INVESTIGATING THE EFFECT OF TRANSFER CHANNELS ON REACTION DYNAMICS USING THE QUASI-ELASTIC BARRIER DISTRIBUTION*

Gobind Ram[a], Abhishek Yadav[b,†], Md. Moin Shaikh[c]
A. Jhingan[d], M. Kumar[d], N. Saneesh[d], Indu Bala[d], K.S. Golda[d]
T. Banerjee[d], R. Dubey[e], G. Kaur[f], C. Yadav[d], H. Arora[f]
K. Rani[f], N.K. Rai[f], M.K. Sharma[a], B.P. Singh[g], P. Sugathan[d]
R. Prasad[g]

[a]Department of Physics, University of Lucknow, Lucknow-226 007, U.P., India
[b]AINST, Amity University Uttar Pradesh, Noida-201 301, U.P., India
[c]Department of Physics, Chanchal College, Malda-732 101, West Bengal, India
[d]NP-Group: Inter-University Accelerator Centre, New Delhi-110 067, Delhi, India
[e]Institute of Physics, University of Szczecin, 70-451 Szczecin, Poland
[f]Department of Physics, Punjab University, Chandigarh-160 014, Punjab, India
[g]Department of Physics, Aligarh Muslim University, Aligarh-202 002, U.P., India

Received 1 December 2023, accepted 6 February 2024,
published online 24 April 2024

An attempt has been made to understand the effect of transfer channels on reaction dynamics for the $^{16}\mathrm{O}+{}^{165}\mathrm{Ho}$ system through the measurement of a quasi-elastic excitation function at backward angles, which was translated to the corresponding barrier distribution. The results were explained in light of coupled channel calculations performed with the inclusion of different possible coupling schemes describing the structure of the projectile and target nuclei. Analysis reveals that the rotational coupling of the target nuclei along with the coupling due to the $2n$-transfer (pick-up) channel satisfactorily reproduces the experimental data.

DOI:10.5506/APhysPolBSupp.17.3-A24

1. Introduction

It is well known that the internal structure of the colliding nuclei has a significant impact on the heavy-ion collisions at energies near the Coulomb barrier [1, 2]. This is due to the fact that near the barrier, the interacting nuclei have enough time to excite the intrinsic degrees of freedom from the relative energy. Therefore, the single potential barrier (1BPM) is replaced by a collection of dispersed barriers due to the coupling of the relative

* Presented at the XXXVII Mazurian Lakes Conference on Physics, Piaski, Poland, 3–9 September, 2023.

† Corresponding author: abhishekyadav117@gmail.com

motion to the intrinsic degrees of freedom. Generally, the coupling results in redistributing of the cross section around the barrier, therefore, the fusion barrier distributions are highly sensitive to the structure of the interacting nuclei [1–3], which opens up the possibility to investigate their static and dynamical properties [4]. Barrier distributions became one of the effective probes which provide fingerprints of a change in the effective potential with and without including structural properties and other degrees of freedom. In order to get the experimental barrier distribution, a method was proposed [4, 5] to extract it from the precise measurement of the fusion excitation function by taking the second derivative with respect to the center-of-mass energy of the quantity $E\sigma_{\mathrm{f}}$, where E is the center-of-mass energy and σ_{f} is the fusion cross section. This method is quite effective in deriving the shape of the fusion barrier distribution. Further, the same information has been extracted through the quasi-elastic backscattering method [6, 7], using the first derivative of the ratio of quasi-elastic cross section σ_{qel} to the Rutherford cross section σ_{R} with respect to the center-of-mass energy.

Further, this method has been validated by Timmers *et al.* [6, 7] by showing that the quasi-elastic barrier distribution is indeed similar to that of the fusion barrier distribution. From the experimental point of view, the quasi-elastic barrier distribution is easier to measure than the fusion barrier distribution, as it uses the first derivative rather than the second derivative, and also requires a simple charged particle detector instead of a sophisticated detecting set-up or recoil separator to measure the fusion cross section. In addition, it allows to measure quasi-elastic cross sections at multiple effective energies using a single incident energy and applying the centrifugal approximation [8]. Thus, these advantages help to get the experimental information about the barrier distribution efficiently and effectively. A number of systems has been analysed using the above method to identify the coupling effects of various degrees of freedom in dynamics of heavy-ion reactions [9–13].

