195.
4) M.C. Cross, Phys. Rev. B15 (1977) 602.
5) G.H. Gillespie, Phys. Rev. A18 (1978) 1967.
6) R. Shakeshaft and L. Spruch, Rev. Mod. Phys. 51 (1979) 369.
Dz. Belkic, R. Gayet and A. Salin, Phys. Rep. 56 (1979) 279.
7) M.R.C. McDowell and J.P. Coleman, Introduction to the Theory of Ion-Atom Collision (Amsterdam, North-Holland 1970).
8) V.S. Nikolaev, Sov. Phys. JETP 24 (1967) 847.
9) R.M. Drisko, PhD Thesis Carnegie Inst. of Technology 1955, unpublished.
10) H. Knudsen H.K. Haugen and P. Hvelplund, Phys. Rev. A23 (1981) 597.