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Nuclear One-Body Proximity Friction

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Abstract

We study the friction between two juxtaposed leptodermous systems in relative motion, arising from the exchange of particles between them. For gently curved geometries a proximity treatment is valid and leads to a factorization into a simple geometrical factor and a universal key function related to the flux between two parallel surfaces as a function of their separation. On the basis of the nuclear Thomas-Fermi approximation, this key function is calculated and tabulated; a simple analytical approximation is also given.

1. Introduction

A variety of experiments have established the importance of dissipative processes in nuclear dynamics. At moderate energies, where the nucleon mean free path is long, the dissipation is expected to be predominantly produced by the inelastic collisions of individual nucleons with the time-dependent average single-particle potential. This one-body dissipation mechanism has received increased interest in recent time ¹⁻³⁾. In particular, ref. ³⁾ explores simple formulas for the dissipation rate, based on a picture of independent classical particles confined by a time-dependent container.

In the simplest version, this picture assumes that for colliding nuclei the individual nucleons are exchanged via a sharply defined and fully open window ^{3,4)}. Although qualitatively correct, this treatment neglects the diffuseness of the nuclear surface. If quantitative applications are to be made the separation dependence of the friction must be treated with the same care that is accorded to the conservative part of the force between the nuclei.

In this paper the calculation of the one-body friction between nuclei is brought to the same level of

accuracy as has been accomplished for the calculation of the conservative nuclear force by virtue of the proximity treatment ⁵⁾. First we derive the general expression for the dissipation rate for grazing collisions. Then the dependence on the actual geometry is factorized out by the usual proximity treatment and the appropriate proximity-friction function is introduced. Finally this key function is calculated numerically and approximated by a simple analytical expression; this makes calculations of grazing nuclear collisions within the one-body dissipation framework not only feasible but in fact quite simple to carry out.

2. The dissipation rate

The general expression for the dissipation rate can be obtained as follows. Consider first two systems of independent nucleons which can communicate through a thin "window" of unit area. Let the two systems have a relative drift velocity $\vec{U}$ at the window and let the intrinsic nucleon velocity distribution be given by $\rho(\vec{v})$; it is no serious restriction to assume that $\rho(\vec{v})$ is isotropic. For the sake of generality, and

later convenience, we shall assume that the window is only partially transparent so that only nucleons with certain restricted values of the velocity $\vec{v}$ can pass through. In the following only nucleons belonging to this class are considered.

The nucleons with velocity $\vec{v}$ pass through the window at a frequency ν given by

$$\nu(\vec{v}) = \rho(\vec{v}) (\vec{v} - \vec{u}) \cdot \hat{a} \Theta((\vec{v} - \vec{u}) \cdot \hat{a})$$

where $\hat{a}$ denotes the unit vector normal to the window. The theta function ensures that only those nucleons moving towards the window can pass through. A nucleon passing through the window carries with it and eventually deposits a relative momentum given by

$$\Delta \vec{p}(\vec{v}) = m(\vec{v} - \vec{u})$$

Hence the force $\vec{F}$ exerted by one system on the other due to the exchange of particles through the window is given by

$$\vec{F} = \int \nu(\vec{v}) \Delta \vec{p}(\vec{v}) d^3\vec{v}$$

As remarked above, the $\vec{v}$ -integration extends only over

those velocity values for which the window is open.

Under the assumption that the drift speed U is small compared to typical nucleonic speeds the force $\vec{F}$ may be expanded through first order in this ratio, yielding

$$\vec{F} \approx P \hat{a} - n \vec{U} \cdot (\vec{r} + \hat{a} \hat{a})$$

Here P is the static pressure exerted by the nucleons on the window; this force produces conservative work only. In the second term, n denotes the mass flux through the window from one system to the other. This term is proportional to the relative velocity and produces the dissipation. Hence the Rayleigh dissipation function $\mathcal{F}$, which is half the rate of energy dissipation, is given by

$$\mathcal{F} = \frac{1}{2} n \vec{U} \cdot (\vec{r} + \hat{a} \hat{a}) \cdot \vec{U}$$

From this function the friction forces acting on the collective variables can be obtained by partial differentiation with respect to the corresponding collective velocities.

The above expression for $\mathcal{F}$ was derived for a window with unit area. In general that expression must be integrated over the entire proximity region, taking

into account the variation of the transparency. Hence the local flux n must be replaced by the total flux through the window, $\int n d\sigma$, assuming that the variation of the relative velocity $\vec{U}$ can be neglected. An approximate but quite general scheme for calculating the total flux is described in the following section; the treatment is analogous to the calculation of the proximity potential between leptodermous systems ⁵⁾. The fact that the nuclear one-body friction for nuclear collisions can be treated by the proximity scheme was recently pointed out in the literature ⁶⁾.

