e-ISSN: 2455-667X

Annals of Natural Sciences
(Peer Reviewed and UGC Approved International Journal)
Vol. 3(3), September 2017: 135-139
Journal's URL: http://www.crsdindia.com/ans.html
Email: crsdindia@gmail.com

Annals of Natural Sciences

ORIGINAL ARTICLE

Number of Nucleons of Target Nucleus, Participating in Heavy-Ion Collisions

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ABSTRACT

To understand the reaction mechanism of nucleus-nucleus interactions, the Fire-ball model of heavy-ion interactions has been considered in the present work. This model refers to the participant and spectators of target and projectile produced at high energies. The number of nucleons of the target nucleus, participating during fire-ball formalism, is calculated using Swaiticki's formula. The heavy-ion collisions ^{12}C+ ^{16}O and ^{20}Ne + ^{238}U are considered for such calculations. The validity of the results is explained on the basis of the distribution of nucleon density inside the nucleus and the explanation has been found to be in well agreement with the nuclear density curve.

Key words: *Heavy-ion collisions, nucleus-nucleus collisions, fire-ball model, abrasion-ablation*

Received: 14th June 2017, Revised: 23rd August 2017, Accepted: 26th August 2017

How to cite this article:
Gupta J.P. (2017): Number of Nucleons of Target Nucleus, Participating in Heavy-Ion Collisions. Annals of Natural Sciences, Vol. 3[3]: September, 2017: 135-139.

INTRODUCTION

During last six decade or so, it has become possible to accelerate heavy ions to energy, sufficient to enable them to surmount the coulomb barrier of a range of target nuclei. The fragmentation of target as well as of projectile and the production of nuclear fragments, exotic nuclei and super-heavy nuclei as well as their mass and energy spectra are the reasons behind the growing interest in such reactions. The history of modern heavy-ion interaction starts in 1960 with the famous study by Bromley, Kuehner and Almqvist (Bromley, D.A. 1960, Kuehner, J.A. 1963, and Almqvist, E. 1963).

Various models have been proposed to account for nucleus-nucleus interaction behavior and to explain the experimental results, viz; Rows on Rows model (Hufner, J. 1977), Sharp Cut-off Model (Dar, A. 1957), Knock-out model (Koonin 1977), Optical model and Fire-ball model (Myers, W.G., 1978), etc. The Fire-ball model of heavy-ion collisions have been considered to study in the present work. The heavy-ion collisions at high energies produce large showers of different kinds of particles. Nucleons, light nuclei and some types of hadrons have been observed over a wide range of energy and angle (Brambilla, 2011). These products seem to be associated with three distinct sources. In the more peripheral collisions, substantial parts of both the target and projectile may survive, but may be in highly excited states leading to particle emission. The overlapping parts of the two nuclei fuse together in highly excited state and form a fire-ball. The particles and fragments produced from the fire-ball are likely to have a wide velocity and angular distribution. The value of the impact parameter plays a crucial role in such reactions. For central collisions, where the entire projectile overlaps the targets, no projectile spectator survives as such and the entire nucleus seems to be involved.

The target and the projectile make clear cut of cylindrical form through each other, leaving the spectator piece of target and if the impact parameter is sufficiently large, also a spectator of projectile. The sharp cut parts of both the nuclei fuse together. The projectile participants transfer their momentum to the effective centre of mass system of all the participant nucleons forming the fire-ball (Spousta, 2013 and David, 2008). The average internal kinetic energy per nucleon is much higher than the binding energy per nucleon.

