Investigation of Carbon and Oxygen Induced Fusion Reactions

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Abstract: *Fusion reactions involving moderately light projectiles such as carbon and oxygen are of significant interest due to their potential to overcome the high Coulomb barriers that usually inhibit fusion in heavier systems. The study highlights the critical roles of Coulomb interaction parameters and center of mass energy in carbon and oxygen induced fusion reactions. Using a statistical approach and computational modeling, the study finds an optimal range of entrance channel parameters that maximize fusion probability. Outside this range, the chance of fusion drops. Results highlight the interplay between nuclear forces and quantum effects, contributing to a better understanding of fusion mechanisms and supporting efforts in synthesizing new super-heavy elements. This article aims to examine the influence of Coulomb interaction parameters and center of mass energy on fusion cross sections in carbon and oxygen induced nuclear reactions.*

Keywords: Fusion reactions, Coulomb interaction, center of mass energy, fusion cross section

1. Introduction

Nuclear Fusion is a process in which one or more light atomic nuclei combine to form a relatively heavier nucleus, releasing energy in the process. This is the process that powers the sun and other stars. However, achieving controlled nuclear fusion has proven challenging due to the difficulty in maintaining the high temperatures and pressures required. Researchers are developing new materials and technologies to overcome these obstacles and use the power of nuclear fusion.

The history of nuclear fusion began with the discovery of quantum tunneling, which was first proposed by Friedrich Hund. Ernest Rutherford carried out nuclear transmutation experiments successfully and later in 1929, Fritz Houtermans and Robert Atkinson measured the masses of light elements to predict the amount of energy that would be released during fusion of light elements. The experimental fusion of hydrogen isotopes was first achieved by Mark Oliphant in 1932. Hans Bethe worked extensively on the nuclear fusion cycle in stars [1].

During fusion reactions there is interplay of long range Coulomb forces, short range nuclear forces and quantum effects. The fusion cross section (σ) is a measure of the probability of fusion reaction as function of center of mass energy (E_{cm}). For moderately light ions, the center of mass energy determines barrier height and possible compound nuclear states [2][3].

The entrance channel parameters are those that describe the condition and properties of the nuclei involved in the nuclear fusion. The entrance channel parameters that affect fusion reactions include center of mass energy, Coulomb factor, mass asymmetry, charge asymmetry, Q value, projectile structure, target deformation and angular momentum of the projectile target system. For successful fusion, the entrance channel parameters must complement with the potential energy of the colliding nuclei. The potential energy arises due to the Coulomb barrier and the nuclear barrier. The Coulomb barrier arises from the electrostatic repulsion between the positively charged interacting nuclei, and nuclear barrier arises from the nuclear forces involved between the interacting nuclei. The barrier height is crucial because it affects the probability of fusion reactions occurring at a given energy. The barrier height must be surmounted for the fusion reaction to take place [4]. Understanding these parameters is essential for the advancement of nuclear physics and could support future developments in controlled fusion energy, and the creation of new elements.

2. Methodology

In the present work, the dependence of fusion cross section on Coulomb factor and center of mass energy are discussed for fusion reactions induced by moderately light nuclei such as carbon and oxygen. The fusion cross sections and Coulomb factor are statistically calculated for the reactions, given in Table 1., using Gemini++ (version 3.0) statistical code [5], that uses Hauser-Feshbach formula. This approach assumes many overlapping nuclear resonant states in the compound nucleus and predicts cross sections based on statistical properties of nuclear levels. The formula emphasizes Bohr's idea that "the decay of compound nucleus is independent of how it was formed". The Hauser-Feshbach formula provides an estimate of the compound nuclear cross section by taking into account the transmission coefficients, level density parameters, and using average angular momentum dependence of the level density. This formalism provides a good description of the data for light nuclei, but some deviations are observed for heavy nuclei at high excitation energies [6], [7].

3. Results and Discussions

In the work presented here, the Coulomb factor and the fusion cross section of carbon and oxygen induced fusion reactions are analyzed.

In light ion fusion reactions, the fusion cross section depends strongly on the Coulomb factor (χ). The Coulomb factor quantifies the strength of Coulomb repulsion between the interacting nuclei.

