Chapter 6

The Fusion of $^{32}\text{S} + ^{208}\text{Pb}$
6.1. EXPERIMENTAL DETAILS

The results for the reactions $^{40}\text{Ca} + ^{90,96}\text{Zr}$ reported in the previous chapter confirm earlier evidence\textsuperscript{1} that double phonon excitations are of particular importance in nuclear fusion at barrier energies. It is thus of interest to consolidate this evidence in an independent study. Since there has been a long search for double phonon excitations in $^{208}\text{Pb}$ using spectroscopic means\textsuperscript{2}, a reaction with $^{208}\text{Pb}$ as target nucleus should be a good choice for such a study. In fact, there is now some spectroscopic evidence that double phonon excitations do occur in this nucleus\textsuperscript{3}. The fusion of $^{208}\text{Pb}$ has already been investigated\textsuperscript{4,5} in some detail for the projectiles $^{16}\text{O}$ and $^{28}\text{Si}$. In order to continue this series of experiments the reaction $^{32}\text{S} + ^{208}\text{Pb}$ was selected for the new study. While there are some indications of the effects of double phonon excitations in the distributions $D_{\text{fus}}(E)$ for the fusion of $^{208}\text{Pb}$ with the lighter projectiles, the larger product of charges $Z_pZ_t$ in case of $^{32}\text{S}$ should result in a better separation of the peaks in $D_{\text{fus}}(E)$, so that the effects of double phonon excitations are more easily identified. The system $^{32}\text{S} + ^{208}\text{Pb}$ is also interesting, because it features several positive $Q$-value transfer channels. Among them is the two neutron pick-up channel, which has been found to be important\textsuperscript{6} in the fusion of $^{32}\text{S}$ with $^{110}\text{Pd}$. A study of the reaction $^{32}\text{S} + ^{208}\text{Pb}$ may thus provide support for the conclusions reached for the palladium target.

6.1 Experimental Details

For the system $^{32}\text{S} + ^{208}\text{Pb}$ the contribution of the evaporation residue cross section to the fusion cross section is negligible, so that the fusion cross section can be established through a measurement of the fission cross section. In the coupled-channels model the fusion yield is defined as the flux which passes over the potential barrier. Although in quasi-fission the system never forms a compound nucleus, it nevertheless overcomes the fusion barrier. Thus quasi-fission events have to be included in the fusion cross section, if the results are to be compared with predictions of the coupled-channels model\textsuperscript{5}.

The experiment to measure the fusion excitation function for $^{32}\text{S} + ^{208}\text{Pb}$ was

performed at the Nuclear Physics Department of the Australian National University. The $^{32}$S beam was delivered by the tandem accelerator of the Department. The beam energy $E_{\text{lab}}$ was defined by the 90° analysing magnet. It was in the range $E_{\text{lab}} = 154 - 182$ MeV. The target was a thin strip of 17 $\mu$g/cm$^2$ of PbS which was evaporated onto a 20 $\mu$g/cm$^2$ carbon foil. The fission fragments were detected using the fission fragment spectrometer which has been described in Section 2.6. The angular distributions of the measured differential fission cross sections are shown in Figure 6.1 for several energies.

The measured angular distributions have been fitted using a procedure\(^7\) based on the transition state model. The experimental angular distributions show consistently large deviations from these smooth fits which are also shown in Figure 6.1. These deviations are artifacts caused by the low setting of a threshold in the electronics which processed the position information of the detectors. This had the effect that there was no linear relationship between event-location and signal-timing for noise-affected pulses and led to an incorrect distribution of the fission events over the angular bins. However, the detection of the total number of fission events was not affected.