PRESENT WORK

The number of nucleons of target and projectile, participating in fire-ball may be calculated as a function of impact parameter, by calculating the volume of intersection of sphere and a cylinder. Assuming spherical symmetry of nuclei, with radii $R = 1.2A^{1/3}$ Fm. and straight trajectories, the volume of the related problem may be obtained. The number of nucleons from the target nucleus, participating in the fire-ball is given by (Bowmaid 1975),

$$N_t = A_t.F(\nu,\beta) \qquad \text{........(1)}$$

Where A_t is the mass number of the target nucleus and F is a function of two dimensionless parameter ν and β, where $\nu = [R_t/(R_t + R_p)]$ and $\beta = [b/(R_t + R_p)]$. Here R_t and R_p are the radii of target and projectile respectively and b is the impact parameter. For the calculation of the function F, the following four approximate formulae may be used in four different situations as follows *i.e.*

(i). If the radius of the target nucleus is larger than that of projectile $R_t > R_p$, and a cylindrical hole is gauged in the target nucleus A_t, then the function F_I may be given as,

$$F_I = [1-(1-\mu^2)]^{3/2}[1-(\beta/\nu)^2]^{1/2} \qquad \text{........(2)}$$

(ii). When a cylindrical channel is gauged in the target with a radius smaller than that of A_t, there may be three possibilities,

(a) $2R_p \le R_t$ (b) $R_t \le 2R_p \le 2R_t$ and (c) $R_t \le R_p$, then,

$$F_{II} = \frac{3}{4}(1-\nu)^{1/2}\left(\frac{1-\beta}{\nu}\right)^2 - \frac{1}{8}\left[\frac{3(1-\nu)^{1/2}}{\mu} - \frac{[1-(1-\mu^2]^{3/2}][1-(1-\mu^2)]^{1/2}}{\mu^3}\right]\left(\frac{1-\beta}{\nu}\right)^3 \qquad \text{........(3)}$$

(iii). When a cylindrical channel is gauged in the target with a radius larger than that of R_t, there may be two possibilities

(a) $R_t \le 2R_p \le R_t$ and (b) $R_t \le R_p$ then,

$$F_{III} = \frac{3}{4}(1-\nu)^{1/2}\left(\frac{1-\beta}{\nu}\right)^2 - \frac{1}{8}\left[3(1-\nu)^{1/2}-1\right]\left[\frac{1-\beta}{\nu}\right]^3 \qquad \text{........(4)}$$

(iv). When the entire target is obliterated by the projectile i.e. the radius of the projectile is larger than that of the target nucleus, then,

$$F_{IV} = 1 \qquad \text{........(5)}$$

These approximations are based on the solution for a number of limiting situations when analytical expressions can be derived. In the present work an effort is made to calculate the number of target nucleus nucleons, participating in fire-ball as a function of impact parameter. The heavy-ion interactions $^{12}C + {}^{16}O$ and $^{20}Ne + {}^{238}U$ have been considered for such calculations.

RESULTS AND DISCUSSION

Since the radii of the targets are greater than the radii of the projectiles in the considered heavy-ion collisions, according to the reaction mechanism, only the functions F_I and F_{II} are used to calculate the number (N_t) of nucleons from the target nucleus, participating in nuclear fire-ball. For the different values of impact parameter 'b', the results of the calculations, for the heavy-ion interactions $^{12}C + {}^{16}O$ and $^{20}Ne + {}^{238}U$ are presented in the Table- 1.

Table1: The number of nucleons of targets participating in the fire-balls produced in the heavy-ion collisions $^{12}C + ^{16}O$ and $^{20}Ne + ^{238}U$

S.No.	Heavy-ion interaction $^{12}C + ^{16}O$ R_t = 3.024 fm and R_p = 2.747 fm		Heavy-ion interaction $^{20}Ne + ^{238}U$ R_t = 7.44 fm and R_p= 2.74 fm	
	Impact Parameter 'b' (fm)	N_t	Impact Parameter 'b' (fm)	N_t
1.	0.0	15	0.0	64
2.	0.25	15	0.5	64
3.	0.50	14.5	1.0	64
4.	0.75	14	1.5	63
5.	1.00	13	2.0	62
6.	1.25	12	2.5	61
7.	1.50	11	3.0	59
8.	1.75	10	3.5	56
9.	2.00	9	4.0	53
10.	2.25	8	4.5	49
11.	2.50	7	4.7	44
12.	2.75	6	5.0	40
13.	3.00	5	5.5	37
14.	3.50	3.5	6.0	30
15.	3.75	3	6.5	24
16.	4.00	2.5	7.0	20
17.	4.25	2	7.5	17
18.	4.50	1.4	8.0	12
19.	4.75	1	8.5	8
20.	5.00	0.5	9.0	5
21.	5.25	0.2	9.5	3
22.	5.50	0.0	10.0	1
23.	5.77	0.0	10.2	0.0

