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DYNAMICS OF NUCLEAR FISSION AND HEAVY-ION REACTIONS

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Abstract

We study large-amplitude collective motion in fission and heavy-ion reactions by solving classical equations of motion for the time evolution of the nuclear shape. In the nuclear potential energy of deformation, we calculate the generalized surface energy by means of a double volume integral of a Yukawa-plus-exponential function, which was obtained by requiring that two semi-infinite slabs of constant-density nuclear matter have minimum energy at zero separation. The collective kinetic energy is calculated for nuclear flow that is a superposition of incompressible, nearly irrotational collective-shape motion and rigid-body rotation. Nuclear dissipation is included by means of the Rayleigh dissipation function, which depends upon the physical mechanism that converts collective energy into internal energy. For both ordinary two-body viscosity and a combined wall and window one-body dissipation, we calculate fission-fragment kinetic energies for the fission of nuclei throughout the periodic table and compare with experimental results. Finally, we study explicitly the one-body dynamics of nucleons inside a cylinder colliding with a moving piston by solving exactly the collisionless Boltzman equation for the distribution function. By examining the relative phases of the pressure at the piston and the piston's velocity, we are able to separately identify a dissipative force and an elastic restoring force.

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As illustrated in Fig. 1, we study large-amplitude collective motion in fission and heavy-ion reactions by solving classical equations of motion for the time evolution of the nuclear shape.[1,2] In the nuclear potential energy of deformation, we calculate the generalized surface energy by means of a double volume integral of a Yukawa-plus-exponential function, which was obtained by requiring that two semi-infinite slabs of constant-density nuclear matter have minimum energy at zero separation.[3,4] The resulting potential for heavy-ion reactions is compared with experimental results in Fig. 2 and with other heavy-ion potentials in Fig. 3. As shown by the solid curves in Fig. 4, our potential reproduces heavy-ion elastic scattering with approximately the same accuracy as does a Woods-Saxon potential (dashed curves).

The collective kinetic energy is calculated for nuclear flow that is a superposition of incompressible, nearly irrotational collective-shape motion and rigid-body rotation.[1,2] Nuclear dissipation is included by means of the Rayleigh dissipation function, which depends upon the physical mechanism that converts collective energy into internal energy. Figure 5 compares results that have been calculated for various types of dissipation and an earlier version of the potential energy with the result of a time-dependent Hartree-Fock calculation.[5] Figure 6 illustrates the type of potential-energy surface that is involved in the macroscopic calculations.[6]

Figure 7 shows dynamical trajectories calculated with the Yukawa-plus-exponential potential for both ordinary two-body viscosity[1] and a combined wall and window one-body dissipation.[7] In the latter case, the wall formula relative to the center of mass of the entire system is used until the neck radius reaches the indicated value, at which point a transition is made to a wall formula relative to the centers of mass of the two nascent fragments plus a window formula for the neck between them. As shown in Figs. 8 and 9, experimental fission-fragment kinetic energies for the fission of nuclei throughout the periodic table are reproduced by either ordinary two-body viscosity with a coefficient $\mu = 0.015$ TP or by a combined wall and window one-body dissipation with a transition neck radius $r_{neck} = 2.5$ fm.

In Fig. 10 we examine the ability of the wall formula to predict the experimental widths of giant multipole resonances. By comparing the solid curve with the solid circles (giant quadrupole)[8] and the dashed curve with the open circle (giant octupole),[9] we see that for both resonances the wall-formula predictions are about three times as large as the experimental values.

Finally, as illustrated in Fig. 11, we study explicitly the one-body dynamics of nucleons inside a cylinder colliding with a moving piston by solving exactly the collisionless Boltzman equation for the distribution function. By examining the relative phases of the pressure at the piston and the piston's velocity, we are able to separately identify a dissipative force and an elastic restoring force.

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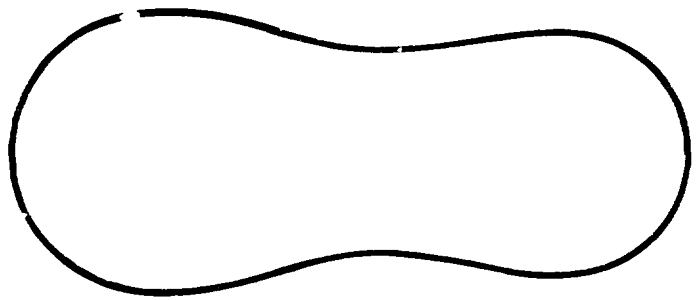
References

1. K. T. R. Davies, A. J. Sierk, and J. R. Nix, Phys. Rev. C 13, 2385 (1976).
2. J. R. Nix and A. J. Sierk, Phys. Rev. C 15, 2072 (1977).
3. H. J. Krappe, J. R. Nix, and A. J. Sierk, Phys. Rev. Lett. 42, 215 (1979).
4. H. J. Krappe, J. R. Nix, and A. J. Sierk, Phys. Rev. C, to be published.
5. J. W. Negele, S. E. Koonin, P. Möller, J. R. Nix, and A. J. Sierk, Phys. Rev. C 17, 1098 (1978).
6. P. Möller and J. R. Nix, Nucl. Phys. A272, 502 (1976).
7. J. Błocki, Y. Boneh, J. R. Nix, J. Randrup, M. Robel, A. J. Sierk, and W. J. Swiatecki, Ann. Phys. (N. Y.) 113, 330 (1978).
8. F. E. Bertrand, Ann. Rev. Nucl. Sci. 26, 457 (1976).
9. M. Sasao and Y. Torizuka, Phys. Rev. C 15, 217 (1977).

