Veritas Volume1|Issue1|July 2026
Edmundian Journal of Multidisciplinary Research (EJMR) ISSN: PP: 61-67

Sub-barrier Fusion Cross Section and Its Dependency on Neutron Transfer Form Factor for ^{18}O + ^{116}Sn system

Nabendu Kumar Deb*

Department of Physics, Kamrup College, Chamata, Nalbari-781306, Assam

Received: 20 April 2026 | Reviewed: 25 June 2026 | Revised: 09 July 2026 | Accepted: 15 July 2026

ABSTRACT

The ^{18}O + ^{116}Sn system's fusion excitation functions were revisited in the energy regime below the Coulomb barrier, where the experimental fusion cross sections enhancement was noted compared to that of the simple barrier penetration model. To understand such enhancement, analyses were carried out with different values of transfer coupling strength or transfer form factor in the coupled channels formalism. The ground state Q value is positive for this system. A comparative study of the system selected for this work with different coupling schemes indicated that the coupling of 2 neutron transfer channel with the collective excitations is the reason behind such sub-barrier fusion enhancement. To carry out such calculations considering neutron transfer coupling, a parameter called transfer form factor is required which depends on a factor called transfer coupling strength. It is discovered that as the transfer coupling strength is increased or decreased, the fusion cross-section likewise increases or decreases below the barrier energy and exhibits the opposite trends above it. Such variations have been emphasized in this work through the system considered.

KEYWORDS: Sub-barrier fusion cross section, Neutron transfer, Transfer form factor, Q – values, CCFULL.

INTRODUCTION

The heavy-ion nuclear fusion dynamics at energies surrounding the Coulomb barrier is strongly influenced by coupling to different reaction channels (Deb et al., 2022). Many experimental results clearly conveyed the fact that coupling to collective excitations could enhance the sub-barrier fusion cross sections, i.e., the fusion cross sections at energies below the barrier on comparison with the one-dimensional barrier penetration model (1DBPM) predictions (Deb et al., 2022; Stefanini et al., 1995a, 1995b). Few experiments even pointed out that the sub-barrier fusion enhancement that was seen is due to the neutron transfer that takes place in addition to the inelastic couplings (Dasso et al., 1983a, 1983b). However, an unambiguous statement cannot be made regarding the role of transfer reactions in fusion in the presence of strong inelastic couplings. The role of various couplings in the behaviour of sub-barrier fusion is still being investigated because the present experimental and theoretical research are insufficient to draw firm conclusions. More experiments on different projectile-target combinations will produce enough data to study theories and formulations to be made regarding the role of neutron transfer on the sub-barrier fusion cross section. Most of the experiments were carried out on systems having positive ground state *Q* value neutron transfer channels because they create barrier energy of lower values than the inelastic couplings and, therefore, can be identified. In this paper, the role of different couplings, including inelastic and neutron transfer, in sub-barrier fusion is studied for the ^{18}O + ^{116}Sn system. To highlight the pertinent significance of couplings to collective states and neutron transfer channels having + Q values at ground state as well as the variations of the parameters involved in the cross-section formula, we examine the fusion cross-section measurements from Ref. (Deb et al., 2020) for this same system. This ^{18}O + ^{116}Sn system possesses positive Q value for 2 neutron transfer channels. The Sn isotopes are

*Author for Correspondence: Nabendu Kumar Deb
nd_globe@yahoo.co.in

© IQAC, St. Edmund's College, Shillong, Meghalaya, India

collective in nature as they have the lowest quadrupole and octupole states. A complete level structure of Sn has been studied up to excitation energy of 4.3 MeV and the existence of two- and three-quadrupole phonon states could be identified (Raman et al., 1991). The $B(E_2) \uparrow$ values of the transitions from the first 4^+ state and the second and third 2^+ states are found to be more compared with that of the single particle estimates, therefore indicating that these states have a character of two-phonon vibrational state. The $J^\pi = 1^-$ states have been studied in many even-even isotopes of Sn nuclei (Bryssinck et al., 1999), and this has been identified as a member of the multiplet of the mixed quadrupole - octupole ($2^+ \otimes 3^-$) multiphonon states. Therefore, there is enough experimental data to confirm that the Sn isotopes have two or more phonon states. The $^{18}O + ^{116}Sn$ system studied enables us to study the fusion excitation function due to coupling to positive Q value neutron transfer channels. The ground state Q values for the different neutron transfer channels are given in Ref. (Deb et al., 2020).