Among all other degrees of freedom, nucleon(s) transfer reactions are of great interest [14–19] due to their wide application such as extraction of exact spectroscopic factors, production of super-heavy nuclei, study of halo nuclei, *etc.* At below-barrier energies, the fusion enhancement due to transfer coupling can be related to positive Q values for the transfer processes. Additionally, there are some cases where a less negative Q-transfer value affects the fusion above the barrier [18, 19]. In the quasi-elastic scenario, small error bars at above-barrier energies can be advantageous to see the effect of transfer since barrier distributions reveal coupling more effectively. Therefore, this can be used as a probe to see the effect of negative Q-value transfer reactions on the barrier distribution and the effect of transfer can be quantitatively estimated in terms of a form factor. An effort has been made to study the role of transfer channels in the $^{16}\mathrm{O}+^{165}\mathrm{Ho}$ system.

2. Experimental details

The experiments were performed with the General Purpose Scattering Chamber (GPSC) using the ^{16}O beam from 15UD Pelletron accelerator at the Inter-University Accelerator Centre (IUAC), New Delhi. A target of ^{165}Ho of thickness ≈ 373 μg/cm^2 was prepared using the rolling technique. The incident energy of the ^{16}O beam was varied from 61 MeV (17% below the barrier) to 85 MeV (16% above the barrier). The HYTAR detecting setup was used to detect the scattered beam-like particles [20]. The setup consists of 13 ΔE–E-type detectors. Four telescope detectors, each at angle of 173°, have been arranged in a symmetrical cone geometry to measure the back-scattered quasi-elastic events. Nine telescopes, six at angles from +60° to +160° with the angular separation of 20° from each other, three telescopes at angles −110°, −122°, and −134° were used to measure the scattered particles. Each detector had an opening diameter of 10 mm and was placed at 70 cm from the target. Each ΔE chamber was backed by a Si detector, which measured the residual energy. The combined information from these ΔE–E detectors allowed for the identification of the atomic number of the incoming nuclei. Two monitor detectors were used for beam normalisation and to determine the absolute cross section. A CAMAC system was used for on-line data acquisition in an event-by-event mode. The CANDLE data collection and analysis software was used to analyse the data. Numbers of quasi-elastic scattering events at a given beam energy and angle were extracted from the two-dimensional (2D) correlation plot of ΔE (energy loss) *versus* E (total energy). Using the quasi-elastic events rate, the excitation function has been extracted which further translated to the barrier distribution (BD).

3. Results and discussion

The experimental results have been interpreted with the aid of the scattering version of the CCFULL code [8]. In this program, the nuclear potential has real and imaginary components, which are assumed to have a Woods–Saxon form. The interaction potential parameters were chosen in such a way that the one-dimensional barrier height ($V_{\rm b}$) was equal to the average experimental barrier height ($V_{\rm e}$). The potential parameters ($V_0 = 63.199$ MeV, $r_0 = 0.178$ fm, $a_0 = 0.654$ fm) were chosen in such a way that the calculated cross sections matched well with the experimental data at lower energies. The uncoupled calculation was carried out considering both the projectile and the target to be inert. As can be seen from Fig. 1, the BD without inclusion of coupling shows a single peak at $E_{\rm cm} = 64.17$ MeV, whereas the experimental BD shows a peak at 62.68 MeV with a small peak at 59.90 MeV. The ^{165}Ho target nuclei have a positive hexadecapole deformation, which suggests that the minor peak (at 59.90 MeV) could be the result of the coupling to hexadecapole deformation, which would produce a peak on the lower side of the barrier. The calculation does not reproduce the experimental results, so it is clear that due to some coupling, scattering is influenced, so there is an enhancement in the cross section which can be seen also in the barrier distribution. The subsequent calculations were carried out using different coupling schemes according to the structure of the projectile and target nuclei.

