Resolution of the Fusion Window Anomaly in Heavy-Ion Collisions

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Time-dependent Hartree-Fock theory is used to study fusion in $^{16}O+{}^{16}O$ collisions. The Hamiltonian density is obtained from Skyrme forces including the spin-orbit interaction. The inclusion of spin has a dramatic effect on the observed dissipation for central collisions. At a center-of-mass energy of 34 MeV, fusion is found for all angular momenta less than the experimental critical angular momentum. Thresholds for inelastic scattering increase to a bombarding energy per nucleon of about 9 MeV. The decrease in transparency is in general agreement with experiment.

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It is generally acknowledged that the time-dependent Hartree-Fock (TDHF) method provides a useful foundation for a fully microscopic many-body theory of low-energy heavy-ion reactions.[1] This assumption is predicated in part on the results of fusion excitation-function calculations for light-mass systems, and particular energy-angle correlation-function calculations for strongly damped heavy-mass collisions.[2] The details of these calculations suggest that the Pauli principle plays an important role in simultaneously building up a time-dependent mean field and suppressing the propagation of the strong N-N interaction terms.

However, these calculations exhibit an unusual degree of transparency for the very central collisions, which manifests itself as a lower angular momentum limit to fusion (TDHF angular momentum window), or equivalently, a central region of deep-inelastic scattering. This transparency produces a strong interplay between fusion and fully damped inelastic scattering having a particular experimental signature. There have been several attempts to experimentally observe this effect.[2-5] The most conclusive experimental work to date, Ref. 3, finds a lack of transparency in central low-energy collisions. Here the $^{16}O+{}^{16}O$ collision was studied at a center-of-mass (c.m.) energy of 34 MeV. At this energy the authors note an inelastic two-body yield from central collisions of approximately 5.9 mb, whereas detailed TDHF calculations predict a corresponding inelastic yield of 132 mb. The TDHF result arises from a component of the reaction with angular momenta less than $6\hbar$ which appears to be fully relaxed.[2,3] This discrepancy is presently viewed as a breakdown of the TDHF method.

Even so, for strongly damped collisions having a combined mass number of about 100 or more, TDHF calculations show mean outgoing kinetic energies and scattering angles in good agreement with experiment, where as much as 50% of the fully damped branch of the reaction originates from inelastic central collisions.[2,6] In these reactions measurements of other observables, such as N-N correlations,[7] are sensitive to the entrance-channel angular momentum and may provide additional tests for the existence of a central transparency region.

It has been noted that three effects could resolve this anomaly[2,8-11]: (i) Inclusion of two-nucleon collision terms in the description of the reaction. Studies of the effect of two-nucleon collision terms on the TDHF central transparency show the disappearance of the inelastic scattering for particular values of the two-body interaction strength.[10,11] These results are principally phenomenological and may be unphysical since realistic calculations for $^{16}O+{}^{40}Ca$ show little or no modification of the TDHF window.[2,8] (ii) Modification of the effective forces used in the calculations. In heavy-mass systems, both the low-energy threshold for fusion (extra push threshold) and the high-energy transparency threshold are dependent on the choice of the effective interaction.[12,13] Since various parametrizations of the Skyrme force have differing physical properties (velocity dependence, density dependence, incompressibility, etc.), they also give different fusion barriers, and consequently different inelastic thresholds. (iii) Relaxation of the approximate symmetries that are used to simplify the computations. It has been noted in TDHF calculations[2,14] of $^{40}Ca+{}^{40}Ca$ fusion excitation functions that the assumption of an isospin degeneracy can alter the fusion cross sections by as much as 20%. All of the TDHF fusion calculations have been carried out with approximations which impose spin symmetry on the TDHF wave functions. Generally it is argued that the restoration of symmetries to a system decreases the amount of dissipation and hence the amount of fusion.