Role of neutron transfer in sub-barrier fusion

The optimum Q value (Q_{opt}) controls nucleon transfer between interacting partners in heavy ion driven nuclear processes (Deb et al., 2020) Q_{opt}, derived from smoothly matching the trajectories before and after the transfer (Liang et al., 1994) is given by

$$Q_{opt} = \left(\frac{Z_p' Z_t'}{Z_p Z_t} - 1\right) E_{c.m.} \qquad (1)$$

where Z_p and Z_t are the atomic numbers of projectile and the target respectively, Z_p' and Z_t' are the atomic numbers of the ejectile and the recoil nucleus respectively, and $E_{c.m.}$ is the energy of the projectile in the center of mass frame. The relevant quantity to be considered for the transfer channel is the difference between the ground state Q value and the optimum Q value. For neutron transfer channels $Q_{opt} = 0$ because the atomic number of the interacting partners remain the same before and after the reactions as neutrons being neutral in charge. As a result, the ground state Q value is considered in the current work for interpreting fusion cross-sections. Even though the Q value is positive for numerous neutron transfer pathways, only valence neutrons (primarily one or two neutron transport channels with ground state Q values that are positive) contribute significantly to fusion. Additionally, if coupling to collective states is less prominent for spherical or magical nuclei, the substantial contribution from the transfer channels can be anticipated (Khushboo et al., 2017). The transfer form factor (F), which is generated from the empirically obtained transfer probability and is provided by the following equation (Hagino et al., 1999; Dasso & Vitturi, 1986), is a transfer-related parameter needed to include transfer coupling in the computation

$$F = F_t \frac{dV_N}{dr} \qquad (2)$$

where V_N is the ion-ion nuclear potential and the factor, F_t, is known as the transfer coupling strength which is expressed as

$$F_t = \frac{\beta_p R}{3A_T} \qquad (3)$$

where β_p is the pairing deformation parameter scale which plays the analogous role as the standard dynamical deformation parameter, β. Just as β displays the character of inelastic transitions, β_p measures the collective strength of the pair modes. Here R and A_T are the radius and mass of the target respectively. Thus, the transfer form factor is radial dependent which can be further simplified as (Mahon et al., 1997)

$$F = F_t \frac{1}{\sqrt{4\pi}} \exp\left[-\frac{(r-R_B)}{1.2\, fm}\right] \qquad (4)$$

where R_B is the barrier radius. The transfer probability, in the form of transfer form factor (Saha et al., 1994), is written as

$$P(r_o, Q_x) = \frac{\pi}{\sigma^2} |F(r_o, Q_x)|^2 \exp\left[-\frac{(Q_x - Q_{opt})^2}{2\sigma^2}\right] \qquad (5)$$

where $\sigma = \sqrt{\frac{\hbar^2 \alpha \ddot{r}_o}{2}}$ .This Eq. (5) gives the probability of transfer to a given excited state x with Q value Q_x. α is the amplitude for the colliding system to be in a channel x after the reaction ($t = \infty$) and is given by

© IQAC, St. Edmund's College, Shillong, Meghalaya, India

$$\alpha_x(\infty) = \frac{1}{i\hbar}\int_{-\infty}^{\infty} F_x(r, Q_x) e^{i\frac{(Q_x - Q_{opt})t}{\hbar}} dt, \quad (6)$$

where F_x is a form factor describing the transition from the incoming channel to the channel x having Q value Q_x. The integral in Eq. (6) is evaluated by considering the trajectory around the distance of closest approach, r_o, given by

$$r(t) = r_o + \frac{1}{2}\ddot{r_o}t^2 \quad (7)$$

where $\ddot{r_o}$ is the acceleration at r_o which is calculated for the entrance and exit channels by assuming a Coulomb trajectory using the relation

$$r_o = \frac{Z_1 Z_2 e^2}{2(E_{c.m.}+Q)}\left(1 + cosec\frac{\theta_{c.m.}}{2}\right) = d_0\left(A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}}\right) \quad (8)$$

The d_0 value can be found out by knowing the $\theta_{c.m.}$ value that can be determined from the transfer measurement. Thus, using Eq. (4) and Eq. (7), the integral in Eq. (6) is evaluated as $\alpha_x(\infty) =$

$$\frac{1}{i\hbar}F_x(r_o, Q_x)\sqrt{\frac{2\pi}{\alpha\ddot{r_o}}}\exp\left[-\frac{(Q_x - Q_{opt})^2}{2\hbar^2\alpha\ddot{r_o}}\right] \quad (9)$$

