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Spin-orbit effect in low-energy heavy-ion collisions

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INTRODUCTION & METHOD

In Skyrme energy-density functionals the spin–orbit (SO) term controls shell gaps and deformation. We quantify how SO strength alters the oscillation frequency f and the equivalent coefficient of restoring force k. We use Sky3D (TDHF) to simulate head-on collisions for nuclei with Z=6–40 and N∈[Z−4, Z+4]. The center-of-mass energy is set by E = A+eZ²/r_0 with A=Z+N to ensure a comparable initial approach across systems. From the density, we compute the relative distance

$$R(t) = 2\iiint |z|\rho(t,x,y,z)\,dxdydz$$

identify the first minimum t_{min} and the first subsequent maximum t_{max} , define T/2 =$t_{max} - t_{min}$ and f = 1/T, and coefficient of restoring force k = 4π² μ / T² with μ the reduced mass. We switch the Skyrme SO coefficient t_4 on/off and also scan t_4 ∈ [0, 150] MeV·fm⁵. All runs employ identical grids and time steps;

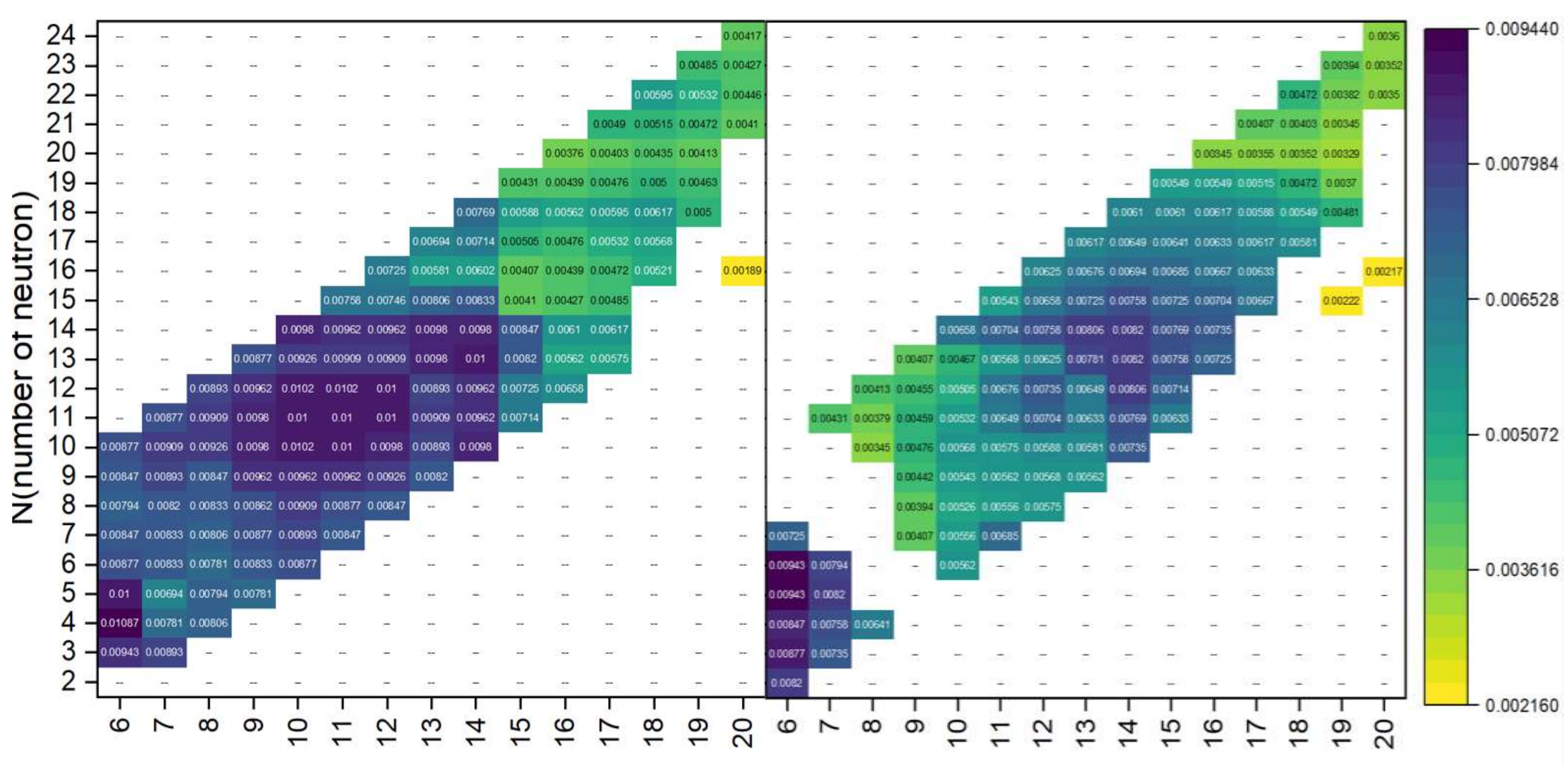


Fig. 1 — f(Z,N) map with spin–orbit (SO) enabled (SV-bas). Map of the frequency f as a function of proton number Z and neutron number N, calculated with (left) and without (right) spin–orbit (SO) coupling using the SV-bas.

To quantify fusion dissipation, we employ Physics-Informed Neural Networks (PINNs) to map microscopic TDHF trajectories onto macroscopic transport parameters. By assuming explicit distance and velocity-dependence (R, v) for reduced mass, Interaction potential, and friction coefficient the PINN is constrained by a generalized Euler-Lagrange equation. This framework successfully extracts these coefficients from $^{16}O+^{16}O$ collisions, revealing significant hysteresis in potential surfaces and offering a model-independent perspective on energy dissipation.