For the heavy-ion interaction $^{12}C + ^{16}O$, R_t = 3.024 fm and R_p = 2.747 fm, (i.e. $R_t > R_p$). Thus the minimum value of impact parameter should be zero and with reference to case I (i.e. for F_1) the maximum value of impact parameter is ($R_t - R_p$) = 0.277 fm and similarly w.r.t. case II (i.e. for F_{II}) the maximum value of impact parameter is ($R_t + R_p$) = 5.771 fm. In the similar manner for the heavy-ion interaction $^{20}Ne + ^{238}U$, R_t = 7.44 fm and R_p = 3.26 fm, (i.e. $R_t > R_p$). Thus the minimum value of impact parameter should be zero and with reference to case I (i.e. for F_I) the maximum value of impact parameter is ($R_t - R_p$) = 4.18 fm and w.r.t. case II (i.e. for F_{II}) the maximum value of impact parameter is ($R_t + R_p$) = 10.7 fm. The other two cases (i.e. for F_{III} and F_{IV}) are not applicable in such collisions.

The calculated values of the number of nucleons of the target nucleus, participating in nuclear fire-ball have been plotted against the impact parameter in the Fig. 1 and Fig. 2.

As we can see from the results of the calculations, the values of N_t decreases on increasing the values of the impact parameter 'b'. Larger the value of 'b', smaller is the extent of the overlap of the target and projectile nuclei. Consequently, the number of nucleons participating in the nuclear fire-ball should decrease. The rate of decrease in the value of N_t increases as one goes from head-on collision to the grazing reaction. The features of the curve, showing the variation N_t with 'b' reproduces the variation of the density of nuclear matter as a function of nuclear radius. Consequently, the maximum emission of nucleons takes place in head-on collisions between the two nuclei. But on increasing the impact parameter, the probability of the emission of nucleons decreases and at the grazing reaction the emission probability is negligible.