MACROSCOPIC APPROACH



Collective coordinates

$q = q_1, \ldots, q_n$

Fundamental nuclear properties

1. Potential energy $V(q)$
2. Kinetic energy $T(q,\dot{q})$
3. Dissipation $F(q,\dot{q})$

Lagrangian $L = T - V$

Equations of motion

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) + \frac{\partial F}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = 0 , \qquad i = 1, \ldots , n$$

Figure 1

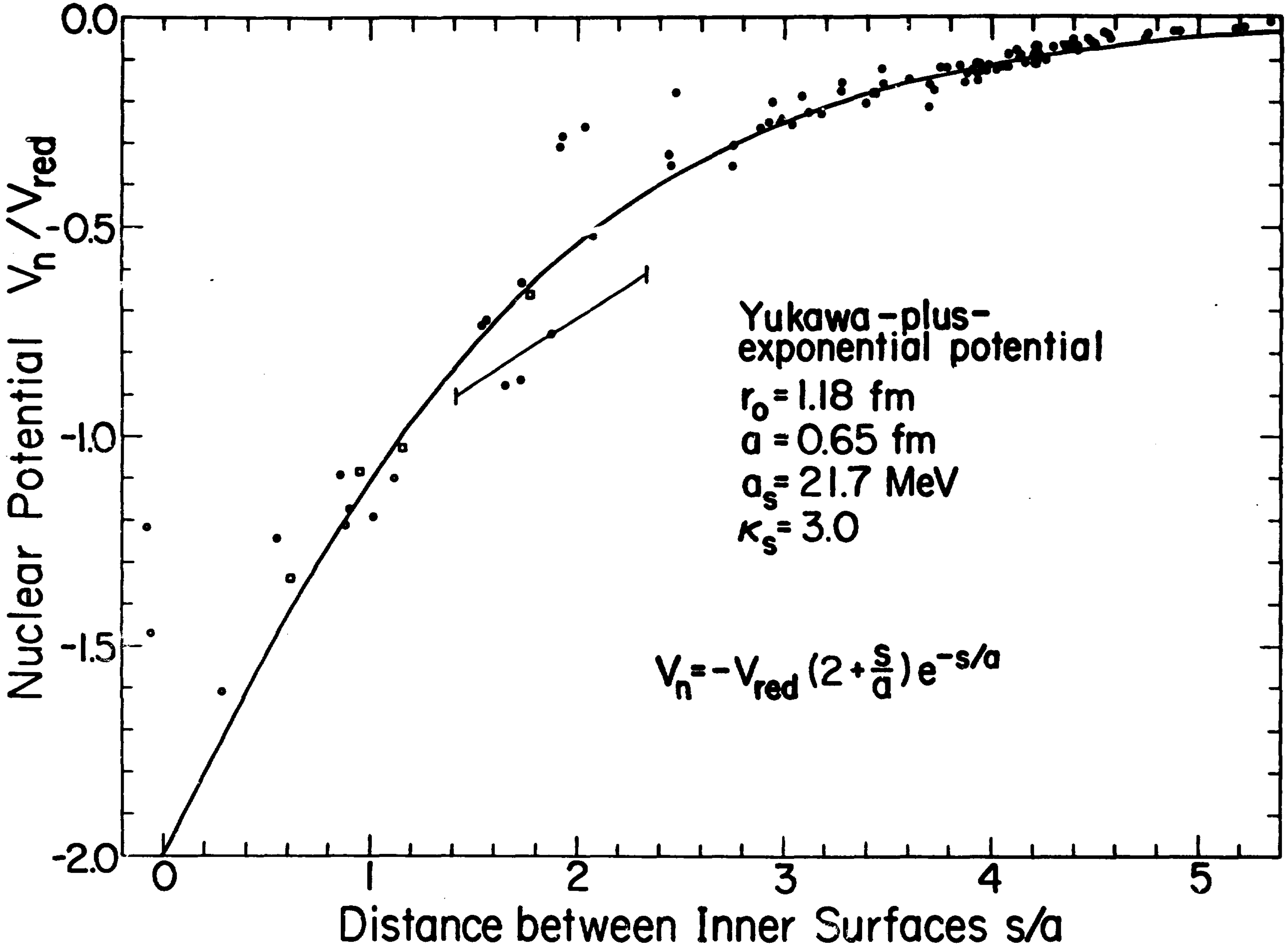
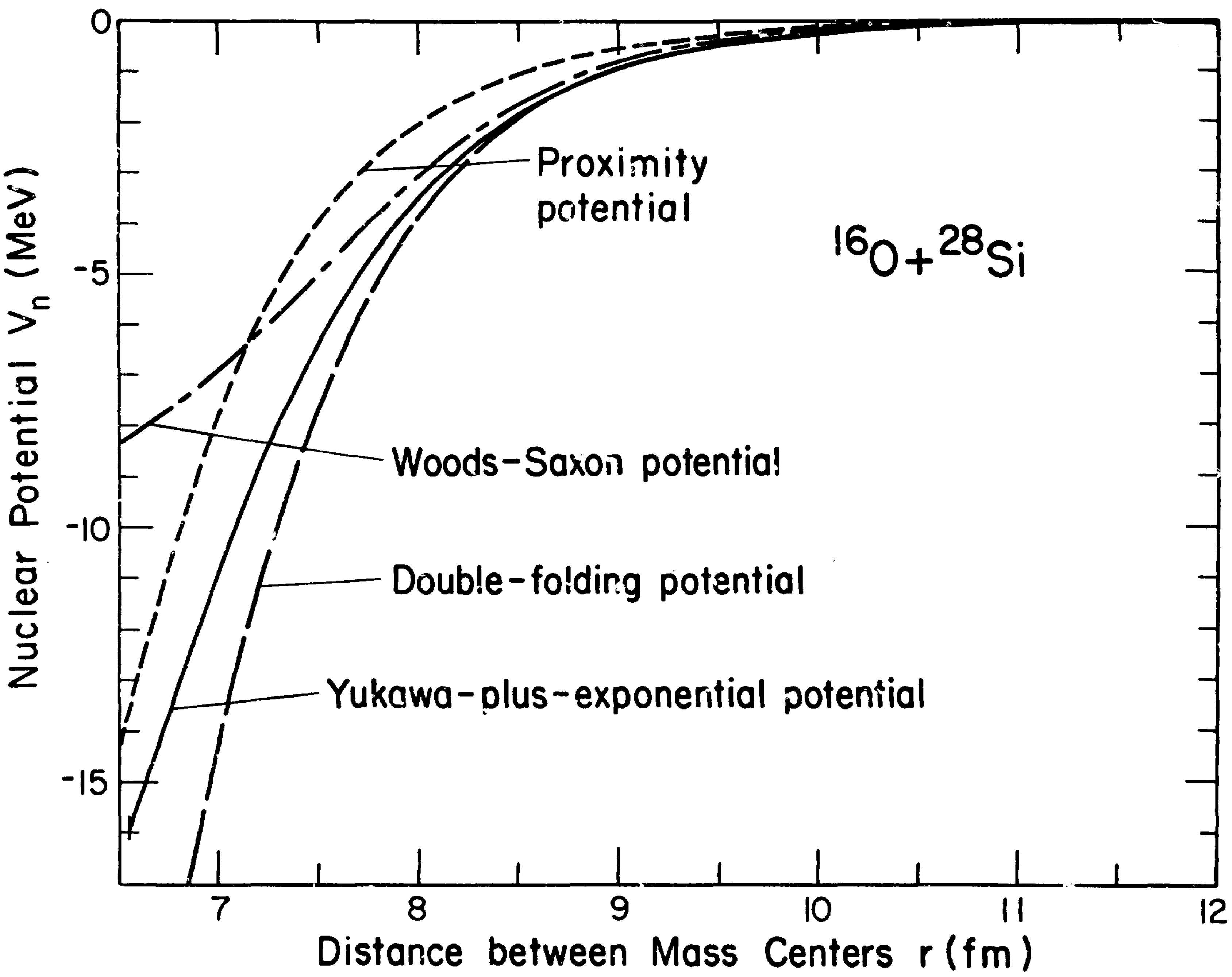
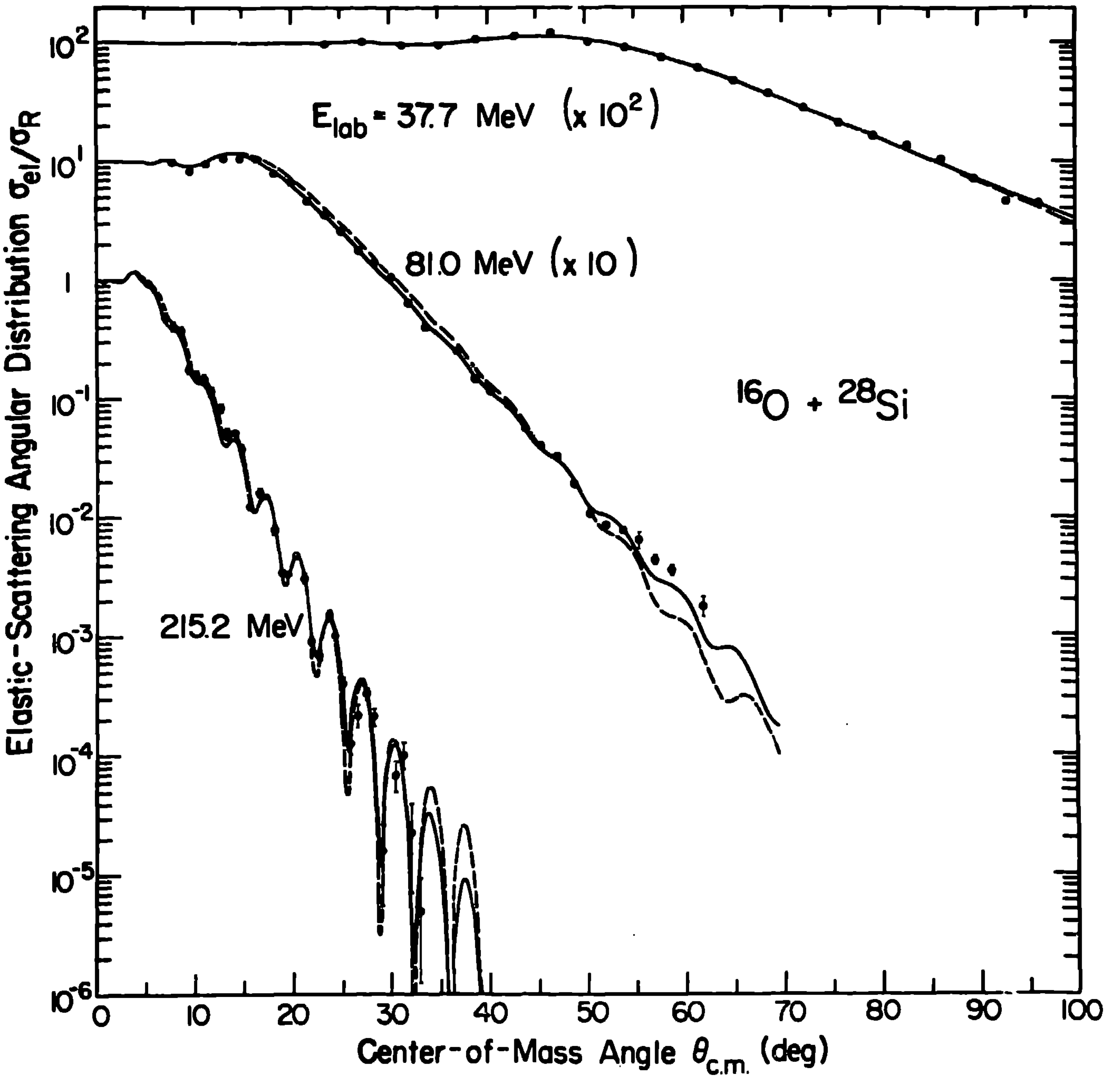