RESULTS & DISCUSSION

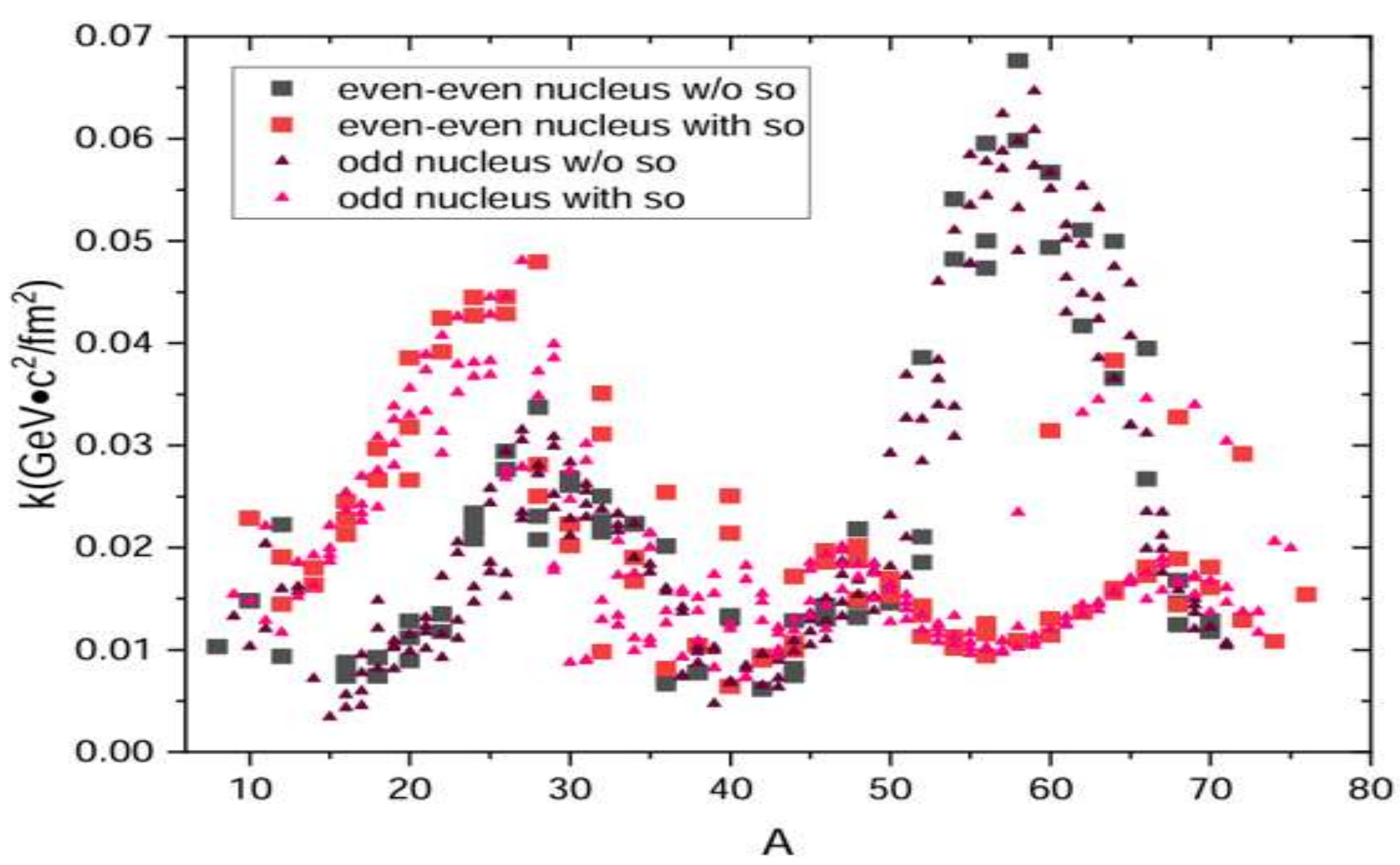


Fig. 2 — Restoring force coefficient k as a function of mass number A. The coefficient of restoring force k is derived from measured periods T via k = 4π² μ / T² . SO-on vs. SO-off: Enabling spin–orbit coupling enhances k near A≈30 but suppresses it near A≈60, consistent with frequency map trends.