To investigate the latter we consider the addition of spin-orbit current interaction terms to the TDHF Hamiltonian. Thus far all TDHF calculations have ignored these terms by assuming completely spin-degenerate and spin-saturated states. Inclusion of the spin-orbit–coupling terms in Skyrme forces results in additional terms to the TDHF Hamiltonian density,[15,16]

$$H_{ls}(\mathbf{r},t) = -\tfrac{1}{2}t_4(\rho\nabla\cdot\mathbf{J} + \textstyle\sum_q \rho_q \nabla\cdot\mathbf{J}_q). \tag{1}$$

In (1), t_4 is the strength of the spin-orbit force, ρ_q is the nuclear density for isospin $q = \pm\frac{1}{2}$, and the divergence of the current is given in terms of the single-particle wave functions, ϕ_q as

$$\nabla\cdot\mathbf{J}_q = i\textstyle\sum_{\alpha\sigma}\nabla\phi^*_{\alpha q}\cdot\boldsymbol{\sigma}\times\nabla\phi_{\alpha q}. \tag{2}$$

We obtain the TDHF equations by using Eq. (1) together with the spin-independent Skyrme Hamiltonian density.[17] Details of this procedure will be given elsewhere.[18] This form of the energy functional was used in Ref. 15 to construct solutions of the axially symmetric static Hartree-Fock equations.

We have solved the TDHF equations in two dimensions using an axial-symmetry assumption for collisions of $^{16}O + ^{16}O$ at a variety of bombarding energies for Skyrme II and Skyrme M*,[19] finite-range forces with the spin-orbit interaction as given above. For these forces the strength of the spin-orbit force is determined by the fitting of a variety of single-particle properties and bulk properties of nuclei over the periodic table. In Fig. 1 we observe the time dependence of various quantities for the central collision at $E_{c.m.} = 34$ MeV using the Skyrme II + LS force. Here E is the single-particle energies summed over all occupied states (not a constant of motion),

$$E(t) = \textstyle\sum_\lambda \epsilon_\lambda(t). \tag{3}$$

The quantity ΔE shows the time dependence of the splitting of $1p$ states,

$$\Delta E = \textstyle\sum_{1p}(\epsilon_{p3/2} - \epsilon_{p1/2}), \tag{4}$$

and hence is a measure of the strength of the spin-orbit part of the Hartree-Fock field in ^{16}O. Here we see that after the immediate contact of the two ^{16}O nuclei the splitting reduces significantly, indicating the preference for the strongly interacting system to relax into a spherical shape. The remaining two quantities are calculated by our defining the spin mixing probability

$$p_\lambda(t) = \int d^3r[|\chi^+_\lambda(\mathbf{r},t)|^2 - |\chi^-_\lambda(\mathbf{r},t)|^2], \tag{5}$$

where χ^+ and χ^- are the spin-up and spin-down components of the nucleon spinor. Note that we quantize spin along the TDHF collision axis. In terms of p_λ we have

$$P(t) = \textstyle\sum_\lambda p_\lambda(t), \tag{6}$$

and

$$\Delta p(t) = \textstyle\sum_{1p}(p_{3/2} - p_{1/2}). \tag{7}$$

Again in the immediate overlap region the quantity Δp increases rapidly, indicating the strong surface coupling to the spin-orbit part of the field.

For head-on collisions we study the outgoing kinetic energy of the system as a function of the bombarding energy, with particular attention to the thresholds for inelastic scattering. In this case the reduction of the TDHF equations to two dimensions is exact. We also study the fusion and inelastic cross sections at a c.m. energy of 34 MeV, using the rotating-frame approximation, in order to compare with the results of Ref. 3. At this energy the axial rotating-frame approximation has an error of about 10%.[17] The threshold c.m. energies are presented in Table I for two different finite-