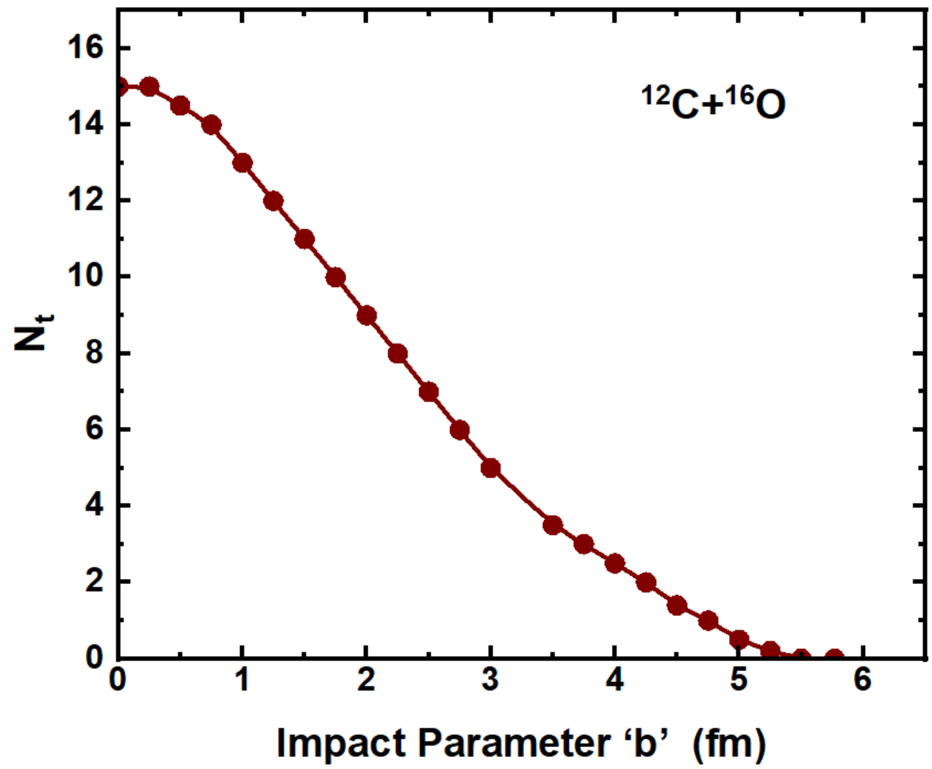

Fig. 1: Variation of the number of target nucleus nucleons, participating in the nuclear fire-ball as a function of impact parameter for ^{12}C+ ^{16}O interaction

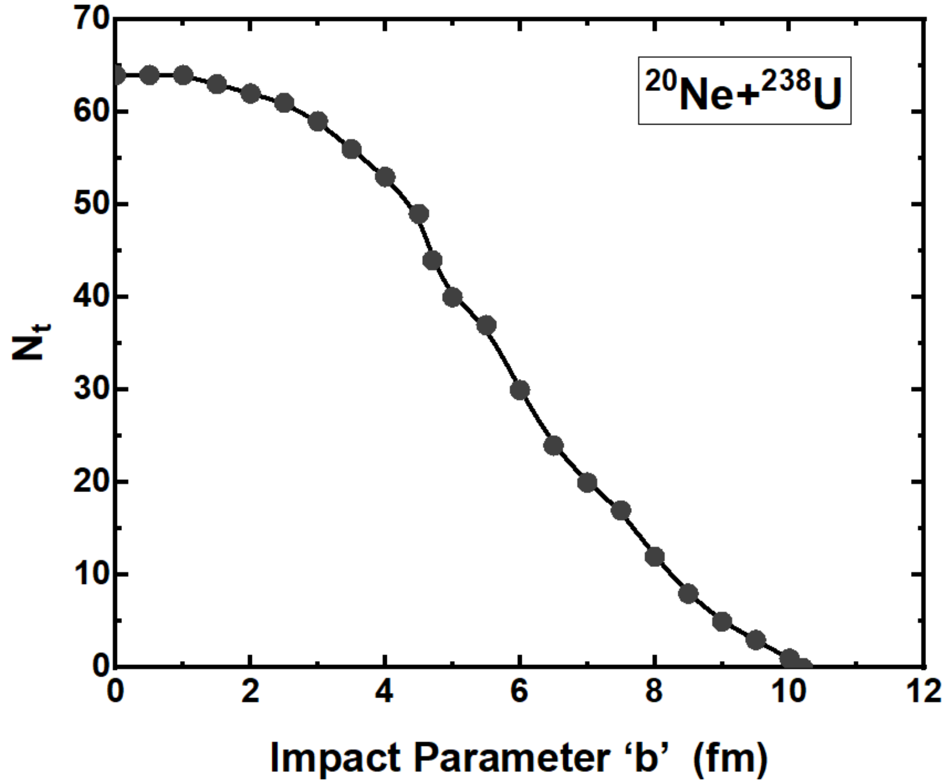

Fig. 2: Variation of the number of target nucleus nucleons, participating in the nuclear fire-ball as a function of impact parameter for ^{20}Ne + ^{238}U interaction.

CONCLUSION

From the results of present study, we conclude that the number of nucleons of the targets, participating in the nuclear fire-ball, produced in heavy-ion interactions, is maximum in head-on collisions. This number decreases on increasing the impact parameter and tends to become zero at grazing reactions. The results, broadly, follow the features of the distribution of nuclear matter.

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