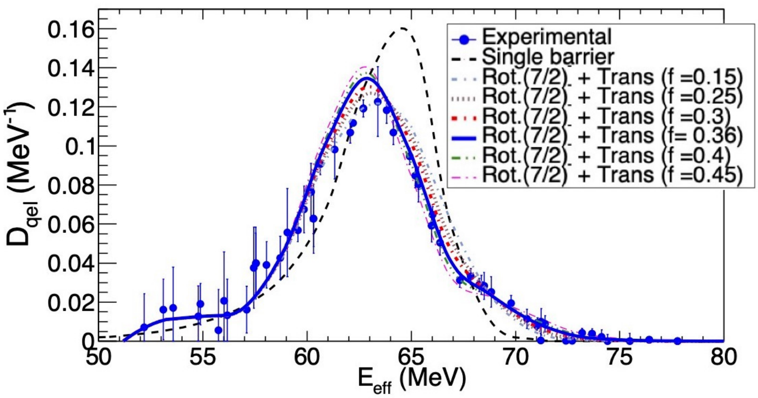

Fig. 1. (Colour on-line) The experimental quasi-elastic barrier distribution for the $^{16}O+^{165}Ho$ reaction shown using blue/black filled circles. The CCFULL calculations with different couplings are, also, plotted using different curve styles as indicated in the figure.

The coupled-channel model [8] treats the nuclei as harmonic vibrators or rigid rotors, but generally, nuclei do not possess a pure collective structure. As ^{165}Ho is lying in the lanthanides region, it may be a transitional nucleus *i.e.* it can behave as both vibrational and rotational. The second excited state of ^{165}Ho is at 0.209 MeV and lies approximately halfway between the vibrational estimate (0.189 MeV) and the rotational value (0.317 MeV), based on the experimental energy of the first excited state at 0.095 MeV. Therefore, from this consideration, it is not clear which of the coupling schemes for ^{165}Ho is more appropriate. The ^{16}O nucleus can be considered as inert due to its high octupole states around 6 MeV. Hence, only the coupling of states of ^{165}Ho can be responsible for the enhancement in the cross section around the barrier. First, a rotational band with $K = 7/2$ and $E^* = 0.095$ MeV and $E^* = 0.210$ MeV was considered. In this step of the calculation, the coupling with the $(7/2)^-$, $(9/2)^-$, $(11/2)^-$, and $(13/2)^-$ rotational states was taken into account without considering any excitations of the projectile. It is observed from Fig. 1 that the experimentally measured barrier distribution is narrower than that obtained from the corresponding theoretical calculation. For this reason, there was a necessity for the inclusion of other possible coupling schemes. As ^{165}Ho has two vibrational bands, further calculations were carried out by the inclusion of a vibrational mode of excitation. The peak-like structure of the obtained barrier distribution is matched slightly better but not for the entire energy range. The barrier distribution due to the coupling to rotational states along with the coupling to the $2n$-pickup with various values of the strength is shown in Fig. 1. It may be summarised that coupling to the low-lying excited states of ^{165}Ho could describe all experimental data. However, coupling of the rotational states gives a better agreement with the experimental barrier distribution as compared to what it obtained by the inclusion of low-lying vibrational states into the coupling. However, since data is not reproduced, there may be some other coupling responsible for the enhancement of the cross section. In addition to rotational and vibrational coupling schemes, there are choices to be made regarding various neutron and proton transfer channels to be included in the calculations. Only positive Q-value transfer channels and slightly negative Q-value transfer channels are important in the coupling processes, and these are known to play a role in fusion barrier distributions [21]. From earlier experimental studies, the importance of coupling to positive and negative Q-values transfer channels in determining the fusion barrier distribution is now well established [3, 13].

