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TIME DEPENDENT HARTREE-FOCK AND ONE-BODY DISSIPATION
FOR HEAD-ON COLLISIONS OF $^{84}$Kr + $^{209}$Bi

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The purpose of the present study is to get more insight into
the dissipation mechanism of heavy ion collisions. To this end we
have made a comparison of the extensive TDHF calculations of head-
on collisions of $^{84}$Kr + $^{209}$Bi [1] with predictions of the one
body dissipation theory of the Berkeley group [2].

The TDHF calculations [1] show that the projectile is stopped
by the target in a very short time of the order of $5 \times 10^{-22}$ s .
Between $E_{lab} \sim 850$ MeV and $E_{lab} \sim 1100$ MeV there is a fusion
region. For $E_{lab} < 850$ MeV the projectile "bounces" off the
target while for $E_{lab} > 1100$ MeV it "passes through" the target.

Here we define a stopping time $t_s$ as the interval from the
instant when the nuclear surfaces touch ($s = 0$) to the instant
of closest approach. Such stopping times are extracted from the
TDHF calculations [3] and are indicated in Table 1 as a function
of the bombarding energies.

One can see that larger is the energy shorter is the
stopping time.

We have made calcu-
lations using the "window for-
mula" [2] and several choices
for a conservative force. If $s$ is the separation distance
between the surfaces of the
interacting nuclei the equa-
tion to be solved is :

<table>
<thead>
<tr>
<th>$E_{lab}$ (MeV)</th>
<th>$t_s$ ($10^{-22}$ s.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>4.9</td>
</tr>
<tr>
<td>550</td>
<td>4.0</td>
</tr>
<tr>
<td>600</td>
<td>3.4</td>
</tr>
<tr>
<td>714</td>
<td>3.0</td>
</tr>
<tr>
<td>800</td>
<td>2.5</td>
</tr>
<tr>
<td>1000</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 1. Stopping times $t_s$ as a function of the bombarding
energy. [3]

*) This work has been supported by the NATO Research Grant n°1782.
\[ \mu \frac{d^2s}{dt^2} = -2N(s) \frac{ds}{dt} - \frac{dV}{ds} \]  

where \( \mu \) is the reduced mass, \( N(s) \) is the proximity flux [4] and \( V(s) \) the interaction potential. Four different choices have been made for \( V(s) \):

1. Pure Coulomb potential for overlapping charge distributions using the formula of Bondorf et al. [5].
2. Coulomb (Bondorf) + nuclear potential of Wilczyński and Siwek-Wilczyńska [6].
3. Coulomb (Bondorf) + standard proximity potential [7].
4. Coulomb (Bondorf) + modified proximity potential of Randrup [8].

Fig. 1 shows the various potentials as a function of the separation distance between nuclear centres \( R = R_1 + R_2 + s \) \((R_1 - \text{nuclear radii})\). The standard proximity potential has a very shallow pocket at \( s = 0 \), about 2 MeV deep with respect to the barrier. In the Siwek-Wilczyński potential the pocket at \( s = 1.6 \text{ fm} \) is somewhat deeper, 6 MeV below the barrier. The modified proximity potential has a broad barrier beyond which it decreases linearly towards the centre.

Fig. 2 shows the surfaces separation \( s \) as a function of time in units of \( 10^{-22} \text{ s} \) at two bombarding energies \( E_{\text{lab}} = 500 \text{ MeV} \) and \( E_{\text{lab}} = 1200 \text{ MeV} \) for each potential. The origin \( t = 0 \) corresponds to \( s = 3.2 \text{ fm} \), i.e. the distance at which the friction starts to act [4]. One can see that in the considered energy range none of these potentials gives the behaviour observed in TDHF calculations. The friction by itself is not the only factor to stop the projectile and the stopping time is very sensitive to the non-conservative force. For potentials which stop the projectile the stopping time is comparable with but somewhat longer than that of Table 1. For the Siwek-Wilczyński and the standard proximity potentials it decreases with the energy, like in TDHF calculations, and the values of \( t_s \) given by the standard proximity potential are nearest to the TDHF results (\( 5 \times 10^{-22} \text{ s} \) for \( E_{\text{lab}} = 500 \text{ MeV} \), \( 3 \times 10^{-22} \text{ s} \) for \( E_{\text{lab}} = 800 \text{ MeV} \) and \( 2.8 \times 10^{-22} \text{ s} \) for \( E_{\text{lab}} = 1000 \text{ MeV} \)). But after the instant of closest approach in the standard proximity potential the projectile gets captured in the pocket at low energies \( \sim 500 \text{ MeV} \).
and the fragments separate at high energies. The low energy capture at 500 MeV is more reminiscent of the situation found for a lighter pair $^{86}$Kr $+$ $^{139}$La at $E_{\text{lab}} = 410$ MeV [1]. On one hand this result is related to the existence of a shallow pocket, the presence of which depends on the choice of the Coulomb interaction. On the other hand it is due to the "window formula" friction which is too strong to allow the separation of the fragments even if there is a shallow pocket. The strong effect of friction given by the "window formula" was also discussed in Ref. [9] for much lighter pairs. For the Siwek-Wilczyński potential it produces a similar effect, the projectile being captured in the pocket for the whole range of bombarding energies between 500 MeV and 1200 MeV. The modified proximity potential is so deep inside the barrier that the projectile gets captured near the centre at all energies.

In conclusion this study suggests that the true nucleus-nucleus interaction might be time and/or energy dependent. At lower energies it might have a hard core which stops the projectile and which crumbles at high energies. In the TDHF calculations of Ref. [10] it is shown that at the beginning of the collision the single particle energies exhibit some stiffness which persists for a while. This is consistent with the sudden approximation on which the standard proximity potential is based. Our calculations suggest that such a stiffness would last for a shorter time at larger bombarding energies leading to a potential shape closer to the modified proximity potential.

We would like to thank the authors of Ref. [1] for discussions of their TDHF results and for providing information about the stopping times.

References

Four different choices for the interaction potential of $^{84}$Kr + $^{209}$Bi as a function of the separation distance R between nuclear centres: (······) - pure Coulomb (Berdord), (-----) - Siwek-Wilczyńska and Wilczyński + Coulomb, (·····) - modified proximity + Coulomb, (−−−−−) - standard proximity + Coulomb.
Trajectories for $^{84}$Kr + $^{209}$Bi at $E_{lab} = 500$ MeV and $E_{lab} = 1200$ MeV for the corresponding potentials of Fig. 1 (same legend). Here $s$ is the separation distance between nuclear surfaces $s = R - R_1 - R_2$. 