3. Proximity treatment

Consider two juxtaposed leptodermous systems with slightly curved surfaces. In the limit of small curvature the local flux from one system to the other depends only on the separation s between the local elements of the two surfaces. To leading order, this separation has a quadratic dependence on the distance from the point of smallest separation: $s \approx s_0 + \rho^2/2\bar{R}$. Hence $d\sigma = 2\pi \bar{R} ds$ and the integral can be reduced, in the usual way, to a one-dimensional integral over the surface separation s :

$$\int n d\sigma \approx 2\pi \bar{R} \int_{s_0}^{\infty} n(s) ds = 2\pi \bar{R} \mathcal{N}(s)$$

As in ref. ⁵⁾, $1/\bar{R} = 1/C_1 + 1/C_2$ is the mean curvature of the gap between the two surfaces and the matter density profile radii C_i are related to the equivalent sharp radii R_i by $C_i = R_i - b^2/R_i$ where b is the surface diffuseness of the matter density distribution ^{7,8)}. Moreover, the function $\mathcal{N}(s)$ is the incomplete integral of $n(s)$, the flux per unit area between two semi-infinite systems positioned with surface separation s .

The functions $n(s)$ and $\mathcal{N}(s)$ can be expressed in dimensionless form by adopting the inherent surface diffuseness b as the unit of length and the inherent bulk flux n_0 as the unit of flux. Thus $\zeta = s/b$ is the dimensionless separation and we define the universal proximity transparency function by

$$\Psi(\zeta) = n(\zeta b) / n_0$$

and its incomplete moments by

$$\Psi_n(\zeta_0) = \int_{\zeta_0}^{\infty} \zeta^n \Psi(\zeta) d\zeta$$

For $\Psi_0(\zeta)$ we shall usually write simply $\Psi(\zeta)$; it shall be referred to as the universal proximity flux function, in analogy with the universal proximity

potential function $\Phi(\zeta)$ of ref. 5). In terms of $\Psi(\zeta)$ the total flux across the curved gap can be written

$$\int n d\sigma = 2\pi n_0 \bar{R} b \Psi(\zeta_0)$$

with $\zeta_0 = s_0/b$. The advantage of introducing the dimensionless form is that a calculation of the friction will then tend to be less sensitive to possible defects of the model employed; the model is only asked to yield the form of the friction function and not its absolute scale. This leaves the possibility of adjusting the parameters b and n_0 to experimental values.

The final proximity formula for the Rayleigh dissipation function thus becomes

$$\mathcal{F} = \frac{1}{2} 2\pi n_0 \bar{R} b \Psi(\zeta_0) \vec{U} \cdot (\vec{e}_1 + 2\vec{e}_2) \cdot \vec{U}$$

The usefulness of this result lies in the separation of the geometry (entering here as $\bar{R}$) from the inherent surface properties of the particular matter under study. The geometrical part may vary from case to case and is easy to calculate while the second part is specific to the type of material considered and can, thus be calculated once and for all, in a suitable

model (and it is in this sense universal). It should be added that the present approach is not restricted to parabolic gap geometries. Indeed, as discussed in ref. ⁵⁾, a wider class of geometries can be reduced to simple expressions containing the dimensionless functions $\Psi_n(\zeta)$. Moreover, the effect of gentle variations of the relative velocity $\vec{U}$ over the window region can also easily be expressed in terms of the functions $\Psi_n(\zeta)$.

4. The universal functions

The dimensionless transparency function $\psi(\zeta)$ has been calculated in the nuclear Thomas-Fermi model based on the phenomenological Seyler-Blanchard nucleon-nucleon interaction ⁹⁾. The method is similar to the one employed in ref. ⁵⁾: Two semi-infinite equilibrium systems (with equal neutron and proton distributions) are positioned at a certain separation s and the potential generated by the superimposed frozen matter distributions is calculated. It is easy to show that the ratio of the local normal flux and the bulk flux is given by $(P/P_0)^3 V/V_0$ where P and V denote the local Fermi momentum and velocity, respectively, and

the subscript refers to the bulk region. The transparency function $\psi(\zeta)$ is then given as the minimum value of this expression encountered in passing from one system to the other. The resulting function $\psi(\zeta)$ is displayed in fig. 1 and the integrated function $\Psi(\zeta)$ in fig. 2. In addition, table 1 gives $\psi(\zeta)$ together with its first four incomplete moments $\Psi(\zeta)$, $\Psi_1(\zeta)$, $\Psi_2(\zeta)$ and $\Psi_3(\zeta)$. It should be noted that in contrast with the proximity force function $\phi(\zeta)$ the transparency function $\psi(\zeta)$ tends to zero at a finite separation, $\zeta \approx 3.60$, corresponding to the "break-through" distance at which the barrier in the potential just coincides with the Fermi level. As the two systems approach the barrier decreases and the transparency function $\psi(\zeta)$ quickly tends to unity.