For the ^{16}O+^{165}Ho system, experimental data can be well explained by including rotational and vibrational coupling schemes but there was a large ambiguity for the region above the barrier. There are mostly high negative Q-value transfer channels other than the $2n$-pickup channel which has a low negative Q value for the transfer. It is expected that these channels may affect the shape of the barrier distribution at energies above the barrier. Thus, coupling due to $2n$-pickup was included in the coupled-channel calculations along with rotational coupling channels. From Fig. 1, it can be clearly seen that the results reproduced experimental data even on the high-energy side. Thus, transfer channels also play a role in enhancing sub-barrier fusion reactions for the ^{16}O+^{165}Ho system. The CCFULL treats the transfer form factor as a free parameter. As a result, various coupling strengths have been inspected to see how transfer coupling affects the system, as shown in Fig. 1. The form factor has been varied in a wide range from 0.15 to 0.45. It can be clearly seen from Fig. 1 that the form factor $f = 0.36$ reproduces well the barrier distribution in the whole energy range from below- to above-barrier energies.

4. Summary

The barrier distribution, extracted from the quasi-elastic scattering data, can be used to probe the effect of nucleon(s) transfer at above-barrier energies. It has been found that after inserting the structure parameters, the barrier distribution was not reproduced, especially at above-barrier energies. As the ^{16}O+^{165}Ho system has a negative Q value for the $2n$-pickup transfer channel, this was assumed to be the reason for the mismatch of the calculated and experimental barrier distributions at the above-barrier energies. The form factor $f = 0.36$ for the $2n$-pickup transfer channel reproduces well the barrier distribution for energies around the barrier. Therefore, it has been concluded that the transfer channel plays a significant role in the mechanism of ^{16}O+^{165}Ho fusion, although having a negative Q value.

The authors are thankful to the Director of the Inter-University Accelerator Centre (IUAC), New Delhi and the Director of the AINST, Amity University Uttar Pradesh for extending all the necessary facilities for this work. One of the authors (A.Y.) thanks the Department of Science & Technology (DST) and Science and Engineering Research Board (SERB) for financial support through the INSPIRE Faculty scheme and the International Travel support, respectively.

REFERENCES

[1] R. Stokstad *et al.*, *Phys. Rev. C* **23**, 281 (1981).
[2] R.C. Lemmon *et al.*, *Phys. Lett. B* **316**, 32 (1993).
[3] M. Beckerman *et al.*, *Phys. Rev. C* **25**, 837 (1982).
[4] N. Rowley *et al.*, *Phys. Lett. B* **254**, 25 (1991).
[5] M. Dasgupta *et al.*, *Annu. Rev. Nucl. Part. Sci.* **48**, 401 (1998).
[6] H. Timmers *et al.*, *Nucl. Phys. A* **584**, 190 (1995).
[7] H. Timmers *et al.*, *J. Phys. G: Nucl. Part. Phys.* **23**, 1175 (1997).
[8] K. Hagino *et al.*, *Comput. Phys. Commun.* **123**, 143 (1999).
[9] Gurpreet Kaur *et al.*, *Phys. Rev. C* **94**, 034613 (2016).
[10] S. Mitsuoka *et al.*, *Phys. Rev. Lett.* **99**, 182701 (2007).
[11] S. Ntshangase *et al.*, *Phys. Lett. B* **651**, 27 (2007).
[12] E. Piasecki *et al.*, *Phys. Lett. B* **615**, 55 (2005).
[13] M. Beckerman *et al.*, *Phys. Rev. Lett.* **45**, 1472 (1980).
[14] A. Stefanini *et al.*, *Phys. Rev. C* **52**, R1727 (1995).
[15] J. Leigh *et al.*, *Phys. Rev. C* **52**, 3151 (1995).
[16] R.A. Broglia *et al.*, *Phys. Rev. C* **27**, 2433 (1983).
[17] M. Beckerman *et al.*, *Phys. Rev. Lett.* **45**, 1472 (1980).
[18] J. Leigh *et al.*, *Phys. Rev. C* **52**, 3151 (1995).
[19] A. Stefanini *et al.*, *Phys. Rev. C* **52**, R1727 (1995).
[20] A. Jhingan *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **903**, 326 (2018).
[21] K. Schilling *et al.*, *J. Phys. G: Nucl. Phys.* **3**, 1255 (1977).