Orbiting as an interface of the atomic and nuclear process

Yash Kumar and T. Nandi*
Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi - 110067, INDIA

Introduction

The range and coupling constant of the electromagnetic and strong force is vastly different. Therefore, the atomic and nuclear phenomena are expected not to interfere with each other. However, this is not always true and some phenomena have been found exhibiting an interference between the atomic and nuclear regimes [1]. In a recent paper Sharma and Nandi have reported experimental evidence for a new event, where the projectile-ion x-ray energies are measured as a function of ion beam energies, and a sudden increase in the x-ray energy was observed for the systems ^{12}C(^{56}Fe,^{56}Fe), ^{12}C(^{58}Ni,^{58}Ni) and ^{12}C(^{63}Cu,^{63}Cu) [2]. They have successfully described this result in terms of shake-off ionization due to nuclear recoil. However, this explanation fails to account for the anomalous large angle elastic scattering seen in light-heavy ion reactions ($20 \leq A_{target} + A_{projectile} \leq 100$) [3]. Here, we propose an explanation satisfying both the abrupt ionization and anomalous scattering.

Nuclear Orbiting

Enhanced large angle yields in elastic, quasielastic and energy damped inelastic channels in light-heavy ion reactions have been well-studied [3, 4]. For the systems mentioned above, the elastic scattering cross-sections (calculated using FRESCO [5]) clearly show the backward angle rise (Fig. 1). This anomalous behaviour was successfully explained in terms of nuclear orbiting [6]. In ion-atom collisions, as the beam energy increases the projectile enters a region where a local maximum of the effective potential is reached and satisfies the following condition:

$$\frac{d(V_{nuclear} + V_{cb} + V_{centrifugal})}{dr} = 0 \qquad (1)$$

At this energy, the projectile goes around the target many times before exiting through the entrance channel. This phenomenon is called nuclear orbiting [7, 8]. Though initially the orbiting was thought to occur only at high energies, it has been shown later [9] that it can also be prevalent in lower energies. In the orbiting, the total kinetic energy of the projectile is transformed into the potential energy of the long-lived di-nuclear system at the orbiting radius. Instead of forming a compound nucleus, due to weak absorption in fusion channels, the orbiting complex decays back to the entrance channel.

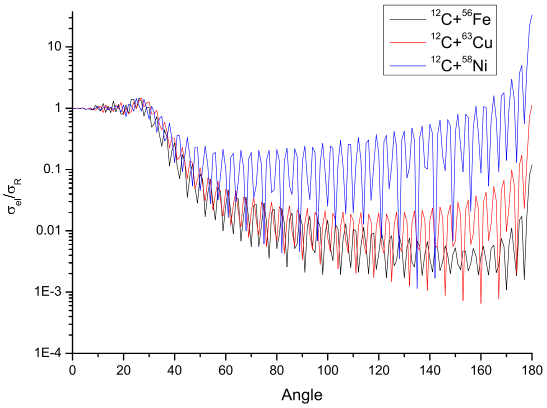

FIG. 1: The graph represents the calculated angular distribution of the relative elastic cross-section for three different systems using the code FRESCO [5].

Present Model

The sudden jump observed in the projectile x-ray energies [2] can be explained in terms of a long-lived orbiting di-nuclear complex.

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*Electronic address: `nanditapan@gmail.com`

Since the two nuclei spend a large span of time before they leave the composite, the Coulomb potential of an electron in the projectile ion can be altered as follows:

$$V(r) = \frac{-(Z_p + C \times Z_t) \times e^2}{4\pi\epsilon_0 r} \qquad (2)$$

where r, Z_p and Z_t are the orbiting radius, the atomic numbers of projectile and target, respectively. C is a constant ($0 < C < 1$) which depends on the lifetime of the composite. According to equation (2), the projectile x-ray energy is enhanced with C. Hence, the experimental jump of the x-ray energy ($\triangle E_x$) can simply be scaled to the $(Z_p + C \times Z_t)^2$ to obtain the value of C for the corresponding system as given in Table. I. We postulate that the value of C varies with the lifetime of the composite as

$$C(t) = 1 - exp(-t/t_0) \qquad (3)$$

where t_0 is a characteristic time relevant to the x-ray emission line of the projectile ion, e.g. for Ly α transition, $t_0 = r_2/v_2$, where r_2 and v_2 are the electronic radius and velocity for $n = 2$ orbital, respectively. $C(t = 0) = 0$ and $C(t = \infty) = 1$. When the value of C is one, it implies that the system has interacted long enough to undergo fusion. Using the values of C calculated from the above method, the lifetime of the orbiting di-nuclear complex can be estimated. In Table. I the lifetimes obtained are compared with the calculated time required for the orbiting system to reach a statistical equilibrium using the code HICOL [10].

TABLE I: Determination of the lifetime of the di-nuclear complex. Here, $\triangle E_x$, $\triangle Z$, as and zs are the measured jump in the x-ray centroid energies (in MeV), $C \times Z_t$, attosecond and zeptosecond, respectively. The characteristic time t_0 is estimated for 1s2s2p^{2}P terms of the Li-like projectile ions. The value t and t_h represent the lifetime calculated using model and computed from HICOL, respectively. The first column represents the projectile ion on the ^{12}C target.

	$\triangle E_x$	E_x	$\triangle Z$	C	$t_0(as)$	$t(zs)$	$t_h(zs)$
^{56}Fe	0.025	6.6	0.0394	0.0066	0.146	0.96	1.3
^{58}Ni	0.032	7.67	0.0547	0.0091	0.126	1.15	1.24
^{63}Cu	0.035	8.3	0.0611	0.0102	0.117	1.19	1.19

Conclusion

We have proposed a phenomenological model to explain the sudden jump in x-ray energies vs beam energy curve [2] in terms of nuclear orbiting. Good agreement between the predicted lifetime values of orbiting complexes from the present model and the computational values from the code HICOL validates the assumptions considered in formulating the model. Hence, the contribution from both the shake-off ionization induced by nuclear recoil and nuclear orbiting are required to explain the observed kink. Our study thus gives physical insights on both the interference between nuclear and atomic phenomena and nuclear orbiting phenomena near the barrier energies.

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References

[1] M. S. Freedman, Annual Review of Nuclear Science, **24**, 209(1974).

[2] P. Sharma and T. Nandi, Phys. Rev. Lett. **119**, 203401(2017).

[3] P. Braun-Munzinger and J. Barrette, Physics Reports **87**, 209-258(1982).

[4] S. J. Sanders et. al., Physics Reports **311**, 487-551(1999) and references therein.

[5] I. J. Thompson, Computer Physics Reports **7**, 167-212(1988).

[6] D. Shapira et. al., Phys. Rev. Lett. **43** 1781(1979).

[7] C. A. Bertulani and P. Danielewicz, Introduction to Nuclear Reactions,(Taylor & Francis, 2004).

[8] Kenneth W. Ford and John A. Wheeler, Ann. of Phys. **7**, 259-286(1959).

[9] Amlan Ray, Nuclear Physics A **787** 499c-506c(2007).

[10] H. Feldmeier, Rep. Prog. Phys. **50** 915 (1987).