Due to the artifacts, the total fission cross sections cannot be extracted by fitting the angular distributions. To overcome this problem for each energy $E_{\text{lab}}$ the ratio of the number of fission events to the number of events in the monitor detectors has been determined as

$$A_{\text{tot}} = \frac{E_0^2}{E_{\text{lab}}^2} \times \frac{\text{Number of Fission Events}}{\text{Number of Events in the Monitor Detectors}}$$  \hspace{1cm} (6.1)

where the factor $E_0^2/E_{\text{lab}}^2$ corrects for the energy dependence of the Rutherford scattering cross section and $E_0$ is an arbitrary energy. The numbers $A_{\text{tot}}$ have then been divided by the cross sections $\sigma^{fit}$ as obtained from fitting the angular distributions to yield for each energy the ratio

$$R = A_{\text{tot}}/\sigma^{fit}$$  \hspace{1cm} (6.2)

The ratios $R$ are shown in Figure 6.2 as a function of $E_{\text{lab}}$. In this plot pronounced deviations from the average occur for some energies. These deviations are most likely due to the artifacts in the experimental angular distributions. On average the ratio $R(E_{\text{lab}})$ increases with $E_{\text{lab}}$. The data have been fitted with a straight line.

Figure 6.1: The measured fission fragment angular distributions for the reaction $^{32}\text{S} + ^{208}\text{Pb}$. The differential cross sections $d\sigma$ are shown as a function of the angle $\theta_{cm}$ in the centre-of-mass system for several beam energies $E_{lab}$. At some angles (e.g. $\theta_{cm} = 121^\circ$ and $143^\circ$) the data deviate markedly from the smooth fits plotted as dashed curves. These are artifacts caused by an electronics problem.
Figure 6.2: The ratio $R$ of the fission fragment yield relative to the integrated cross sections plotted as a function of the beam energy $E_{\text{lab}}$ for some energies. The fluctuations are presumably due to the artifacts in the angular distributions. The solid line is a fit to the data.

This fit has then been used to transform the numbers $A^{\text{tot}}$ into total fusion cross sections $\sigma^{\text{ fus}}(E_{\text{lab}})$ using

$$\sigma^{\text{ fus}}(E_{\text{lab}}) = A^{\text{tot}} \times (aE_{\text{lab}} + b)^{-1}$$

(6.3)

where $a$, $b$ are the slope and intersection of the straight-line-fit, respectively. The scatter of the data in Figure 6.2 results in a systematic uncertainty of the cross sections of approximately $\pm 3\%$, whereas the relative uncertainty of the cross sections is determined by the statistical uncertainty, which, for all data points, is better than $\pm 1\%$. The excitation function $\sigma^{\text{ fus}}(E)$ obtained is shown in Figure 6.3 and documented in the Appendix in Table A.11.
Figure 6.3: The measured fusion excitation function for $^{32}S + ^{208}Pb$. The data are compared with a one-dimensional calculation (dashed curve) and a simplified coupled-channels calculation (solid curve). See text.

6.2 Simplified Coupled-Channels Calculations

The experimental fusion excitation function has been transformed into the barrier distribution representation $D_f^{\text{fus}}(E)$ using Equation 1.60 for different energy step lengths $\Delta E$. The various distributions are consistent with each other. The distribution $D_f^{\text{fus}}(E)$ extracted with $\Delta E_{\text{cm}} \approx 1.8$ MeV is shown in Figure 6.4 as filled circles. At the higher energies data points extracted with $\Delta E_{\text{cm}} \approx 2.7$ MeV (triangles) are also shown. The distribution has two peaks at $E_{\text{cm}} = 139$ MeV and 143 MeV. A third peak may exist at $E_{\text{cm}} = 149$ MeV, however, the data are not as well defined in this energy region as at the lower energies. Qualitatively, the distribution $D_f^{\text{fus}}(E)$ for $^{32}S + ^{208}Pb$ is very similar to the one observed\(^8\) for $^{32}S + ^{110}Pd$.