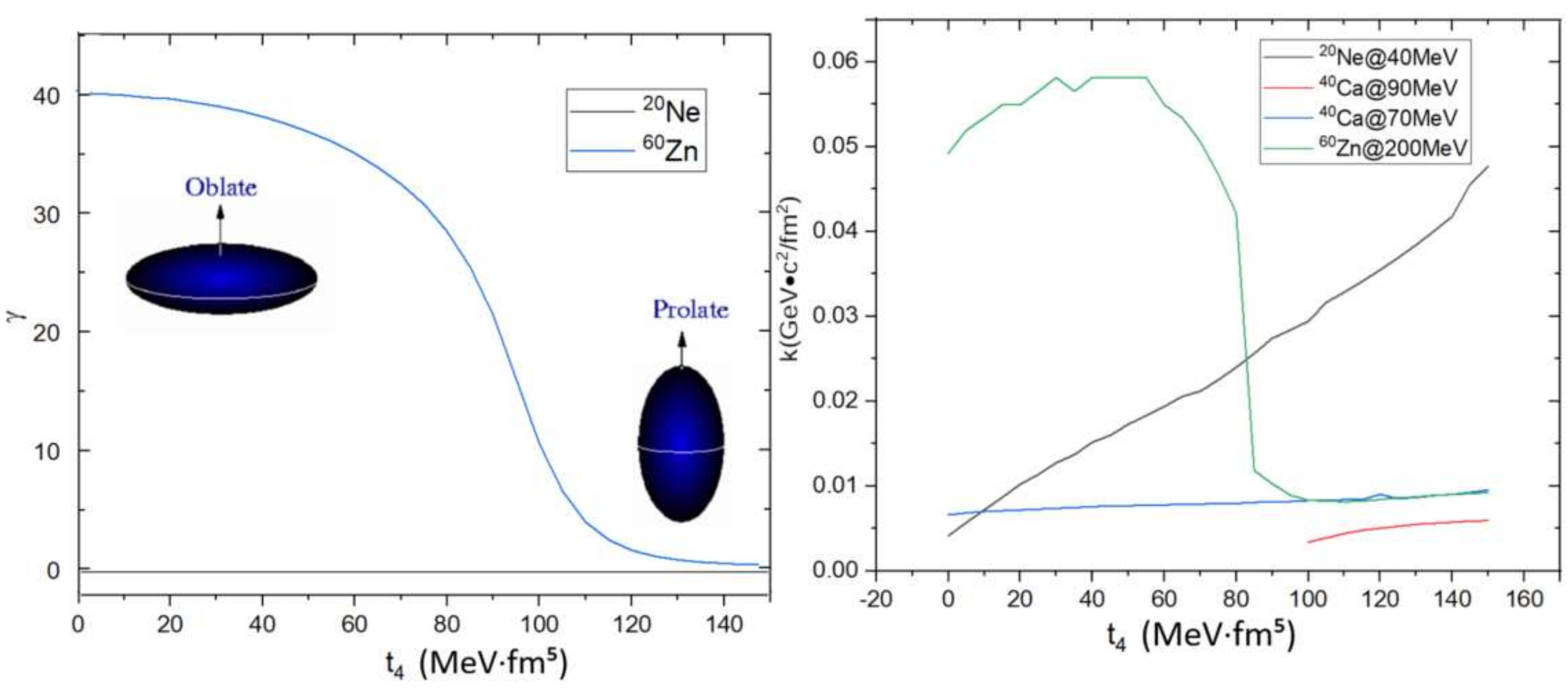
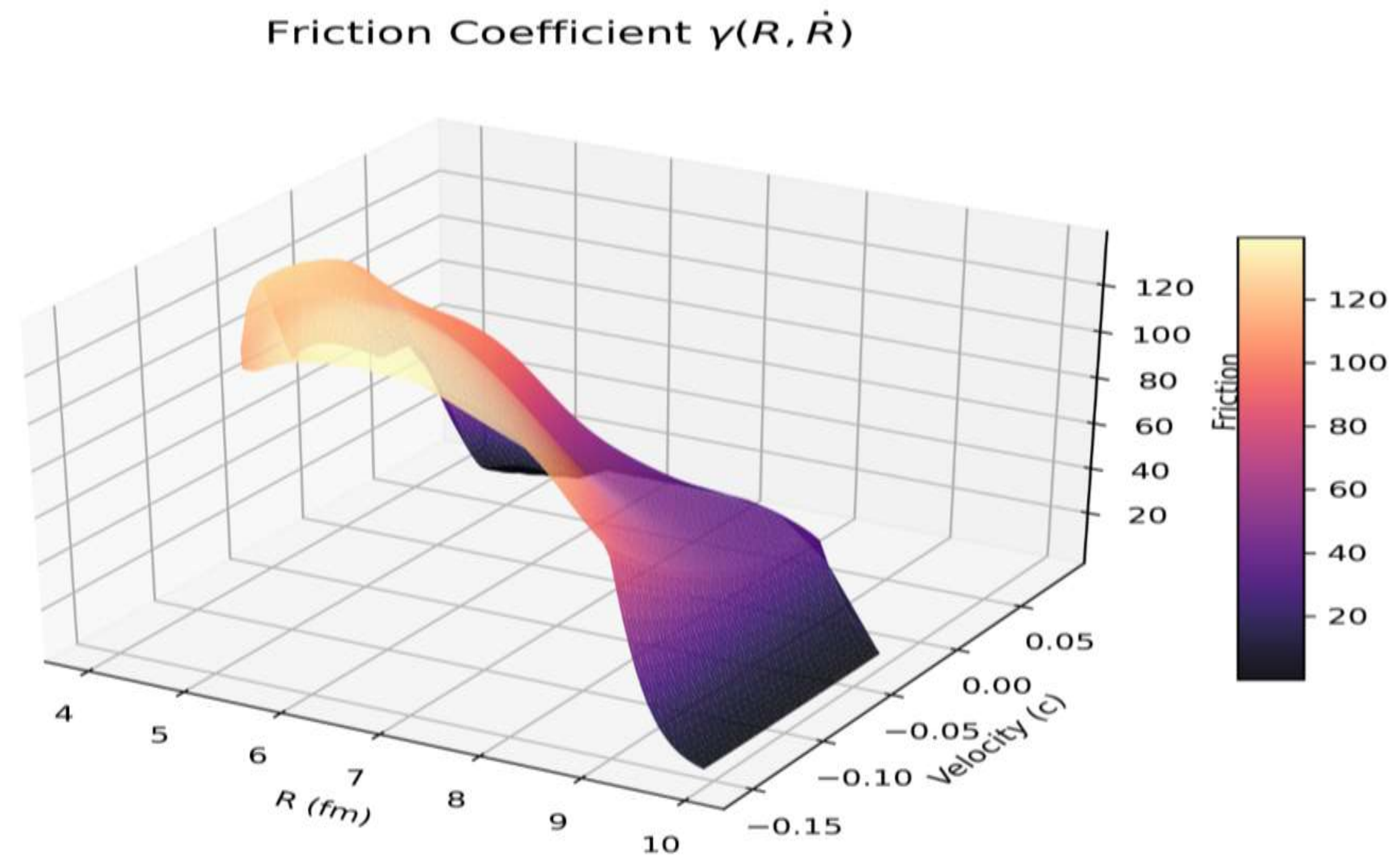


Fig. 3 — Interplay between static triaxiality γ (left) and restoring force coefficient k (right) vs. t_4. Static Deformation (Left): Ground-state HF calculations show ^{20}Ne remains axial (γ≈0°), while ^{60}Zn transitions from triaxial (γ≈40°) to axial, marked by an abrupt drop at t_4≈80 MeV·fm⁵. Restoring Force k (Right): ^{20}Ne stiffens linearly; ^{40}Ca remains insensitive; ^{60}Zn exhibits a sharp "cliff" at t_4≈80 MeV·fm⁵. The synchronized drops in γ and k for ^{60}Zn demonstrate that SO coupling modifies oscillations primarily by reshaping the nucleus's static configuration.