For practical applications it is useful to have available a simple analytical representation of the flux function $\Psi(\zeta)$ appearing in the proximity expression for the Rayleigh dissipation function. One such approximation is

$$\left\{ \begin{array}{l} \Psi(\zeta \leq -0.4) = 1.4 - \zeta \\ \Psi(-0.4 \leq \zeta \leq 3.2) = 1.6 - 0.5\zeta - \frac{1.8}{\pi} \sin\left(\frac{\zeta + 0.4}{3.6} \pi\right) \\ \Psi(3.2 \leq \zeta) = 0 \end{array} \right.$$

The expression is zero beyond 3.2 rather than 3.6 ; this is hardly a serious misrepresentation as the calculated function amounts to only 0.016 at $\zeta = 3.2$ and quickly becomes smaller at larger separation. A reasonably good representation of the unintegrated function $\psi(\zeta)$ is given by the derivative of the expression above:

$$\begin{cases} \psi(\zeta \leq -0.4) = 1 \\ \psi(-0.4 \leq \zeta \leq 3.2) = \cos^2\left(\frac{\zeta + 0.4}{3.6} \frac{\pi}{2}\right) \\ \psi(3.2 \leq \zeta) = 0 \end{cases}$$

Included in figs. 1 and 2 are some values resulting from these approximate expressions, in order to make possible a quick judgement of the degree of validity of these representations. Corresponding representations of the higher moments $\Psi_n(\zeta)$ can be obtained on the basis of the above approximation to $\psi(\zeta)$.

5. Discussion

In applications of the above formulas to nuclear problems the following choice of numerical parameters would be reasonable. For the effective sharp radius one may use the following formula ⁵⁾

$$R(\text{fm}) = 1.28 A^{1/3} - 0.76 + 0.8 A^{-1/3} \approx 1.15 A^{1/3}$$

and for the value of the surface diffuseness one may use $b = 1 \text{ fm}$. Hence, for spherical nuclei the surface separation is given by $s_0 = r - C_1 - C_2$ where $C_i = R_i - b^2/R_i$ are the central radii locating the density profiles. Finally, the bulk flux n_0 can be written $n_0 = \frac{1}{2} m \rho_0 \bar{v}_n$ where m is the nucleon mass, ρ_0 the particle density in the bulk, and $\bar{v}_n$ the average speed in the normal direction; for an isotropic velocity distribution $\bar{v}_n = \frac{1}{2} \bar{v}$, half the average nucleon speed $\bar{v}$, and for a Fermi gas at zero temperature $\bar{v} = \frac{3}{4} V_0$. Hence a reasonable value of the bulk flux n_0 , which determines the overall friction strength, would be

$$n_0 \left(\frac{\text{MeV} \cdot 10^{24}}{\text{fm}^3} \right) = \frac{1}{4} m \rho_0 \bar{v} = \frac{3}{16} \left(\frac{4\pi}{3} \rho_0^3 \right)^{1/3} \hbar k_F = 0.263 \approx \frac{1}{4}$$

where $r_0 = 1.15 \text{ fm}$, $k_F = 1.36 \text{ fm}^{-1}$ and $m V_0 = \hbar k_F$ have been used.

With these parameter values we shall illustrate the magnitude of the proximity friction by calculating the dissipation rate for grazing nuclear collisions. For a grazing collision the velocity is almost exclusively tangential during the interaction and we find for the energy dissipation rate

$$\dot{E} = 2\mathcal{F} \approx 4\pi n_0 \int_{-R}^R b \Psi(\zeta_0) \bar{E}$$

Here μ is the reduced mass of the two nuclei and $\bar{E}$ their relative energy over the barrier. For two nuclei with the same mass number A this amounts to $\dot{E}/\bar{E} \approx 3.80 A^{-2/3} \Psi(\zeta_0)$. Hence, taking as an example $A = 125$, we find $\dot{E}/\bar{E} \approx 0.21/10^{-22} \text{ s}$ for $s_0 = 0$ and $\dot{E}/\bar{E} \approx 0.36/10^{-22} \text{ s}$ for $s_0 = -1$ (s_0 denotes the surface separation at the closest approach). From such figures one gains the impression that the order of magnitude of the one-body dissipation is large enough to degrade a sizeable fraction of the relative kinetic energy between colliding nuclei, as required by experiment. Combining the proximity friction calculated in this paper with the proximity potential of ref. ⁵⁾, one should be in a position to calculate the

the features of collisions between idealized nuclei without introducing any adjustable parameters. Along this line, we are planning in a future paper to calculate the angular deflections and energy losses in grazing collisions and by a comparison with experimental (Wilczynski-type) plots to confront the one-body dissipation theory with collision measurements in a relatively unambiguous way.

