Evidence of Double Phonon Excitations in $^{16}\text{O} + ^{208}\text{Pb}$ Reaction

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Abstract.

The fusion cross-sections for $^{16}\text{O} + ^{208}\text{Pb}$, measured to high precision, enable the extraction of the distribution of fusion barriers. This shows a structure markedly different from the single–barrier which might be expected for fusion of two doubly–closed shell nuclei. The results of exact coupled channel calculations performed to understand the observations are presented. These calculations indicate that coupling to a double octupole phonon excited state in $^{208}\text{Pb}$ is necessary to explain the experimental barrier distributions.

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1. Introduction

The concept [1] that a representation of the distribution of barriers [2], encountered by two colliding nuclei can experimentally be determined [3] from precisely measured fusion excitation functions has led to a renewed interest [4, 5, 6, 7] in heavy–ion fusion studies near the Coulomb barrier. These experiments have shown that the dominant factors, i.e., the nature of couplings, affecting the fusion probability can be very clearly seen in a barrier distribution representation. With the advent of this new tool and the new measurements, it is interesting to re–visit the problem of fusion of two doubly closed shell nuclei, the $^{16}\text{O} + ^{208}\text{Pb}$ system; detailed analysis [8] performed previously could not reproduce the fusion cross-section and the mean square angular momentum by coupled channel calculations. Apart from the interest in the reaction process itself, another aspect is to identify the state(s) in $^{208}\text{Pb}$ which couple strongly and thus contribute to the shape of the barrier distribution in this reaction. With this knowledge, $^{208}\text{Pb}$ can then be used as a probe in understanding the barrier distributions in reactions with other nuclei; this is an advantage due to the large $Z$ of $^{208}\text{Pb}$, leading to large coupling strength and hence well resolved barrier distributions. Further, understanding the reaction mechanism may also have implications in the reactions to produce super–heavy elements, many of which have $^{208}\text{Pb}$ as one of the reaction partners.

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2. Experimental procedure

The experiments were performed using pulsed $^{16}$O beams from the 14UD Pelletron accelerator at the Australian National University. Isotopically enriched targets of lead in the form of $^{208}$PbS of thicknesses $\sim 23\mu g/cm^2$ and $\sim 350\mu g/cm^2$ evaporated onto a $\sim 10\mu g/cm^2$ carbon backing were used for the fission–fragment and evaporation residue measurements respectively. The fission fragments were detected in two large–area position sensitive multiwire proportional counters in the forward and backward hemispheres. Fission events were identified by their energy loss, time–of–flight information with respect to the pulsed beam. The angular distributions of the fission–fragments, obtained from the position information, were used to calculate the total fission cross–sections as detailed in Ref. [9]. Two silicon surface barrier detectors located at $\pm 22^\circ$ were used to detect elastically scattered events for normalization purposes.

For the measurements of evaporation residues an aluminium catcher foil was placed behind the target in order to stop the recoiling products. The evaporation residue cross–section was measured by detecting the $\alpha$–activity from the decay ER and their daughters, using an annular silicon surface barrier detector as detailed in Ref. [9]. The total fusion cross-section was obtained by summing the fission–and evaporation residue cross–sections.

3. Results

The results of the measurements are presented in two forms: (i) total fusion excitation functions and (ii) the function $d^2(E\sigma)/dE^2$, where $E$ is the energy and $\sigma$ is the fusion cross-section. It has been shown [1] that the quantity $d^2(E\sigma)/dE^2$ gives a representation of the distribution of barriers, and in the following discussions will be referred to as the barrier distribution. This quantity has been extracted from the fusion data using the point difference formula [3] with a step length of 1.86 MeV in centre–of–mass frame. The theoretical excitation functions have been treated in exactly the same way as the experimental data to obtain the theoretically expected barrier distributions. Calculations have been performed using a realistic coupled channel code [10]. The results of simplified coupled channels code CCMOD [11] which is a modified version of the code CCDEF [12, 13] are also presented for comparison.

