Effective charge state of projectiles

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Introduction

Synthesis of superheavy nuclei includes the process of heavy ion fusion reactions. An electron capture and loss processes, which occur with high probability in ion—atom collisions, cause the charge of high-speed ions travelling through matter to fluctuate. The investigation of fission fragments and alpha rays leads to the concept of concept of charge-changing phenomena. Later on, particle accelerators have become more efficient to produce heavy ions in high-charge states. Kreussler et al., [1] investigated dependence of effective charge of projectile on target.

Using a Monte Carlo based simulation known as SRIM and TRIM a group of programs which calculate the stopping and range of ions (10eV^{-2} GeV/amu) into matter using a quantum mechanical treatment of ion-atom collisions, matter can be created [2]. The ion and atom undergo a screened Coulomb collision during collisions, which includes exchange and correlation interactions between the overlapping electron shells. Long-range interactions between the ion and the target result in electron excitations and plasmons. Hence in the present work we have analyzed effective charge state of different projectiles such as ^{4}He, ^{16}O, ^{27}Al, ^{40}Ca, ^{63}Cu, ^{107}Ag and ^{127}I on targets such as ^{208}Pb and ^{238}U is studied.

Theoretical Framework

Two models are used to study the charge state inside the solid. First one is the Bohr-Lindhard [3] and the Betz-Grodzins [4] models. Another method is inferring the charge state of the ions inside the solid is from its energy loss. This has led to the concept of the effective charge [5]. The number of electrons were effectively carried by heavy ions. Using perturbation theory.

$$\frac{Z_{eff}}{Z'_{eff}} = \left[\frac{S_{\exp}(\upsilon, Z_1)}{S_{\exp}(\upsilon, Z'_1)}\right]^{1/2} \quad (1)$$

where $S\exp(v, Z_1)$ is the experimental stopping power of the ion Z_1 and $S\exp(v, Z_1)$ is the corresponding stopping of a chosen reference ion with atomic number Z_1**.** Usually hydrogen or helium ions are taken as reference with the same velocity v.

The swift velocity of electrons by Thomas Fermi model are evaluated as follows;

$$q_{eq}e \cong Z_1 e(1 - e^{-\upsilon/\upsilon_{TF}})$$
(2)

The Thomas-Fermi velocity is given by

$$\upsilon_{TF} = Z_1^{2/3}\upsilon_0 \quad (3)$$

The empirical formula for mean charge state using Fermi gas model [6] is as follows;

$$q_m = Z_1\left(1 - \frac{\upsilon_F}{\upsilon_1}\right) \quad (4)$$

where, Z_1, υ_F and υ_1 are the atomic number of projectile, Fermi velocity of target electron and velocity of projectile respectively. Among the effective charge state and mean charge state, effective charge state is important in accelerator Physics.

Results and Discussions:

Using Thomas Fermi model, the effective charge state of projectiles such as ^{4}He, ^{16}O, ^{27}Al, ^{40}Ca, ^{63}Cu, ^{107}Ag and ^{127}I on targets such as ^{208}Pb and ^{238}U were studied as explained in the theory section. The effective charge state has been evaluated using Northcliffe's scaling rule. The term stopping potential $\left(\frac{dE}{dx}\right)_{Z_1=1}$ is evaluated by the code SRIM [2]. The stopping power is not directly proportional to power of the charge.

Furthermore, the effective charge projectiles and targets were plotted as a function of ion energy. The figure 1(a) shows the variation of effective charge of ^{4}He projectile as a function of ion energy on ^{208}Pb and ^{238}U targets. From this figure it is clear that the, initially the effective charge state is having smaller value and as the ion energy increases the charge state of the projectile also increases. Whereas, in figure 1(b-g), the effective charge state of projectiles such as ^{16}O, ^{27}Al, ^{40}Ca, ^{63}Cu, ^{107}Ag and ^{127}I on ^{208}Pb and ^{238}U targets with ion energy per nucleon.

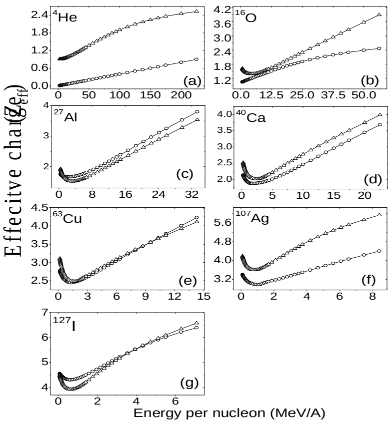

Fig 1: A plot of effective charge state of projectile such as ^{4}He, ^{16}O, ^{27}Al, ^{40}Ca, ^{63}Cu, ^{107}Ag and ^{127}I on targets such as ^{208}Pb and ^{238}U with ion energy per nucleon.

From these figures it is clear that the value of effective charge state initially decreases with increase in ion energy per nucleon. These effects are due to an increase in Colombian force of repulsion and nuclear force of attraction between projectile and the medium through which the projectile enters. Again, there is a gradual increase in effective charge state of projectile due to an interaction between the projectile and target nuclei.

Furthermore, we have also evaluated and predicted effective charge state of projectiles in targets for different fusion reactions. The table-1 shows the tabulation of Tabulation of projectile-target combinations with ion energy per nucleon and effective charge state of projectile on target nuclei. From this table it is inferred that the value of effective charge state increases with increase in projectile atomic and mass number. Hence, the role of effective charge state plays an important role in the heavy ion fusion reactions.

Table-1: Tabulation of projectile-target combinations with ion energy per nucleon and effective charge state of projectile on target nuclei.

Projectile	Target	Energy/A	Effective Charge State
^{4}He [5]	^{208}Pb	7.69	0.03
^{16}O [6]	^{208}Pb	5.375	1.21
^{40}Ca [7]	^{208}Pb	7.83	2.39
^{4}He [8]	^{238}U	5.65	0.91
^{16}O [9]	^{238}U	5.25	1.39
^{40}Ca [10]	^{238}U	4.58	2.28

Conclusions:

The effective charge state of a projectile has been studied using Thomas–Fermi model. The effective charge state of ^{4}He, ^{16}O, ^{27}Al, ^{40}Ca, ^{63}Cu, ^{107}Ag and ^{127}I on targets such as ^{208}Pb and ^{238}U have been studied. The effective charge state increases with increase in energy per nucleon. The role of effective charge state on heavy ion fusion reactions gives an insight on the synthesis of superheavy element.

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