# Orbiting as an interface of the atomic and nuclear process

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# 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 shakeoff 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 ionatom collisions, as the beam energy increases the projectile enters a region where a local maximum of the effective potential is reached



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

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.

## **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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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:

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

TABLE I: Determination of the lifetime of the dinuclear 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  $1s2s2p^2P$  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)	$t_h(zs)$
<sup>56</sup> Fe	0.025	6.6	0.0394	0.0066	0.146	0.96	1.3
<sup>58</sup> Ni	0.032	7.67	0.0547	0.0091	0.126	1.15	1.24
<sup>63</sup> Cu	0.035	8.3	0.0611	0.0102	0.117	1.19	1.19

the value of C varies with the lifetime of the composite as

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

where  $t_0$  is a characteristic time relevant to the x-ray emission line of the projectile ion, e.g. for Ly  $\alpha$  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) = 0and  $C(t = \infty) = 1$ . 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].

### 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

- 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).