0.0
-0.5
-1.0
-1.5
-2.0
Nuclear Potential V_n/V_{red}
0
1
2
3
4
5
Distance between Inner Surfaces s/a
Yukawa-plus-exponential potential
$r_0 = 1.18$ fm
$a = 0.65$ fm
$a_s = 21.7$ MeV
$\kappa_s = 3.0$
$V_n = -V_{red}\left(2 + \frac{s}{a}\right)e^{-s/a}$

Figure 2



0
-5
-10
-15
7
8
9
10
11
12
Nuclear Potential V_n (MeV)
Distance between Mass Centers r (fm)
Proximity potential
$^{16}O+^{28}Si$
Woods-Saxon potential
Double-folding potential
Yukawa-plus-exponential potential

Figure 3



Elastic-Scattering Angular Distribution σ_{el}/σ_R
E_{lab} = 37.7 MeV (x 10^2)
81.0 MeV (x 10)
215.2 MeV
$^{16}O + ^{28}Si$
Center-of-Mass Angle $\theta_{c.m.}$ (deg)

Figure 4

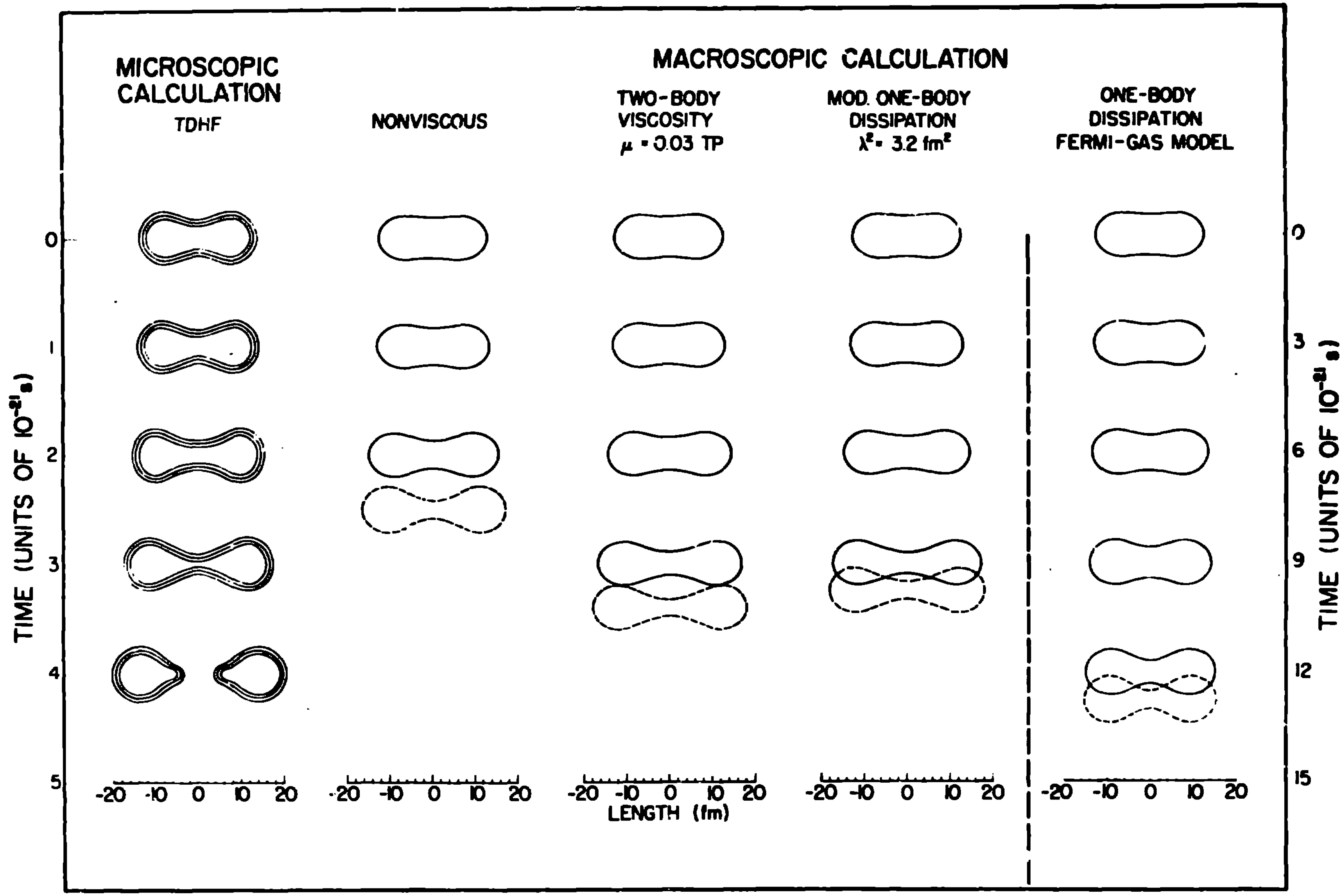
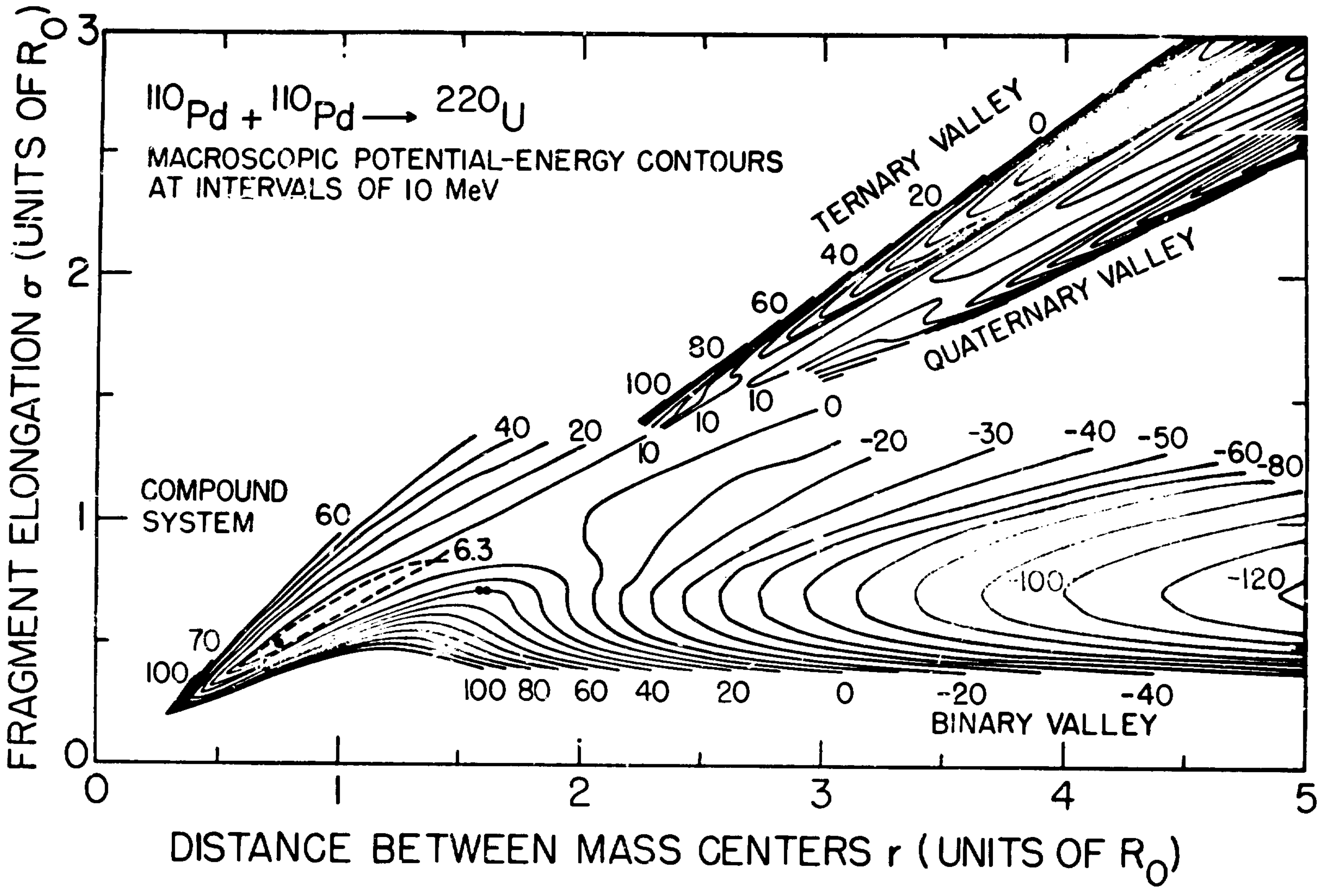
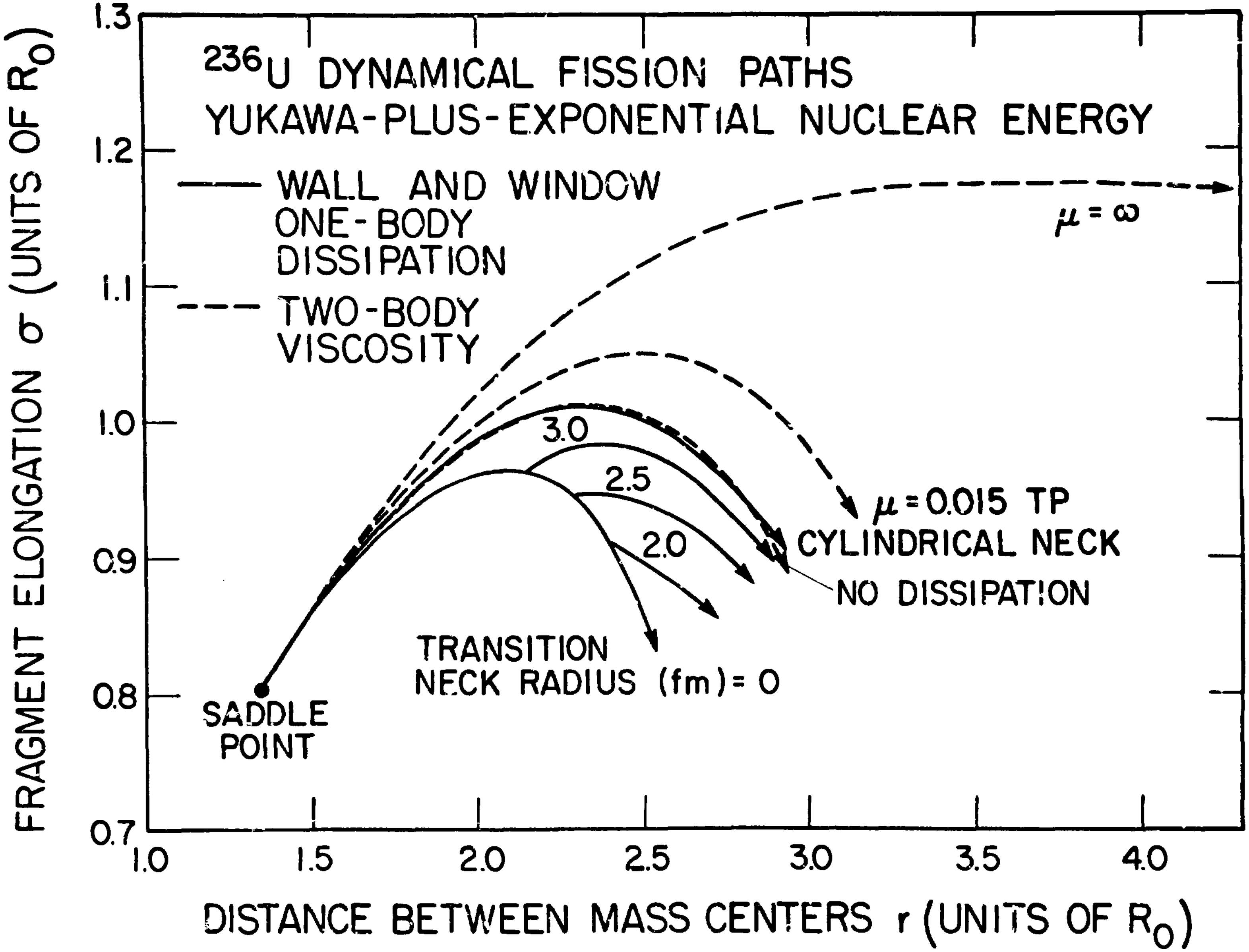