3.1. No coupling calculations

The measured excitation function and the extracted barrier distribution is presented in figure 1 along with the predictions of a single–barrier penetration model (no coupling). The best fit to the high energy data requires a diffuseness of 0.85 $fm$, and yields values of $V_b = 74.8$ MeV, $R_b = 11.6$ $fm$ for the barrier height and position respectively. As in this case, a fit to the fusion data for other systems [8], with calculations in the no–coupling limit also required large values of the diffuseness parameter. However, it has been shown [14] explicitly for the $^{16}$O+$^{144}$Sm system that the large diffuseness is a result of not considering the couplings to all orders. This seems to be true for the $^{16}$O+$^{208}$Pb system too, as calculations (i) with $a = 0.85$ $fm$ and no couplings and (ii) with $a = 0.65$ $fm$ but including the 2–phonon couplings (see section 3.3), fit the high energy data equally well. The best fit Woods–Saxon potential parameters for the latter, obtained by fixing $a = 0.65$ fm are, $V_0 = 235.5$ MeV, $R_0 = 1.1$ $fm$ for the depth
and radius parameter, yielding barrier parameters of $V_b = 75.2$ MeV, $R_b = 11.85$ fm and $\hbar \omega = 5.0$ MeV. All the calculations in this paper have been performed with these parameters.

The calculations which do not include any couplings underpredict the excitation function as also indicated by the comparison of barrier distributions, where experimentally there is significant strength below (and above) the single–barrier. The failure of the no–coupling calculations to reproduce the wide experimental barrier distribution clearly indicates that couplings with other channels need to be considered.

3.2. Couplings to single phonon states

Comprehensive coupled channel analysis of elastic, inelastic and fusion cross–sections were performed by Thompson et al [8] with the inclusion of the lowest $2^+$, $3^-$ and $5^-$ states of $^{208}$Pb and $3^-$ state of $^{16}$O in addition to neutron pick–up, proton stripping and $\alpha$–transfer channels. In this paper, only the inelastic excitations have been included in the coupled channel calculations. It was shown in reference [8] that the $\alpha$–transfer channel, despite its large cross–section, has very little effect on the fusion cross–section. Further, past studies [4, 5, 6, 7, 8] which have included couplings to transfer channels, show that while couplings to $Q > 0$ transfer channels increase the sub–barrier cross–sections, they do not significantly effect the cross–sections at higher beam energies; the effect of $Q < 0$ transfer channels is less significant when couplings to inelastic channels are present. Thus, it is expected that for the $^{16}$O + $^{208}$Pb system, where the single–nucleon transfers $Q$–values are negative, the dominant features of the fusion barrier distribution will be due to couplings to inelastic channels.

The solid lines in figure 1 shows results of realistic coupled channels calculation [10] which includes couplings to the $2^+$, $3^-$ and $5^-$ vibrational states in $^{208}$Pb. Coupling to the $3^-$ state of $^{16}$O has not been considered in any of the calculations presented here, as it gives rise to a shift in the barrier distribution without changing its shape i.e., in this reaction its effects are only to renormalize the real potential. The equivalent CCMOD [11] calculations are shown by the dashed line for comparison; the differences are due to the approximations inherent in a simplified coupled channels calculation, mainly the linear coupling approximation (derivative form–factors) and the approximate treatment of excitation energies of the intrinsic states. As seen from the figure, the coupled channel calculations fail to reproduce the experimental barrier distribution and the low energy part of the excitation function. The calculations predict a double peaked structure as opposed to the more complex structure seen experimentally; the calculations miss the barrier strength at the lowest energies and also at around 77 MeV. It should be noted that the double–peaked structure of the calculated barrier distribution will remain essentially unchanged even when couplings to other single–phonon states is considered. The agreement cannot be improved by increasing the coupling strength which, while decreasing the weight of the lower barrier will simultaneously shift the higher barrier to still higher energies. It is thus clear that couplings to single phonon states in $^{208}$Pb are not sufficient to explain the data.

