Title
DYNAMICS OF THE DINUCLEUS

Author
Randrup, J.

Publication Date
1985-06-01

LBL-20914

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Invited paper presented at the Second International
Conference on Nucleus-Nucleus Collisions,
Visby, Sweden, June 10-14, 1985

DYNAMICS OF THE DINUCLEUS

J. Randrup

June 1985

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

DYNAMICS OF DINUCLEUS

Jørgen Randrup

Nordita, Blegdamsvej 17, DK-21000 Copenhagen 0, Denmark

and

Lawrence Berkeley Laboratory, University of California,
Berkeley, California 94720, USA

June 1985

DYNAMICS OF THE DINUCLEUS*

Jørgen RANDRUP

NORDITA, Blegdamsvej 17, DK-2100 Copenhagen 0, Denmark
and
Lawrence Berkeley Laboratory, Berkeley, California 94720, USA

Damped reactions between heavy nuclei have revealed the temporary formation and evolution of a novel nuclear system, the dinucleus. This system possesses macroscopic degrees of freedom not present in the more ordinary mononucleus. Most important are: the energy associated with the relative dinuclear motion, the partition of the microscopic excitation energy (heat) and the total mass and charge among the two parts of the dinucleus, and their angular momenta. This paper briefly highlights the characteristic features of the dynamics of these dinuclear degrees of freedom and our current understanding of them.

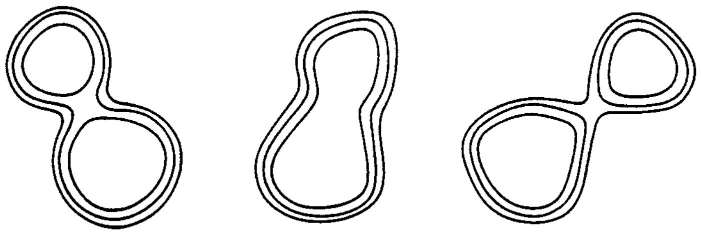
1. INTRODUCTION

Most low-energy nuclear physics studies have dealt with situations in which the nuclear system appears as a single object, a mononucleus. For example, studies of low-energy single-particle and collective excitations, giant resonances, nuclear structure at high angular momentum, and fission barriers for heavy nuclei. However, there are situations in which the system is very far from a mononuclear configuration. This is the case, for example, at the late stages of a nuclear fission process where the system develops a distinctly binary character. More generally, dinuclear systems can be created (temporarily) in nuclear collisions, under suitable kinematical conditions, and the advent of heavy-ion accelerators has provided a powerful and flexible tool for exploring the physical properties of the dinucleus. As an illustration, fig.1 shows how a dinucleus is formed and develops in a damped nuclear reaction, as calculated in the time-dependent Hartree-Fock model[1]. The present contribution to this conference briefly highlights our current understanding of the dinucleus, and indicates possible directions for future research. Most of the experimental information on the physics of the dinucleus comes from damped nuclear reactions and an extensive review of this reaction class can be found in ref.2.

Before going into specifics, it is important to clarify the concept of a dinucleus. It should be realized that a dinucleus is not merely an ordinary nucleus with a binary shape, for example such as those occurring in the quasi-fission

---

* Invited paper for the Second International Conference on Nuclues-Nucleus Collisions, Visby, Sweden, 10-14 June 1985.



Time-dependent Hartree-Fock calculation of the reaction
505 MeV ^{86}Kr + ^{139}La (80$\hbar$)

Fig.1. Illustration of the formation and development of a dinucleus created in the damped reaction 505 MeV ^{86}Kr + ^{139}La at an angular momentum of $J = 80\ \hbar$, as calculated in the time-dependent Hartree-Fock approximation (from ref.1).

process discussed in the preceding contribution.[3] The binary character of the dinucleus sticks deeper that: the environment felt by the individual nucleon is really different in the two parts of the system. For example: (1) the mean field associated with one part of the dinucleus is generally moving relative to the other part, as is readily visualized for a damped reaction (cf. fig.1) or a fission process. (2) The chemical potentials are different in the two dinuclear parts, as is evident from the persistence of the different charge-to-mass ratios in projectile-like and target-like damped reaction products. (3) The degree of excitation, as measured by a nuclear temperature, may be different in the two dinuclear parts. Thus, the dinucleus possesses macroscopic degrees of freedom not present in the mononucleus, and the study of their dynamics may yield new insight into the nuclear many-body system. In fact, the dinucleus is eminently suited for studies of nuclear dynamics far from equilibrium.