MICROSCOPIC CALCULATION
TDHF
MACROSCOPIC CALCULATION
NONVISCOUS
TWO-BODY VISCOSITY
μ = 0.03 TP
MOD. ONE-BODY DISSIPATION
λ² = 3.2 fm²
ONE-BODY DISSIPATION FERMI-GAS MODEL
TIME (UNITS OF 10⁻²¹ s)
0
1
2
3
4
5
0
3
6
9
12
15
-20 -10 0 10 20
LENGTH (fm)

Figure 5



$^{110}Pd + ^{110}Pd \longrightarrow ^{220}U$
MACROSCOPIC POTENTIAL-ENERGY CONTOURS
AT INTERVALS OF 10 MeV
TERNARY VALLEY
QUATERNARY VALLEY
COMPOUND
SYSTEM
BINARY VALLEY
6.3
100
80
60
40
20
10
0
-20
-30
-40
-50
-60
-80
-100
-120
70
FRAGMENT ELONGATION σ (UNITS OF R_0)
DISTANCE BETWEEN MASS CENTERS r (UNITS OF R_0)
0
1
2
3
4
5

Figure 6



^{236}U DYNAMICAL FISSION PATHS
YUKAWA-PLUS-EXPONENTIAL NUCLEAR ENERGY
WALL AND WINDOW ONE-BODY DISSIPATION
TWO-BODY VISCOSITY
$\mu = \infty$
$\mu = 0.015$ TP
CYLINDRICAL NECK
NO DISSIPATION
3.0
2.5
2.0
TRANSITION NECK RADIUS (fm) = 0
SADDLE POINT
FRAGMENT ELONGATION σ (UNITS OF R_0)
DISTANCE BETWEEN MASS CENTERS r (UNITS OF R_0)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
1.0
1.5
2.0
2.5
3.0
3.5
4.0

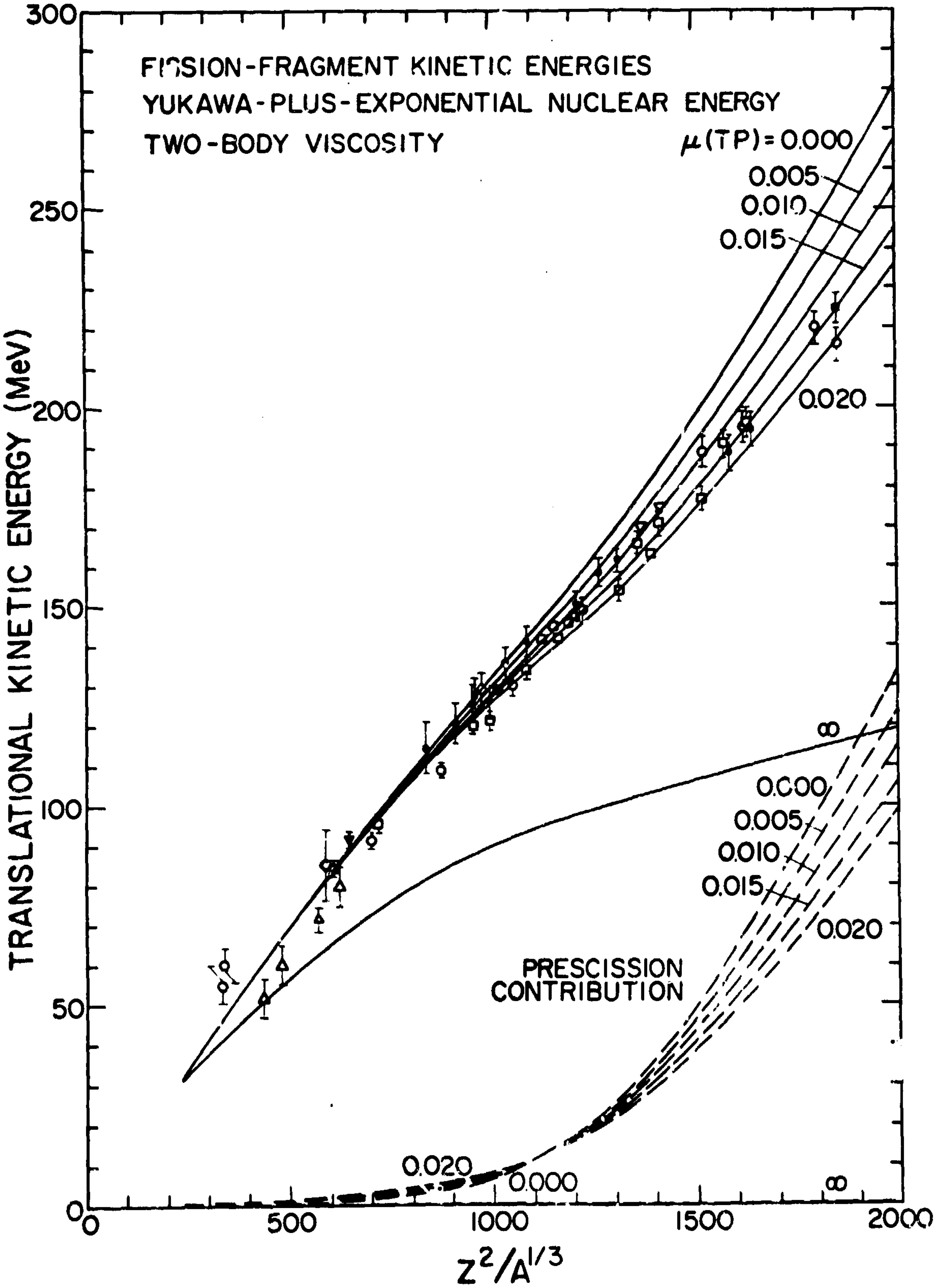

FISSION-FRAGMENT KINETIC ENERGIES
YUKAWA-PLUS-EXPONENTIAL NUCLEAR ENERGY
TWO-BODY VISCOSITY
μ(TP) = 0.000
0.005
0.010
0.015
0.020
∞
0.000
0.005
0.010
0.015
0.020
PRESCISSION CONTRIBUTION
0.020
0.000
∞
TRANSLATIONAL KINETIC ENERGY (MeV)
$Z^2/A^{1/3}$
0
50
100
150
200
250
300
0
500
1000
1500
2000