Table 1: Carbon and Oxygen induced reactions and their cross sections

Reaction	Compound Nucleus	Coulomb factor (χ)	Fusion cross section (σ in mb) for E_{cm} = 10MeV
$^{12}C+^{7}Li$	$^{19}F^{*}$	4.28	1111.03
$^{12}C+^{9}Be$	$^{21}Ne^{*}$	5.49	1062.5
$^{13}C+^{11}B$	$^{24}Na^{*}$	6.56	986.56
$^{12}C+^{10}B$	$^{22}Na^{*}$	6.75	906.41
$^{12}C+^{13}C$	$^{25}Mg^{*}$	7.76	863.89
$^{12}C+^{12}C$	$^{24}Mg^{*}$	7.86	795.01
$^{16}C+^{11}B$	$^{27}Al^{*}$	8.43	759.89
$^{16}O+^{10}B$	$^{26}Al^{*}$	8.56	720.02
$^{12}C+^{14}N$	$^{26}Al^{*}$	8.94	688.56
$^{17}O+^{13}C$	$^{30}Si^{*}$	9.75	552.08
$^{12}C+^{16}O$	$^{28}Si^{*}$	9.98	544.09
$^{16}O+^{12}C$	$^{28}Si^{*}$	9.98	544.09
$^{16}O+^{14}N$	$^{30}P^{*}$	11.36	320.33
$^{16}O+^{14}O$	$^{30}S^{*}$	12.98	52.79

The expression for Coulomb factor is given by the formula,

$$\aleph = \frac{z_1 z_2}{A_1^{1/3} + A_2^{1/3}} \qquad \ldots\ldots\ldots\ldots (1)$$

The terms z_1, z_2, A_1 and A_2, are the atomic numbers and mass numbers of the interacting nuclei. Higher values of the Coulomb factor correspond to stronger Coulomb barriers between the nuclei. Therefore, as the Coulomb factor increases, the height and width of the Coulomb barrier increase, thereby reducing the probability of quantum tunneling through the barrier and, hence, decreasing the fusion cross section as is evident from Table 1.
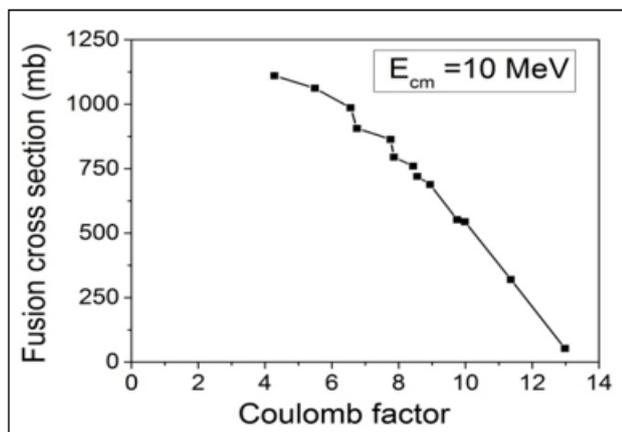

Figure 1: Variation of Fusion cross section with coulomb factor for center of mass energy of 10MeV

The fusion cross sections for different reactions and their Coulomb repulsion factors, at fixed center of mass energy, are calculated. The results are plotted in Figure 1. The fusion cross section is found to decrease with increasing Coulomb factor. This relationship is crucial for understanding the efficiency and feasibility of light ion fusion reactions, where optimizing conditions to minimize the Coulomb factor by using low atomic number nuclei can enhance fusion probabilities. An experimental study validates the inverse relationship between the Coulomb

factor and fusion cross section for various light ion reactions [8].
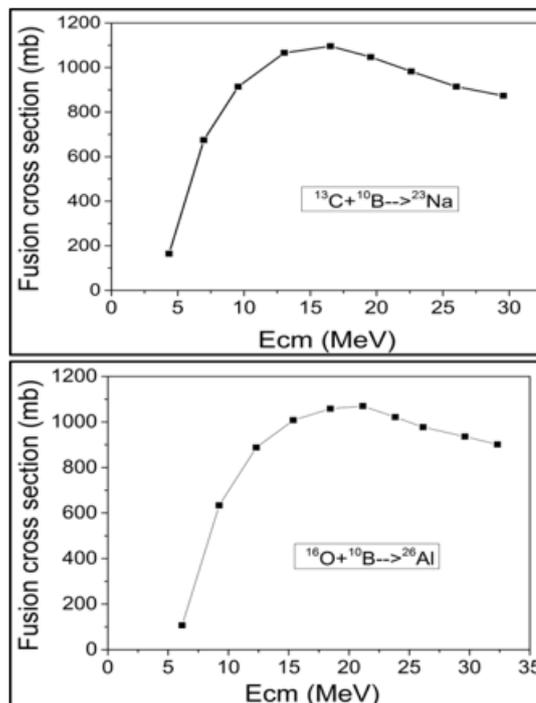