Of course, we have for a long time known and studied situations where the nuclear system is manifestly binary, namely quasi-elastic reactions, and in fact the dinucleus may in some ways be considered as a generalization of a quasi-elastic reaction system. However, using quasi-elastic terminology, the form factors governing the interaction between the two parts are very large for typical dinuclear configurations. In fact, they are so large that ordinary reaction models are not readily applicable, and the dynamical preservation of the individuality of the two dinuclear parts at first appears surprising. But it is an experimental fact that although very intimate dinuclear configurations are produced, as indicated by the observed large energy loss, the system maintains its binary character throughout the reaction, as is evident from the large similarity between entrance and exit channels (i.e. the net change in mass and charge is relatively small).

2. RELATIVE MOTION

The dinucleus is highly dissipative. This is clearly brought out in a damped nuclear reaction, in which essentially all the available energy associated with the relative motion is lost. It is this large dissipation that has given rise to the name 'strongly damped' nuclear reactions for the class of reactions in which a dinucleus is produced. It is therefore natural to discuss this characteristic aspect of the dinuclear dynamics first. Indeed, any theory of the dinucleus must give a reasonable account of this outstanding feature.

Since the discovery of damped nuclear reactions in the early seventies, many damping mechanisms have been suggested and explored theoretically. Figure 2 illustrates in a schematic manner the relationship between the most commonly advocated mechanisms for damping of the relative dinuclear motion.

A major subject of discussion is whether the basic damping mechanism in low-energy nuclear dynamics in general is of a one-body or a two-body nature. In a one-body description, the nuclear system can be considered as a collection of individual nucleons moving in a one-body mean field; the residual two-body interaction between the nucleons is of minor importance, so that the nucleonic motion is predominantly governed by the mean field which generally develops (slowly) in time. In a two-body description, on the contrary, it is essential to explicitly incorporate the direct two-body interaction in order to calculate the damping of the macroscopic motion. The two mechanisms differ with respect to their predictions about the dependence of the macroscopic friction coefficients on the nuclear temperature: while the two-body mechanism yields friction coefficients which are roughly proportional to the square of the nuclear temperature, due to the rapid increase of the available two-body phase-space, the one-body mechanism is generally insensitive to the temperature, since the motion of the individual nucleons in the mean field is rather independent of the temperature, which is small in comparison with the Fermi kinetic energy. This is a central difference which in principle can be tested experimentally and thus help elucidate the basic character of nuclear dissipation.

In low-energy nuclear dynamics, such as probed in damped reactions, the macroscopic velocities characterizing the time evolution of the mean field are generally small in comparison with the Fermi velocity associated with the nucleons. One important consequence of this characteristic feature is that the two-