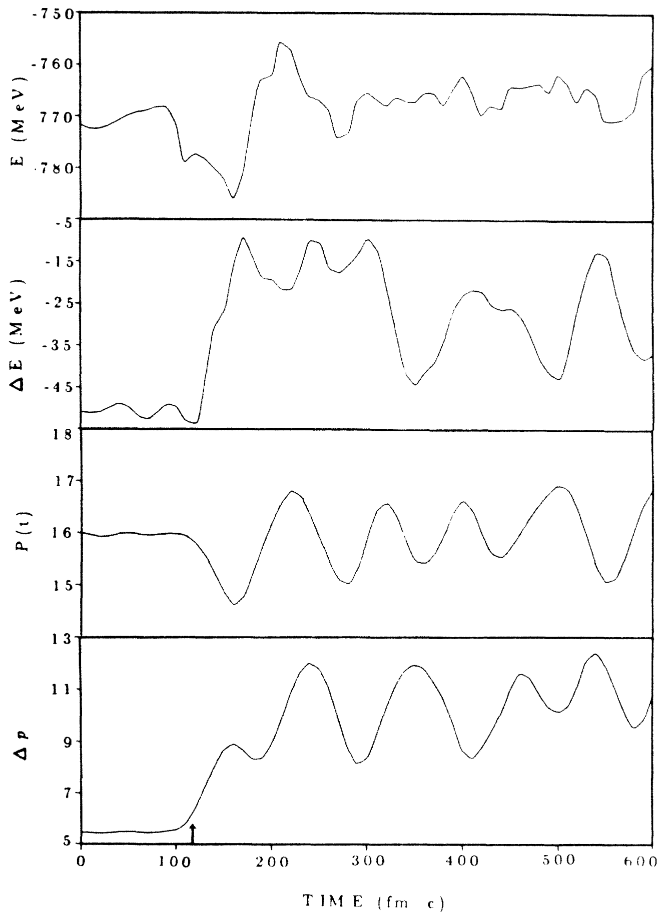

FIG. 1. The time evolution of the quantities E, ΔE, P, and Δp for the central collision of $^{16}O + ^{16}O$ at 34-MeV c.m. energy. The force used is the Skyrme II + LS. The arrow on the time axis indicates the time of first contact.

TABLE I. Thresholds for the inelastic scattering of $^{16}O + ^{16}O$ system.

Force	Skyrme II (MeV)	Skyrme M* (MeV)
Spin orbit	68	70
No spin orbit	31	27

range Skyrme forces. The threshold energy is computed with and without the spin-orbit interaction for each force. Results for Skyrme II in the absence of any spin-orbit force have been given previously in Ref. 13. The results reported in our study have been obtained with a lattice in cylindrical coordinates having r and z dimensions of $N_r \times N_z = 20 \times 60$, and mesh spacings of $\Delta r = \Delta z = 0.5$ fm. This parametrization of the space lattice is commensurate with that used in Ref. 13. In our calculations we employ a time step $\Delta t = 0.25$ fm/c, and a definition of fusion as in Ref. 13. From Table I we note that the addition of the spin-orbit part of the force increases the inelastic thresholds by more than a factor of 2. Whereas, the variations in the threshold energy with changes in the individual force, as reported in Ref. 13 and in our study, are less than 20%. The finite-range forces II and M* are obtained from their zero-range counterparts using the expansion given in Ref. 15. However, we note that the finite-range form of the force has increased the χ^2 fit to 24 pieces of experimental data for spherical nuclei to more than 300. We attribute this unusually high value of χ^2, for the finite-range M* force, to the incorrect surface behavior generated by the expansion of Ref. 15 rather than to the deficiencies in the zero-range parametrization. Calculations with improved finite-range forces are in progress and will be reported elsewhere.[18] Table II displays the fusion cross sections at c.m. energies of 20 and 4 MeV. Here we have also included the results for the Bonche-Koonin-Negele force.[21] We observe from Table II that the inclusion of the spin-orbit force has a dramatic effect on the fusion cross sections at 34 MeV. Despite this improvement the forces II and M* overestimate the experimental fusion cross sections. Upon comparison of the cross sections for the forces II and M* without the spin-orbit part with the cross sections calculated by use of Bonche-Koonin-Negele force we conclude that the finite-range versions of Skyrme force are not appropriately fitted to describe the details of fusion cross sections.

We have performed TDHF calculations of fusion for the $^{16}O + ^{16}O$ system using different versions of the Skyrme force with and without spin-orbit interaction. This work represents the first quantitative TDHF calculations including the spin-orbit part of the Skyrme force. For this system calculations without the spin-orbit force give an onset of inelastic scattering occurring at a bombarding energy per nucleon of about 3.5 MeV. In contrast, the calculations including the spin-orbit part increase this threshold to 9 MeV. Thus we note that the dynamical breaking of the spin degeneracy substantially modifies the amount of dissipation observed in TDHF calculations. Despite this improvement the finite-range versions of the Skyrme force overestimate the experimental fusion cross sections. This we believe is due to the inaccurate parametrization of these forces and will be dealt with in future work.

TABLE II. Total fusion cross sections for the $^{16}O + ^{16}O$ system for different parametrizations of the Skyrme force with and without spin-orbit part. The last row shows the corresponding experimental cross section from Ref. 20.

Force	$E_{c.m.} = 20$ MeV (mb)	$E_{c.m.} = 34$ MeV (mb)
II	1315	~0
II + LS	1466	1694
M*	1389	~0
M* + LS	1460	1822
Bonche-Koonin-Negele	912	794
Expt.	850	1075

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