Thus, the transfer probability is obtained as in Eq. (5) using P (r_o, Qx) = $|\alpha_x(\infty)|^2$. Using such a semi-classical theory, the effective transfer coupling strengths are found from the measured transfer probabilities for each transfer channels of the nucleon. The fusion cross sections at energies below and above the barrier were then determined by incorporating these values into the coupled channel calculations. Although it was discovered that coupled-channel calculations could not replicate the enhancement in the ^{18}O + ^{116}Sn system without considering the neutron transfer channel, no attempt was made to find a quantitative measure of the effect of transfer on the large sub-barrier fusion enhancement observed in these systems (Deb et al., 2020). In the current work, the theoretical coupled-channels code CCFULL (Hagino et al., 1999) is used to investigate the fusion excitation function to comprehend the behavior of sub-barrier fusion in the ^{18}O + ^{116}Sn system.

RESULTS AND DISCUSSIONS

Fig. 1 shows the plot of the experimentally measured fusion cross sections at various energies as a function of $E_{c.m.}$. 1DBPM cross sections have been calculated to comprehend the experimental cross sections in the sub-barrier regions. To fit the cross-sections at above-barrier energies, appropriate Woods-Saxon parameterization of the nuclear potential parameters has been used for the calculations. This is because the effect of static and dynamic properties in the process of complete fusion becomes negligible in that energy range as shown in Refs. (Deb et al., 2020; Hagino et al., 1999; Stefanini et al., 2009). For the ^{18}O + ^{116}Sn system, the nuclear potential parameters considered in this work includes V_0 (potential depth) = 75.6 MeV, r_0 (potential radius) = 1.2 fm, and a_0 (diffuseness parameter) =0.72 fm (Deb et al., 2020). Fig. 1 shows a plot of the computation's result. In comparison to 1DBPM fusion cross sections, it is evident that the sub-barrier region of the ^{18}O + ^{116}Sn system considered for this work, is enhanced. This demonstrates that the experimental fusion cross section cannot be replicated by a straightforward quantum mechanical barrier penetration model. To explain the experimental observations, basic 1DBPM computations and couplings of different inelastic states have been performed, as demonstrated in the Ref. (Deb et al., 2020). But none of the combinations could match the experimental measurements. Coupled-channels calculations, for this system, were done considering ^{18}O nucleus and ^{116}Sn nucleus as vibrators. Their contribution as a rotator is negligible as their deformation parameter values are nearly zero (Deb et al., 2020), because both the nuclei are spherical. The coupled-channels computations underestimate the fusion excitation function of the current system in the sub-barrier energy region, even after considering all low-lying inelastic excitations mutually, as shown in Ref. (Deb et al., 2020). As a result, the sub-barrier fusion boost over the coupled-channels computations might be a sign of a physical

© IQAC, St. Edmund's College, Shillong, Meghalaya, India

effect that has not been considered yet. Subsequently, we needed to examine whether any neutron transfer taking place between the interacting partners could lay any role in reproducing the fusion cross-section of the present system and, therefore, could explain the sub-barrier fusion enhancement. To do this, the couplings of the neutron transfer channel have been included in coupled-channels analysis. The F_t value, as stated in the preceding section, is necessary to include transfer coupling in the coupled-channel calculations using the CCFULL software, which enables one to couple 2 neutron transfer channels only. The coupled-channel calculations are done using several values of F_t in the CCFULL code, in the 0.2 MeV to 0.5 MeV range, since the transfer cross sections have not yet been measured for the current system. Fig. 2 plots the coupled-channels calculations with +2n transfer coupling for the values of F_t in this range. From the figure, we can see the significance of the value of this parameter on the fusion cross section. Different values of F_t do not produce the same cross sections but produce different fusion cross section. Even the slight change of the value of this parameter results in substantial changes in the fusion cross section. The coupled-channels calculations are found to improve the description of experimental fusion cross sections at sub-barrier energies when F_t is increased from 0.2 to 0.5 MeV, but they significantly under-predict the fusion cross section at above-barrier energies. Below the barrier, with the increasing value of F_t, the sub-barrier fusion enhancement increases. But again, with the increasing value of F_t, the cross section above the barrier decreases. Refs. (Khushboo et al., 2017; Sahoo et al., 2020) observed similar trends of F_t. To achieve the best agreement between the experiment and theoretical fusion excitation functions for the $^{18}O + {}^{116}Sn$ system, we also included the Q value of the neutron-pair transfer channel along with the transfer coupling strength, F_t, both of which were treated as free parameters according to the prescription of Bourgin *et al.* (Bourgin et al., 2014). Thus, despite these fluctuations, Fig. 2 shows that the fusion excitation functions, with values of F_t = 0.3 MeV and Q = + 4.08 MeV, which is equal to the Q value of two neutron stripping channels for the current system, fit both below and above the barrier within the experimental uncertainties. This fitting has been displayed separately in the inset of Fig. 2 for clarity. This can be seen in Fig. 1 with the experimental cross section data since it replicates the fusion cross sections very well. Therefore, while evaluating the sub-barrier fusion enhancement, the positive Q value neutron transport routes should be considered. The comprehensive fusion and differential transfer measurements are necessary and must be carried out to provide additional insight into the role of neutron transfer channels in sub-barrier fusion enhancement.