Figure 6.4: The distribution $D^{\text{frac}}(E)$ for $^{32}\text{S} + ^{208}\text{Pb}$ compared with simplified coupled-channels calculations for (a) single and (b) double phonon coupling. In (a) the second peak of the dashed calculation is above $E_{\text{cm}} = 160 \text{ MeV}$. See text.
Table 6.1: Excitation energies $E_x$, angular momenta $\lambda$, parities $\pi$, reduced matrix elements $B(EL)$ and deformation parameters $\beta_\lambda$ of the states which have been included in the simplified coupled-channels calculations. The energies are given in MeV and the reduced matrix elements are in $e^4b^\lambda$. (The data are from: Table of Isotopes 7th edition, ed. C.M. Lederer, V.S. Shirley (1978); S. Raman et al., At. Dat. Nucl. Dat. Tables 36 (1987) 1; R.H. Spear, At. Dat. Nucl. Dat. Tables 42 (1987) 55.)

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$E_x$</th>
<th>$\lambda$</th>
<th>$B(EL)$</th>
<th>$\beta_\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{32}$S</td>
<td>2.230</td>
<td>$2^+$</td>
<td>0.03</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>5.006</td>
<td>$3^-$</td>
<td>0.01</td>
<td>0.7</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>2.615</td>
<td>$3^-$</td>
<td>0.61</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>4.085</td>
<td>$2^+$</td>
<td>0.29</td>
<td>0.07</td>
</tr>
</tbody>
</table>

In order to interpret the observed structure in $D_{1us}(E)$, simplified coupled-channels calculations have been carried out using the code CCMOD\textsuperscript{9}. The potential parameters used in these calculations have been obtained by fitting the fusion cross sections $\sigma_{1us} > 200$ mb with a one-dimensional barrier penetration calculation. In these fits the data points at $E_{lab} = 188$ MeV and 194 MeV have not been considered, since they are inconsistent with the experimental excitation function for $^{28}$Si + $^{208}$Pb, which has been measured in much more detail at the higher energies\textsuperscript{10}. As for the silicon data the diffuseness parameter necessary to obtain agreement, which is $a_0 = 1.24$ fm, is large compared to values obtained from fitting elastic scattering data. The values chosen for the potential depth and the radius parameter are $V_0 = 571.1$ MeV and $r_0 = 0.8$ fm, respectively. This corresponds to a barrier of height $B_0 = 145.9$ MeV and curvature $\hbar\omega_0 = 3.6$ MeV positioned at the inter-nuclear separation $R_0 = 11.5$ fm. The fit is shown in Figure 6.3 as dashed curve.

The calculations considered the lowest quadrupole and octupole excitations of $^{32}$S and $^{208}$Pb. The properties of these states are tabulated in Table 6.1. In CCMOD the coupling strength is estimated from the collective model expression using Equation 1.53. The radius of the excited nucleus was chosen to be $R_a = 1.06A^{1/3}$. Initially only single phonon coupling was considered. Figure 6.4(a) shows the cal-

culations for coupling to the $2^+$ and $3^-$ states of the $^{208}$Pb target nucleus only (solid curve) and for coupling to these states in both the projectile and target nuclei (dashed curve). Neither calculation is in agreement with the experimental distribution $D^{\text{fus}}(E)$.

Figure 6.4(b) shows three calculations which allow higher order couplings. The dashed and solid curves correspond to calculations which treat $^{32}$S as inert, but include up to double phonon excitations for $^{208}$Pb. The calculation represented by the solid curve does not include couplings which involve quadrupole phonons. It is not much different from the full calculation (dashed curve). This demonstrates that the effects of the quadrupole phonons may be neglected in good approximation. The calculation shown as the dot-dashed curve includes up to double excitation of the octupole phonon of $^{208}$Pb and in addition the projectile excitations. All three calculations shown in this panel display only two major peaks in the measured energy range and fail to explain the three-peak-structure of the experimental data. The excitation energies of the double phonon states have been taken as the sum of the phonon energies, while their deformation parameters have been estimated to be the square root of the quadratic sum of the deformation parameters for the single phonons involved.