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Table Caption

Table 1. The universal proximity transparency function $\psi(\zeta)$ and its first four incomplete moments $\Psi_n(\zeta)$, $n = 0, 1, 2, 3$.

Figure Captions

Fig. 1. The universal proximity transparency function $\psi(\zeta)$. The circles indicate values given by the analytic approximation to $\psi(\zeta)$.

Fig. 2. The universal proximity flux function $\Psi(\zeta)$ (identical to the incomplete moment $\Psi_0(\zeta)$). The circles indicate values given by the analytic approximation to $\Psi(\zeta)$.

Table 1

ζ	ψ	Ψ	Ψ_1	Ψ_2	Ψ_3
-2.00	1.0000	3.3960	-.7071	4.4657	-.8888
-1.95	1.0000	3.3460	-.6084	4.2707	-.5035
-1.90	.9999	3.2960	-.5122	4.0854	-.1468
-1.85	.9999	3.2460	-.4184	3.9096	.1828
-1.80	.9999	3.1960	-.3272	3.7431	.4868
-1.75	.9999	3.1460	-.2384	3.5855	.7663
-1.70	.9999	3.0960	-.1522	3.4367	1.0230
-1.65	.9999	3.0460	-.0684	3.2965	1.2581
-1.60	.9998	2.9960	.0128	3.1645	1.4726
-1.55	.9998	2.9460	.0915	3.0404	1.6679
-1.50	.9998	2.8960	.1678	2.9242	1.8453
-1.45	.9997	2.8461	.2415	2.8154	2.0058
-1.40	.9996	2.7961	.3127	2.7139	2.1505
-1.35	.9996	2.7461	.3814	2.6194	2.2804
-1.30	.9995	2.6961	.4477	2.5316	2.3966
-1.25	.9994	2.6461	.5114	2.4504	2.5004
-1.20	.9993	2.5962	.5726	2.3754	2.5923
-1.15	.9991	2.5462	.6313	2.3064	2.6733
-1.10	.9989	2.4963	.6875	2.2432	2.7445
-1.05	.9987	2.4463	.7412	2.1855	2.8066
-1.00	.9985	2.3964	.7923	2.1330	2.8603
-.95	.9982	2.3465	.8410	2.0856	2.9067
-.90	.9979	2.2966	.8872	2.0428	2.9461
-.85	.9975	2.2467	.9308	2.0046	2.9765
-.80	.9970	2.1968	.9720	1.9707	3.0077
-.75	.9964	2.1470	1.0106	1.9407	3.0309
-.70	.9958	2.0972	1.0467	1.9145	3.0498
-.65	.9950	2.0474	1.0803	1.8919	3.0652
-.60	.9941	1.9977	1.1114	1.8724	3.0773
-.55	.9931	1.9480	1.1399	1.8560	3.0868
-.50	.9919	1.8984	1.1660	1.8423	3.0941
-.45	.9905	1.8488	1.1895	1.8311	3.0993
-.40	.9888	1.7993	1.2106	1.8222	3.1031
-.35	.9870	1.7499	1.2291	1.8152	3.1058
-.30	.9848	1.7007	1.2451	1.8100	3.1074
-.25	.9823	1.6515	1.2586	1.8063	3.1085
-.20	.9794	1.6024	1.2697	1.8038	3.1091
-.15	.9761	1.5535	1.2782	1.8023	3.1093
-.10	.9724	1.5048	1.2843	1.8015	3.1095
-.05	.9682	1.4563	1.2880	1.8012	3.1095

(cont.)

Table 1 (cont.)