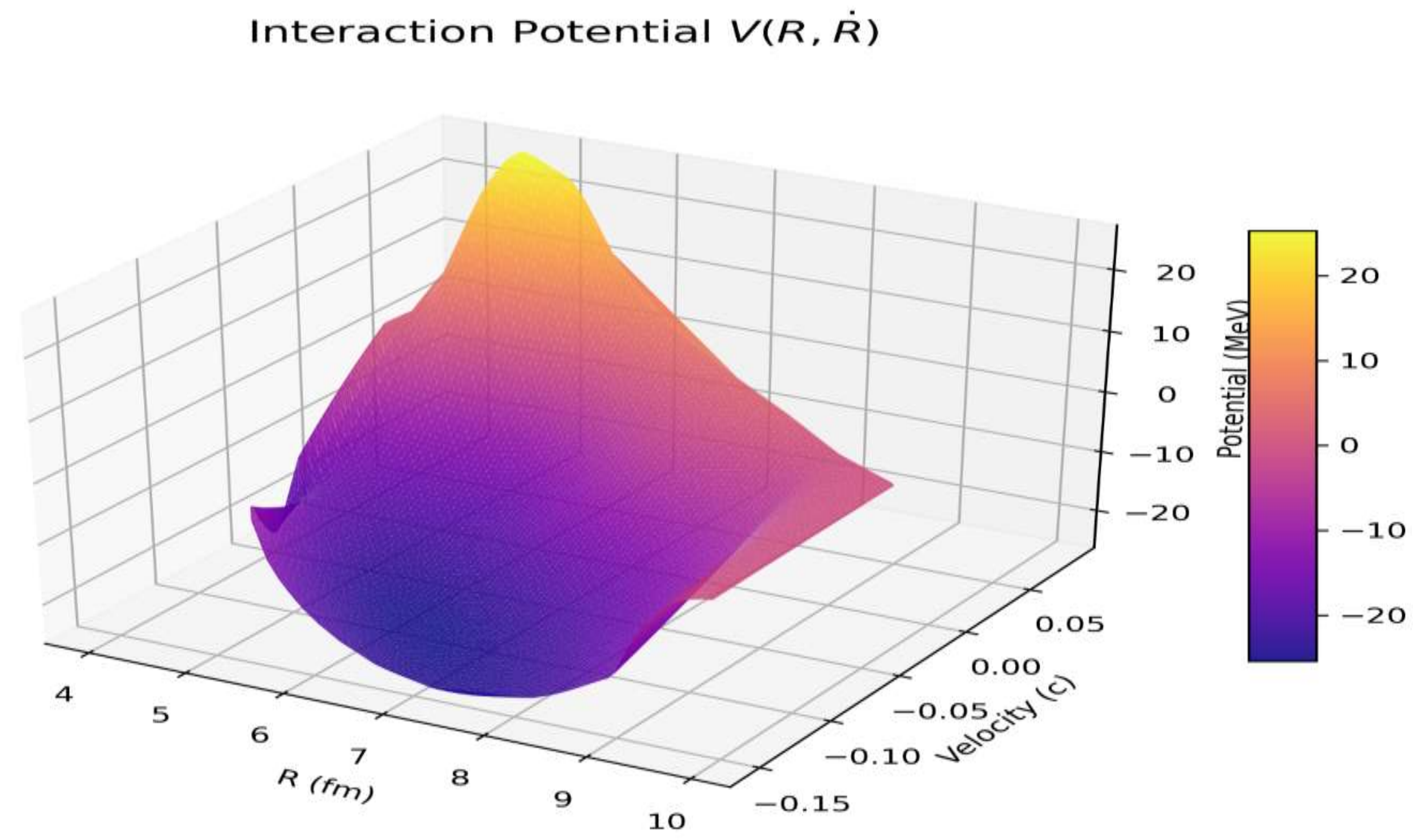


Fig. 4 —PINN-extracted velocity-dependent friction γ(R, v) (top) and potential V(R, v) (bottom). These macroscopic coefficients are derived from 50 $^{16}O+^{16}O$ TDHF trajectories across a range of energies, constrained by a generalized Euler–Lagrange equation to ensure physical consistency.

CONCLUSION & FUTURE WORK

SO coupling significantly alters oscillation dynamics by reshaping nuclear static configurations. Our PINN framework successfully extracts velocity-dependent transport coefficients from TDHF trajectories, revealing potential hysteresis and offering a model-independent perspective on dissipation. Future work will extend this methodology to a broader range of nuclear systems to further decode energy transfer mechanisms.