© IQAC, St. Edmund's College, Shillong, Meghalaya, India

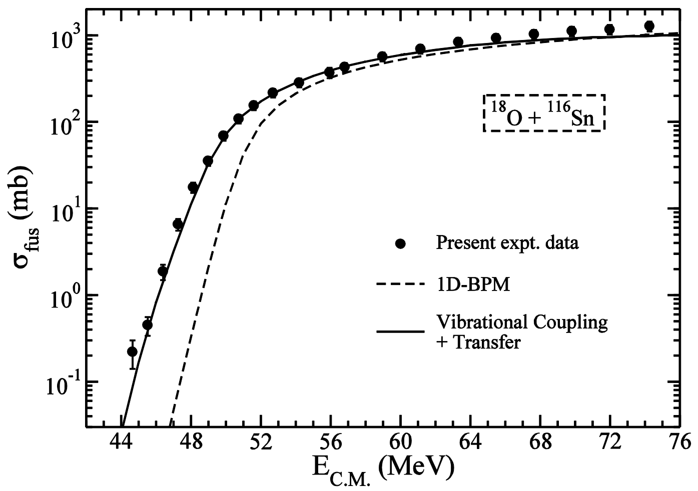

Fig. 1 The experimentally measured excitation function is compared with the 1DBPM using CCFULL. It shows that the couplings of different inelastic excitations of interacting partners in addition to the 2n transfer channel reproduces the experimental excitation function well.

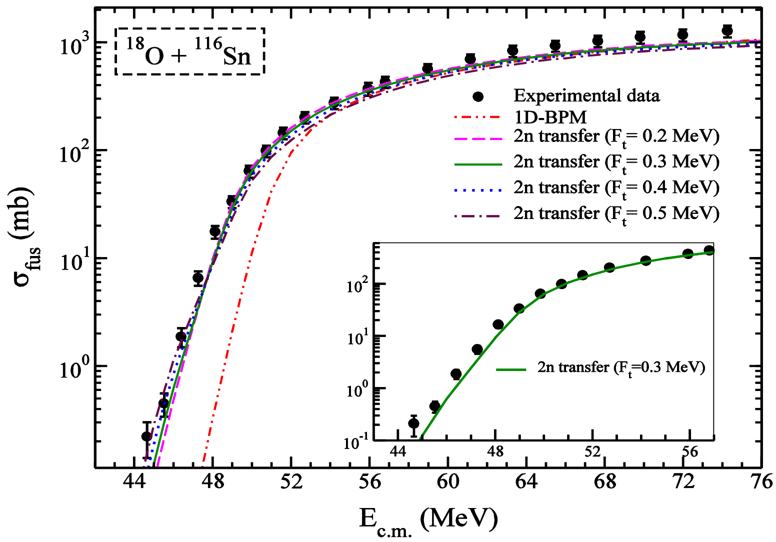

Fig. 2 The fusion excitation function is compared with the 1DBPM and the transfer coupling between interacting partners using CCFULL having various values of transfer coupling strength. It shows that the inclusion of couplings of inelastic excitations of interacting partners with 2n transfer channel having F_t = 0.3 MeV and Q = +4.08 MeV reproduces the experimental excitation function well.