ζ	ψ	Ψ	Ψ_1	Ψ_2	Ψ_3
0.00	.9634	1.4080	1.2892	1.8011	3.1094
.05	.9580	1.3600	1.2880	1.8011	3.1095
.10	.9520	1.3122	1.2844	1.8009	3.1095
.15	.9452	1.2648	1.2785	1.8001	3.1093
.20	.9377	1.2177	1.2702	1.7986	3.1091
.25	.9293	1.1710	1.2597	1.7963	3.1085
.30	.9201	1.1248	1.2470	1.7928	3.1076
.35	.9100	1.0790	1.2321	1.7879	3.1060
.40	.8990	1.0338	1.2152	1.7815	3.1036
.45	.8870	.9891	1.1962	1.7735	3.1001
.50	.8740	.9451	1.1753	1.7636	3.0955
.55	.8599	.9018	1.1525	1.7516	3.0891
.60	.8447	.8592	1.1280	1.7375	3.0810
.65	.8282	.8173	1.1019	1.7212	3.0708
.70	.8105	.7763	1.0742	1.7025	3.0582
.75	.7913	.7363	1.0452	1.6814	3.0429
.80	.7705	.6972	1.0149	1.6580	3.0248
.85	.7481	.6593	.9836	1.6321	3.0033
.90	.7247	.6225	.9514	1.6039	2.9787
.95	.7010	.5868	.9184	1.5735	2.9506
1.00	.6772	.5524	.8848	1.5407	2.9185
1.05	.6534	.5191	.8508	1.5057	2.8827
1.10	.6294	.4870	.8163	1.4687	2.8429
1.15	.6054	.4561	.7816	1.4296	2.7989
1.20	.5814	.4265	.7467	1.3887	2.7508
1.25	.5574	.3980	.7118	1.3459	2.6985
1.30	.5335	.3707	.6771	1.3016	2.6419
1.35	.5097	.3447	.6425	1.2559	2.5814
1.40	.4860	.3198	.6083	1.2038	2.5166
1.45	.4626	.2961	.5745	1.1606	2.4479
1.50	.4394	.2735	.5413	1.1116	2.3756
1.55	.4165	.2521	.5086	1.0618	2.2997
1.60	.3940	.2318	.4767	1.0116	2.2206
1.65	.3718	.2127	.4456	.9611	2.1385
1.70	.3501	.1947	.4154	.9104	2.0536
1.75	.3289	.1777	.3861	.8599	1.9666
1.80	.3081	.1618	.3579	.8098	1.8776
1.85	.2880	.1469	.3307	.7602	1.7870
1.90	.2684	.1329	.3046	.7113	1.6953
1.95	.2495	.1200	.2797	.6633	1.6030

(cont.)

Table 1 (cont.)

ζ	ψ	Ψ	Ψ_1	Ψ_2	Ψ_3
2.00	.2313	.1080	.2560	.6164	1.5105
2.05	.2138	.0969	.2334	.5708	1.4181
2.10	.1970	.0866	.2121	.5267	1.3264
2.15	.1810	.0771	.1921	.4840	1.2357
2.20	.1657	.0685	.1732	.4430	1.1467
2.25	.1513	.0606	.1556	.4038	1.0595
2.30	.1376	.0533	.1392	.3665	.9745
2.35	.1247	.0468	.1239	.3310	.8922
2.40	.1127	.0409	.1098	.2976	.8127
2.45	.1014	.0355	.0969	.2662	.7365
2.50	.0909	.0307	.0850	.2367	.6637
2.55	.0911	.0264	.0741	.2093	.5945
2.60	.0721	.0226	.0643	.1840	.5291
2.65	.0639	.0192	.0554	.1606	.4678
2.70	.0562	.0162	.0473	.1391	.4104
2.75	.0493	.0135	.0402	.1195	.3570
2.80	.0429	.0112	.0338	.1018	.3079
2.85	.0372	.0092	.0281	.0859	.2628
2.90	.0319	.0075	.0232	.0716	.2219
2.95	.0272	.0060	.0189	.0590	.1849
3.00	.0230	.0048	.0151	.0479	.1519
3.05	.0192	.0037	.0119	.0383	.1228
3.10	.0159	.0029	.0093	.0300	.0964
3.15	.0129	.0021	.0070	.0230	.0755
3.20	.0103	.0016	.0052	.0172	.0570
3.25	.0081	.0011	.0037	.0124	.0417
3.30	.0061	.0007	.0025	.0086	.0293
3.35	.0045	.0005	.0017	.0057	.0196
3.40	.0032	.0003	.0010	.0035	.0122
3.45	.0021	.0002	.0006	.0020	.0068
3.50	.0013	.0001	.0003	.0010	.0035
3.55	.0007	.0000	.0001	.0004	.0014
3.60	.0003	.0000	.0000	.0001	.0003
3.65	.0000	.0000	.0000	.0000	.0000
3.70	.0000	.0000	.0000	.0000	.0000

Fig. 1

Fig. 2

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