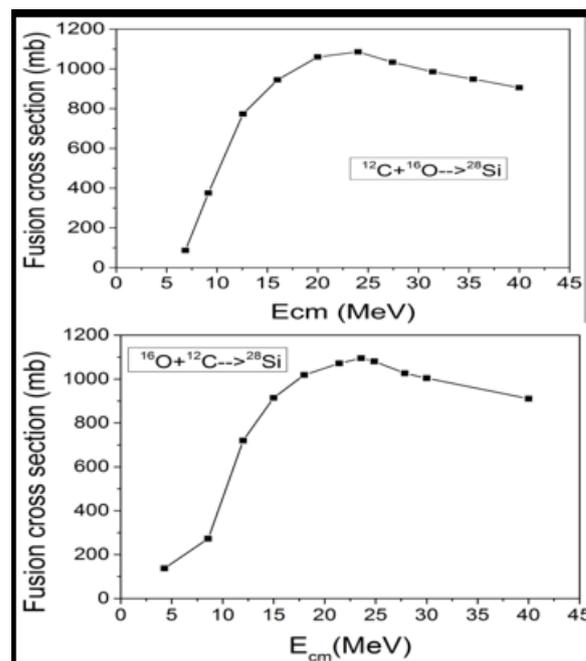**Figure 2:** Variation of fusion cross section with center of mass energy

Figure 3: Variation of Fusion cross section with center of mass energy

The light ion fusion processes are crucially influenced by the interplay between the Coulomb barrier and quantum tunneling effects. At low E_{cm}, the fusion cross section is extremely small due to the dominance of the Coulomb factor, which prohibits the approaching nucleus from overcoming the mutual electrostatic repulsion. As E_{cm} increases, the probability of tunneling through the barrier increases exponentially, leading to a rapid rise in the fusion cross section value. The fusion cross section increases and reaches a certain minimum threshold value, where the fusion

rate becomes appreciable. Above the threshold, the cross section increases steeply and reaches a maximum value, called the Gamow peak. The Gamow peak is defined as the characteristic E_{cm} at which fusion reactions are most likely to happen. A further increase in E_{cm} results in gradual decrease in the cross section, due to the reduced resonance effects and other factors such as nuclear structure effects as is evident from Figure 2 and Figure 3. [9].

4. Conclusion

The study demonstrates that the Coulomb factor, which depends on the charges of the interacting nuclei, affects the fusion cross section strongly and bears an inverse relation with it.

The current work implies the fact that the fusion cross section varies significantly with E_{cm}, starting from negligible values at low energies, peaking near the Gamow energy, and then diminishing at higher energies, reflecting the intricate balance between the Coulomb repulsion and quantum tunneling effects.

Understanding these relationships is crucial for designing and optimizing fusion reactions in experimental contexts and helps in achieving the synthesis of new super-heavy elements.

References

[1] C.A. Bertulani, H.W. Hammer, U. Van Klock, "Nuclear reactions and astrophysics", Nuclear Physics A., 37, 172, 2002.
[2] N. Rowley, G.R. Satchler, P.H Stelson., "On the fusion of heavy ions", Physics Letters B, 254, 25, 1991.
[3] Yu. Ts. Oganessian, V. K. Utyonkov, "Superheavy nuclei from 48Ca-induced reactions", Nuclear Physics A., 944, pp.62-98, 2015.
[4] Long Zhu, Jun Su, Ching Yuan Huang, Feng Shour Zhang, "Effects of entrance channel on fusion probability in hot fusion reactions", Chinese Physics C., 40, 124105, 2016.
[5] R.J. Charity, "A systematic description of evaporation spectra for light and heavy compound nuclei", Phy. Rev. C., 82, 014610, 2010.
[6] H.A. Weidenmuller, "Statistical theory of Compound Nuclear Reactions", AIP Conf. Proc., 1005, pp.3-9, 2008.
[7] Y. Alhassid, G.F. Bertsch, P. Fanto., T. Kawano, "Transmission coefficients in compound nucleus reaction theory", ArXiv:1901.0453v1, Nucl.Th., 2019.
[8] G.R. Satchler, Direct Nuclear Reactions, Clarendon Press, Oxford, England, 1983.
[9] J.T. Hood, Introduction to Nuclear Reactions, CRC Press, Florida, USA, 2003.