CONCLUSIONS

In comparison to the straightforward one-dimensional quantum mechanical barrier penetration model, the system under consideration in this work, ^{18}O + ^{116}Sn, has shown augmentation of the fusion cross section below the Coulomb barrier energy (Deb et al., 2020). Using the theoretical coupled channel formalism code CCFULL, coupled channel calculations were carried out, considering both ^{18}O and ^{116}Sn as vibrators, to explore the cause of such enhancement at the sub-barrier area. Although the calculations were done with inelastic excitations of the several states of the collision partners, they were unable to replicate the experimental observations. Even when all low-lying inelastic excitations were mutually included in the calculations, the sub-barrier fusion cross section could not be replicated. For two-neutron transfer channels from the projectile to the target, the system under consideration has a positive *Q* value. Because

© IQAC, St. Edmund's College, Shillong, Meghalaya, India

the CCFULL code allows for the inclusion of a neutron-pair transfer, calculations were done with two neutron transfer's channels. Neutron transfer coupling is done in the code using the transfer coupling strength, F_t. Transfer measurements are, therefore, desired for to determine the value of F_t. But for the present system, transfer measurements are not available. Hence, the coupled-channel calculations are considered with various trial values of F_t in the CCFULL code ranging from 0.2 MeV to 0.5 MeV, which is the main basis of this work. It was observed that while the fusion cross-section of the above barrier drops, the sub-barrier fusion cross section grows as F_t increases. The experimental findings could, thus, be replicated reasonably well throughout the entire energy regime considering F_t = 0.3 MeV, with the Q value of two neutron stripping channel for the current system being +4.08 MeV. Therefore, when evaluating the sub-barrier fusion enhancement, the positive Q value neutron transfer channels with the F_t value should be considered. Transfer measurements are to be done, in future, for this system to get the correct value of F_t.

ACKNOWLEDGMENTS

The author is grateful to the Pelletron staff of IUAC, New Delhi, for the smooth operation of the accelerator during the experiment; the Target Development Laboratory of IUAC for assistance in preparing the isotopic targets of requisite thickness, and Dr. N. Madhavan, Dr. S. Nath, Dr. J. Gehlot and other HIRA Lab staff of IUAC, for allowing the experiments to be carried out for the system considered in this work. The detailed experimental work for this system has been described in Ref. (Deb et al., 2020). The author is also very much thankful to Dr. K. Kalita, Gauhati University for the constant guidance and supervision; and all the collaborators from different institutes, *viz.,* Department of Physics, Gauhati University; Department of Physics, Central University of Jharkhand; Department of Physics, Visva Bharati; Department of Physics, Banaras Hindu University; Racah Institute of Physics, Hebrew University, Jerusalem, Israel and Nuclear Physics Division, Bhabha Atomic Research Centre (BARC), India. Finally, the author acknowledges the Council of Scientific and Industrial Research (CSIR), New Delhi, for support via a Junior Research Fellowship to carry out the experimental work.

FUNDING:

No financial support from any competing authority was involved while carrying out this work.

CONFLICT OF INTEREST

The author declares having no known competing financial interests or personal relationships of any form with the personnels related to the journals that could have appeared to influence the work reported in this paper. The author is not involved in the editorial review of any form or the decision to publish this article.

REFERENCES

Bourgin, D., Courtin, S., Haas, F., Stefanini, A. M., Montagnoli, G., Goasduff, A., Montanari, D., Corradi, L., Fioretto, E., Huiming, J., Scarlassara, F., Rowley, N., Szilner, S., & Mijatović, T. (2014). Sub-barrier fusion and transfers in the ^{40}Ca +^{58,64}Ni systems. *Physical Review C, 90*(4), 044610. https://doi.org/10.1051/epjconf/201611708010

Bryssinck, J., Gover, L., Belic, D., Bauwens, F., Beck, O., von Brentano, P., De Frenne, D., Eckert, T., Fransen, C., Govaert, K., Herxberg, R.-D., Jacobs, E., Kneissl, U., Maser, H., Nord, A., Pietralla, N., Pitz, H. H., Ponomarev, V. Y., & Werner, V. (1999). High-spin states in 142Sm. *Physical Review C, 59*(4), 1930–1937. https://doi.org/10.1103/PhysRevC.59.1930

Dasso, C. H., & Vitturi, A. (1986). Macroscopic description of pair transfer in heavy-ion collisions with deformed nuclei. *Physics Letters B, 179*, 337. https://doi.org/10.1016/0370-2693(86)90488-0

Dasso, C. H., Landowne, S., & Winther, A. (1983a). Channel-coupling effects in heavy-ion fusion reactions. *Nuclear Physics A, 405*, 381. https://doi.org/10.1016/0375-9474(83)90578-x

Dasso, C. H., Landowne, S., & Winther, A. (1983b). A study of Q-value effects on barrier penetration. *Nuclear Physics A, 407*, 221. https://doi.org/10.1016/0375-9474(83)90316-0

Deb, N. K., Kalita, K., Rashid, H., Das, A., Nath, S., Gehlot, J., Madhavan, N., Biswas, R., Sahoo, R.,