Figure 8

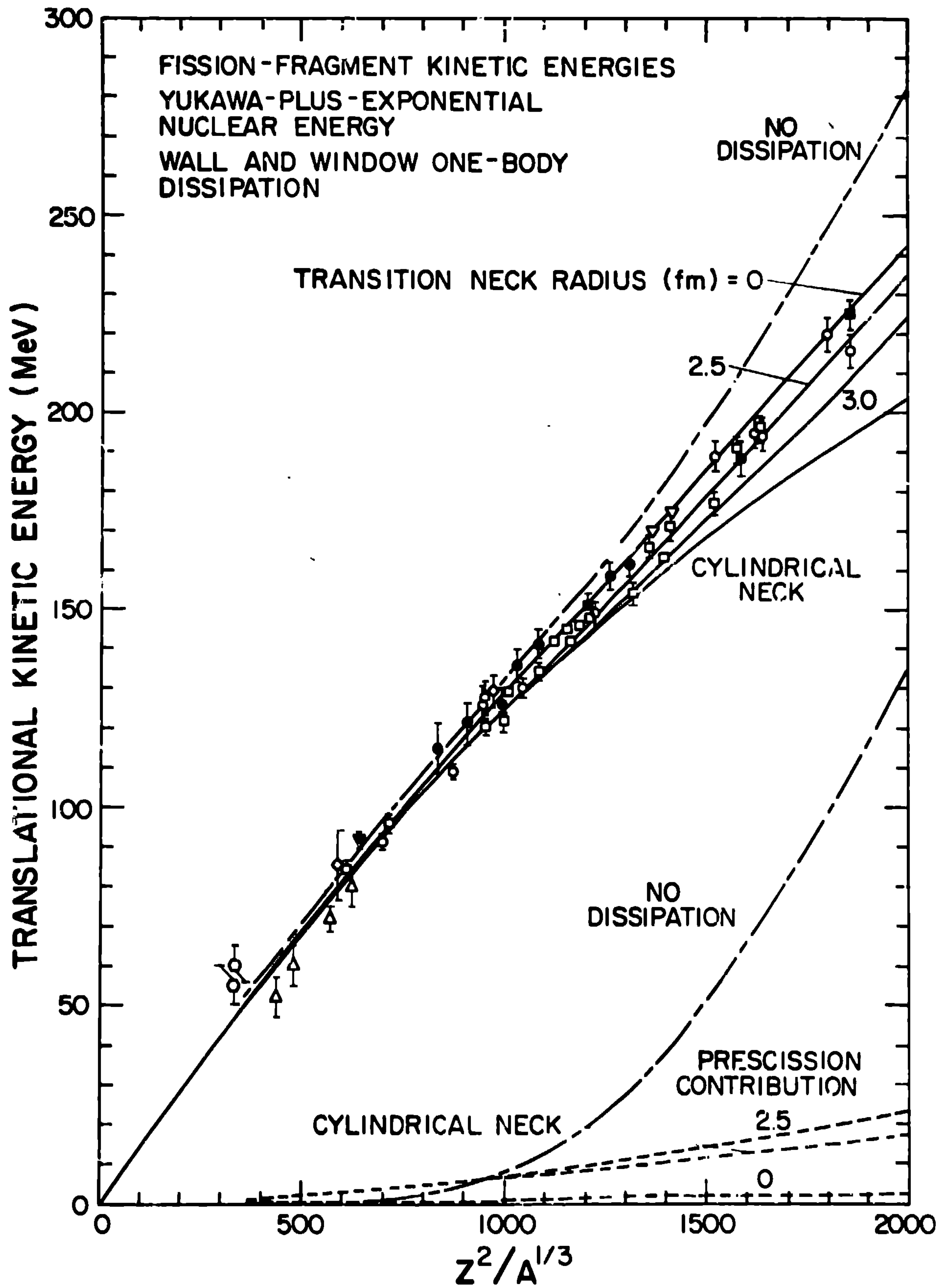
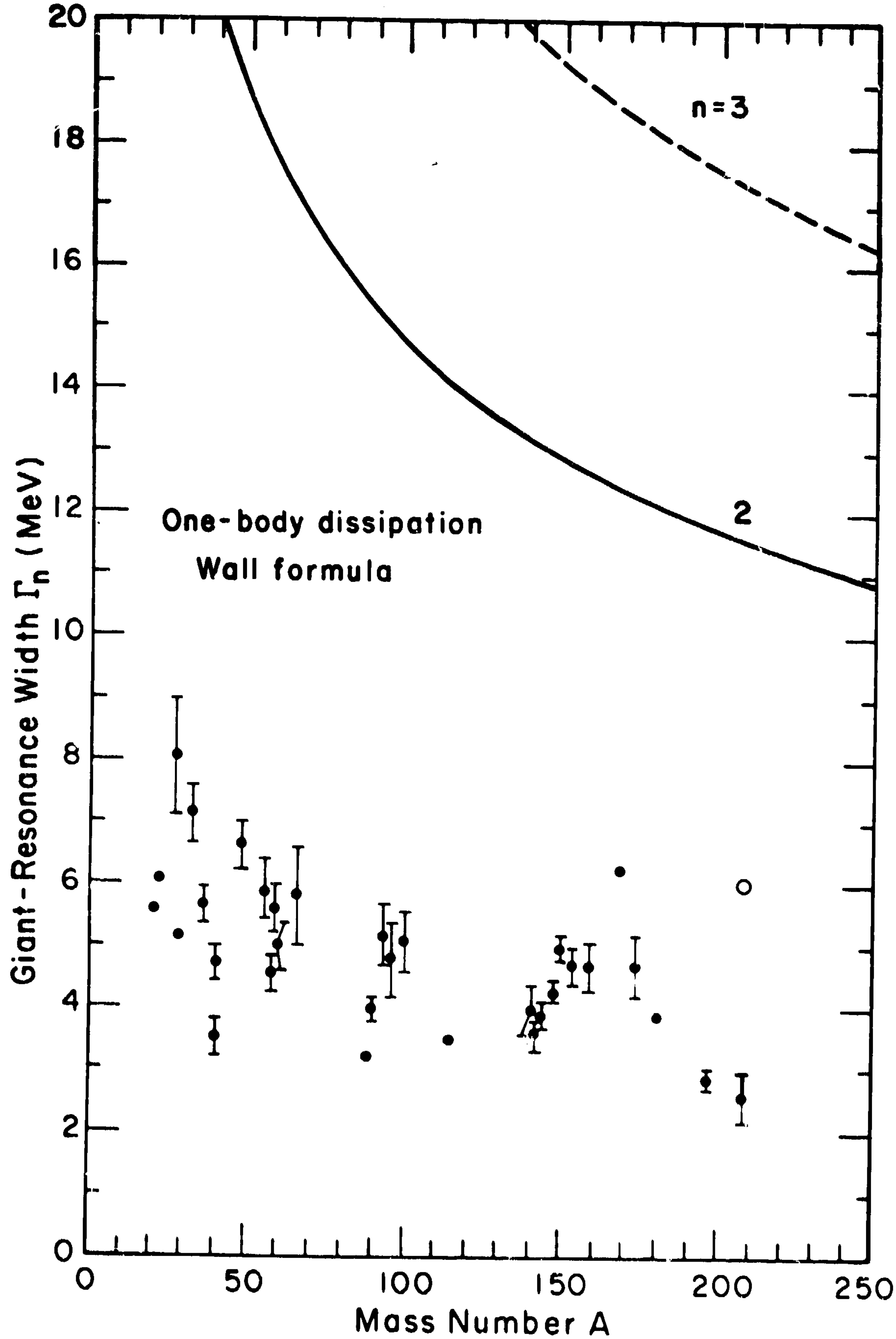