In additional calculations the effects of coupling to neutron transfer channels on $D^{\text{fus}}(E)$ have been studied. These calculations considered coupling to single and double excitations of the octupole phonon in $^{208}$Pb and coupling to one and two neutron pick-up. All channels involving quadrupole phonons and/or projectile excitations have been neglected. The one and two neutron pick-up channels have positive $Q$-values with $Q_{1n} = +1.275$ MeV and $Q_{2n} = +5.953$ MeV, respectively. In CCMOD transfer is treated approximately using Equation 1.54. The transfer coupling strength and diffuseness were chosen as $F_0 = 2$ MeV and $a_F = 1.2$ fm, respectively. The results of these calculations are shown in Figure 6.5. When one and two neutron pick-up is combined with coupling to the single excitation of the octupole phonon in $^{208}$Pb the curve shown in panel (a) is obtained. This calculation shows three peaks in roughly the right positions. Better agreement with the data is, however, achieved, when the double phonon excitation of the octupole phonon is also included in the calculation. The result of this calculation which reproduces the positions and weights of the three peaks in $D^{\text{fus}}(E)$ correctly, is shown in Figure 6.5(b). It should be noted that the inclusion of the neutron transfer channels gives rise to the lowest energy peak of $D^{\text{fus}}(E)$. The corresponding excitation function is shown in Figure 6.3 as solid curve. The sub-barrier fusion enhancement is still under-
Figure 6.5: The distribution $D^\text{full}(E)$ for $^{32}$S + $^{208}$Pb compared with simplified coupled-channels calculations for coupling to neutron transfer channels in conjunction with (a) single and (b) double phonon coupling. See text.
predicted by this calculation. This is mainly due to the tail of the experimental $D_{\text{fus}}(E)$ at the lowest energies which is not reproduced by the calculation. This tail is similar to that observed for $^{28}\text{Si} + ^{208}\text{Pb}$, for which it has been reproduced\textsuperscript{11} by assuming a static projectile deformation. Since the nucleus $^{32}\text{S}$ has a quadrupole moment which may be associated with a prolate deformation\textsuperscript{12}, such an approach would also be possible for the system discussed here. The inclusion of projectile deformation into the calculation shown in Figure 6.5(b), however, does destroy the existing agreement even when the deformation parameter, which is $\beta_2 = 0.4$, is significantly reduced.

Since the calculations suggest that the lowest energy peak of $D_{\text{fus}}(E)$ may be associated with the positive $Q$-value one and two neutron pick-up reactions, it appears more likely that the tail is caused by a distribution of this transfer strength over several channels including those which originate from or lead to excited states. This should broaden the low energy peak, an effect which cannot not show up in the calculation, because there it is assumed that the transfer occurs from ground state to ground state. Another possibility is that, as suggested for $^{40}\text{Ca} + ^{96}\text{Zr}$, sequential transfer occurs.

6.3 Concluding Remarks

The barrier distribution representation $D_{\text{fus}}(E)$ for $^{32}\text{S} + ^{208}\text{Pb}$ as extracted from a precision measurement of the fission excitation function for this system has been analysed with simplified coupled-channels calculations. The features of the distribution can be reproduced when coupling to up to double phonon excitations of $^{208}\text{Pb}$ and one and two neutron pick-up is assumed. The observation that double phonon excitations of $^{208}\text{Pb}$ are important in this system is consistent with the results for $^{16}\text{O}, ^{28}\text{Si} + ^{208}\text{Pb}$. In contrast to the findings for the reactions $^{28}\text{Si} + ^{208}\text{Pb}$ and $^{32}\text{S} + ^{110}\text{Pd}$, the inclusion of projectile deformation or excitation in the calculations reduces the agreement. The effects of the two neutron pick-up channel on fusion which have been reported\textsuperscript{13} for the system $^{32}\text{S} + ^{110}\text{Pd}$, are, however, confirmed by the results for $^{32}\text{S} + ^{208}\text{Pb}$. It appears that in addition to the two neutron pick-up reaction several other positive $Q$-value channels, including transfer

\textsuperscript{12}P. Raghavan, At. Dat. Nucl. Dat. Tables 42 (1989) 189.
to excited states, couple to the relative motion of this system.