© IQAC, St. Edmund's College, Shillong, Meghalaya, India

Giri, P., Parihari, A., Rai, N., Biswas, S., Mahato, A., & Roy, B. (2022). Role of neutron transfer in the sub-barrier fusion cross section in O^{18} + Sn^{116}. *Physical Review C, 105*(5), 054608. https://doi.org/10.1103/physrevc.105.054608

Deb, N. K., Kalita, K., Rashid, H., Nath, S., Gehlot, J., Madhavan, N., Biswas, R., Sahoo, R., Giri, P., Das, A., Rajbongshi, T., Parihari, A., Rai, N., Biswas, S., Khushboo, Mahato, A., Roy, B., Vinayak, A., & Rani, A. (2020). Role of neutron transfer in the sub-barrier fusion cross section in O18 + Sn116. *Physical Review C, 102*(3), 034603.https://doi.org/10.1103/physrevc.102.034603

Khushboo, Mandal, S., Nath, S., Madhavan, N., Gehlot, J., Jhingan, A., Kumar, N., Banerjee, T., Kaur, G., Devi, K. R., Banerjee, A., Neelam, Varughese, T., Siwal, D., Garg, R., Mukul, I., Saxena, M., Verma, S., Kumar, S., Behera, B. R., & Verma, P. (2017). Relationship between and effect of inelastic excitations and transfer channels on sub-barrier fusion enhancement. *Physical Review C, 96*(1), 014614. https://doi.org/10.1103/physrevc.96.014614

Knyazheva, G. N., Novikov, K. V., & Singh, P. (2020). Role of neutron transfer in sub-barrier fusion. *Physical Review C, 102*(2), 024615. https://doi.org/10.1103/physrevc.102.024615

Liang, J. F., Lee, L. L., Jr., Mahon, J. C., & Vojtech, R. J. (1994). Transfer reactions in $^{32}S+^{92,98,100}$ Mo and ^{93}Nb at near barrier energies. *Physical Review C, 50*(3), 1550. https://doi.org/10.1103/PhysRevC.50.1550

Mahon, J. C., Lee, L. L., Liang, J. F., Morton, C. R., Bateman, N. T. P., Yildiz, K., & Young, B. M. (1997). Fusion and transfer in at near barrier energies. *Journal of Physics G: Nuclear and Particle Physics*, 23(10), 1215–1225. https://doi.org/10.1088/0954-3899/23/10/008

Raman, S., Walkiewicz, T. A., Kahane, S., Jurney, E. T., Sa, J., Gacsi, Z., Weil, J. L., Bonsignori, G., & Shriner, J. F., Jr. (1991). Nearly complete level scheme ofSn116below 4.3 MeV. *Physical Review C, 43*(2), 521.https://doi.org/10.1103/physrevc.43.521

Saha, S., Agarwal, Y. K., & Baba, C. V. K. (1994). One-and two-proton transfer reactions in S 32+ 64 Ni and Si 28+ 68 Zn at near-barrier energies. *Physical Review C*, *49*(5), 2578. https://doi.org/10.1103/PhysRevC.49.2578

Stefanini, A. M., Ackermann, D., Corradi, L., He, J. H., Montagnoli, G., Beghini, S., ... & Segato, G. F. (1995). Signatures of multiphonon and neutron transfer couplings in the fusion of S 3 6, 3 2+ Pd 110. *Physical Review C*, *52*(4), R1727. https://doi.org/10.1103/PhysRevC.52.R1727

Stefanini, A. M., Ackermann, D., Corradi, L., Napoli, D. R., Petrache, C., Spolaore, P., Bednarczyk, P., Zhang, H. Q., Beghini, S., Montagnoli, G., Mueller, L., Scarlassara, F., Segato GF, Soramel, F., & Rowley, N. (1995). Influence of complex surface vibrations on the fusion of $^{58}Ni+^{60}Ni$. *Physical Review Letters*, *74*(6), 864–867. DOI: https://doi.org/10.1103/PhysRevLett.74.864

Stefanini, A. M., Montagnoli, G., Silvestri, R., Corradi, L., Courtin, S., Fioretto, E., ... & Szilner, S. (2009). How does fusion hindrance show up in medium-light systems? The case of {sup 48} Ca+{sup 48} Ca. *Physics Letters. Section B*, *679*. https://doi.org/10.1016/j.physletb.2009.07.017

© IQAC, St. Edmund’s College, Shillong, Meghalaya, India