FISSION-FRAGMENT KINETIC ENERGIES
YUKAWA-PLUS-EXPONENTIAL NUCLEAR ENERGY
WALL AND WINDOW ONE-BODY DISSIPATION
NO DISSIPATION
TRANSITION NECK RADIUS (fm) = 0
2.5
3.0
CYLINDRICAL NECK
NO DISSIPATION
PRESCISSION CONTRIBUTION
CYLINDRICAL NECK
2.5
0
TRANSLATIONAL KINETIC ENERGY (MeV)
0
50
100
150
200
250
300
500
1000
1500
2000
$Z^2/A^{1/3}$

Figure 9



20
18
16
14
12
10
8
6
4
2
0
n=3
2
One-body dissipation
Wall formula
Giant-Resonance Width Γ_n (MeV)
0
50
100
150
200
250
Mass Number A

Figura 10

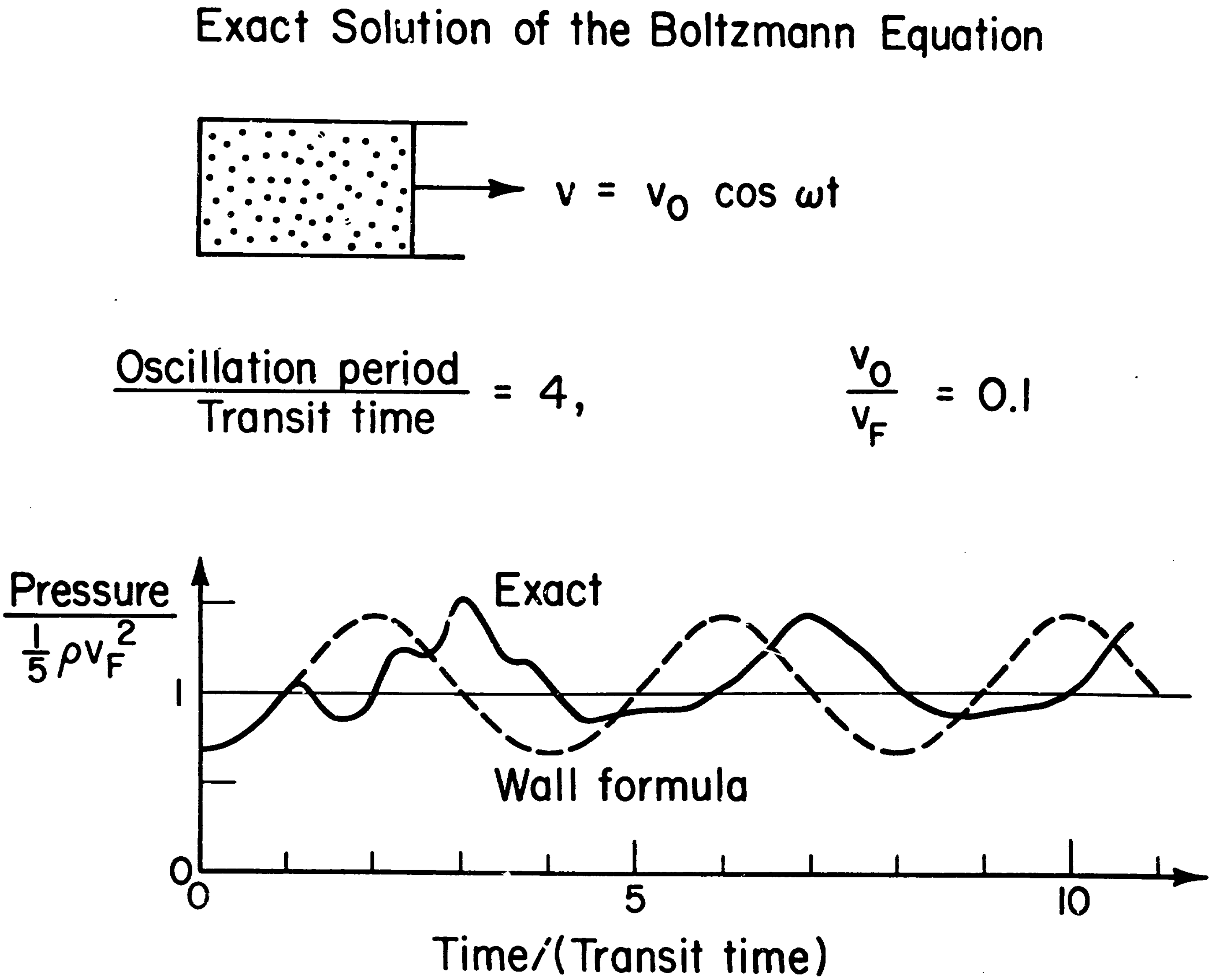

Exact Solution of the Boltzmann Equation
v = v0 cos ωt
Oscillation period / Transit time = 4,
v0 / vF = 0.1
Pressure / (1/5 ρ vF^2)
Exact
Wall formula
1
0
0
5
10
Time/(Transit time)

Figure 11