3.3. Couplings to double phonon states

As detailed above, calculations with couplings to only 1–phonon states are unable to generate a barrier(s) which lies at an energy intermediate between the main barrier and the higher barrier predicted by these calculations. Thus some other mechanism
has to be considered. Using an eigenchannel approximation it has been shown [13] that whereas in the case of coupling to a single phonon state, the lower and the higher barrier repel each other, the introduction of 2–phonon state results in the separation of the lower two barriers being smaller, and the introduction of a third barrier. In the present case, the experimental barrier distribution would seem to indicate this scenario.

The existence of two phonon octupole excitations in $^{208}$Pb was recently shown [16] experimentally. Coupled channel calculations including the $2^+$, $3^-$, $3^-\otimes 3^-$ and $5^-$ vibrational states in $^{208}$Pb and all the resulting cross–coupling terms e.g., $2^+\otimes 3^-$ etc, were performed; the double phonon state was treated in the harmonic limit. The results are shown by the solid line in Fig. 2; the equivalent CCMOD calculations are shown by dashed line. It is clear that the excitation function and the shape of the barrier distribution is better reproduced in the 2–phonon calculations compared with the 1–phonon calculations. However, the lower energy part of the excitation function and barrier distribution is still not reproduced. A priori, one might assign the disagreement to be caused by ignoring the couplings to transfer channels, since it is known [4, 7] that coupling to positive Q–value transfer channels can introduce a barrier at lower energies. Even though it is recognised that yields of transfer cross–sections do not necessarily correlate with their coupling to the elastic channel, it is relevant to point out that for the case of $^{16}$O + $^{208}$Pb, the n–, p– and $\alpha$–transfer reactions observed [17] at energies near the barrier have negative Q–values. This could be taken as an indication that the low energy shoulder is unlikely to be due to couplings to transfer channels. Further, a lower barrier with significant strength and close to the main barrier requires a strongly coupled channel and since the coupling between the elastic and transfer channels are generally small in comparison with inelastic channels, it would be difficult to reproduce the observed barrier distribution by couplings to transfer channels only. Due to limitations of the coupled channels code, at present we are unable to perform the calculations including transfer channels to investigate these suggestions.

4. Conclusions

Comparison of the experimentally measured barrier distribution with the results of coupled channel calculations show that coupling to double octupole phonon excitations in $^{208}$Pb are necessary to explain the fusion cross–sections. The experiment shows the presence of another lower barrier which could not be reproduced by these calculations. While this barrier(s) might arise due to couplings to transfer channels, not included in the present treatment, it is unlikely to reproduce the shape of the barrier distribution as discussed in section 3.3. One might have to look for other reasons like effects of anharmonicities of the 2–phonon state in $^{208}$Pb as discussed by Takigawa et al during this conference.

It is interesting that the dynamics of the fusion process even for reactions between two closed shell nuclei, which might be thought to be a simple process particularly at low energies, is affected by complex surface vibrations like the 2–phonon states. Furthermore, the barrier distribution picture indicates that there are other subtle features of the $^{16}$O + $^{208}$Pb reaction which have yet to be understood, indicating that experiments are being done at a level of precision where a better understanding of the approximations in the theoretical calculations is required.
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Figure 1. Measured and calculated fusion excitation functions and barrier distributions for the $^{16}$O + $^{208}$Pb system. The curves are the result of using a coupled channels code with no coupling (dotted), and couplings to $2^+$, $3^-$ and $5^-$ states of $^{208}$Pb (solid line). Calculations using the simplified coupled channels code CCMOD for the same couplings is shown by the dashed line.

Figure 2. Comparison of the experimental data with calculations including couplings up to two phonon states (see section 3.3) in $^{208}$Pb. Calculations with both the exact coupled channel code (solid line) and the simplified coupled channel code CCMOD (dashed line) are shown.