POSSIBLE DAMPING MECHANISMS

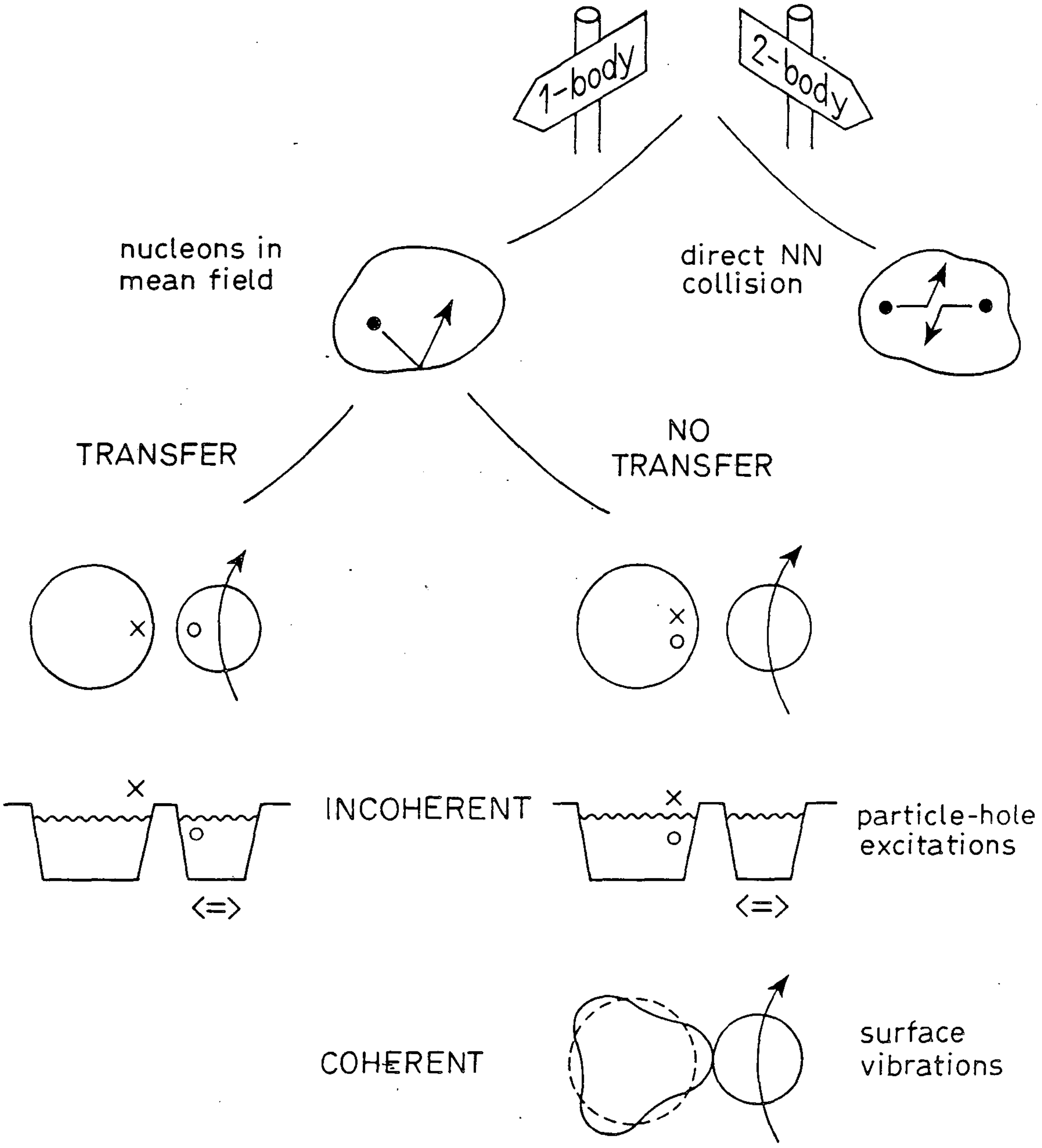


Fig. 2. Schematic illustration of the conceptual relationship between the most commonly advocated mechansims for damping of the relative dinuclear motion (see discussion in the text).

body damping mechanism is strongly suppressed, so that the one-body mechanism is expected to dominate the dynamics. A wealth of data supports this conjecture. Perhaps the most direct evidence for the dominance of one-body dissipation in low-energy nuclear dynamics is the observed temperature independence of the kinetic energy released in induced fission and, as was just reported in the preceding contribution,[3] the observed temperature independence of the nuclear shape dynamics in quasi-fission reactions.

Within the general realm of one-body descriptions, there are several distinct dissipation mechanisms. In a binary system one may distinguish conceptually between two different kinds of mechanism: (1) Either the mean field associated with one part may, by virtue of its time dependence, produce particle-hole excitations in the other part, without transferring nucleons; (2) Or nucleons may be transferred between the two parts, producing particle-hole excitations with the particle excitation in the receptor part and the hole excitation in the donor part. In both cases, the particle-hole excitations may be coherent or incoherent. In case of coherent modes, it is not necessary to explicitly consider the particle degrees of freedom at all, and indeed a model has been formulated entirely in terms of interacting surface modes of two individual nuclei.[4]

The experimental fact that all available relative energy is dissipated in a damped reaction indicates that the relaxation time for the relative energy is shorter than the reaction time. The only single mechanism producing such strong damping is the incoherent nucleon exchange which typically gives $t_E \approx 3\cdot10^{-22}$ s. The large efficiency of this mechanism stems from the relative largeness of the Fermi motion of the nucleons, $V_F \gg U$: when boosted by the relative velocity U, a nucleon transfer generates a substantial amount of excitation, $\approx \frac{1}{2}UP_F$, typically several MeV.[5]

Over the years, there has been much debate about the importance of the various possible damping mechanisms, and no general agreement has been achieved yet. A contributing reason for this unsatisfactory situation is that comparisons with data are often not conclusive as long as they are narrowly focussed on the energy loss. In order to obtain a firmer basis for discriminating between the different dissipation mechanisms, it is necessary to broaden the contact with experiment by including more observables in the considerations. In the following we briefly discuss the most important additional macroscopic degrees of freedom in the dinucleus which must be addressed by theory.

3. PARTITION OF DISSIPATED ENERGY

The energy lost from the macroscopic dinuclear motion is converted into excitation of the microscopic degrees of freedom in the system. So one may ask how this dissipated energy, or heat, is shared between the two parts of the dinucleus.

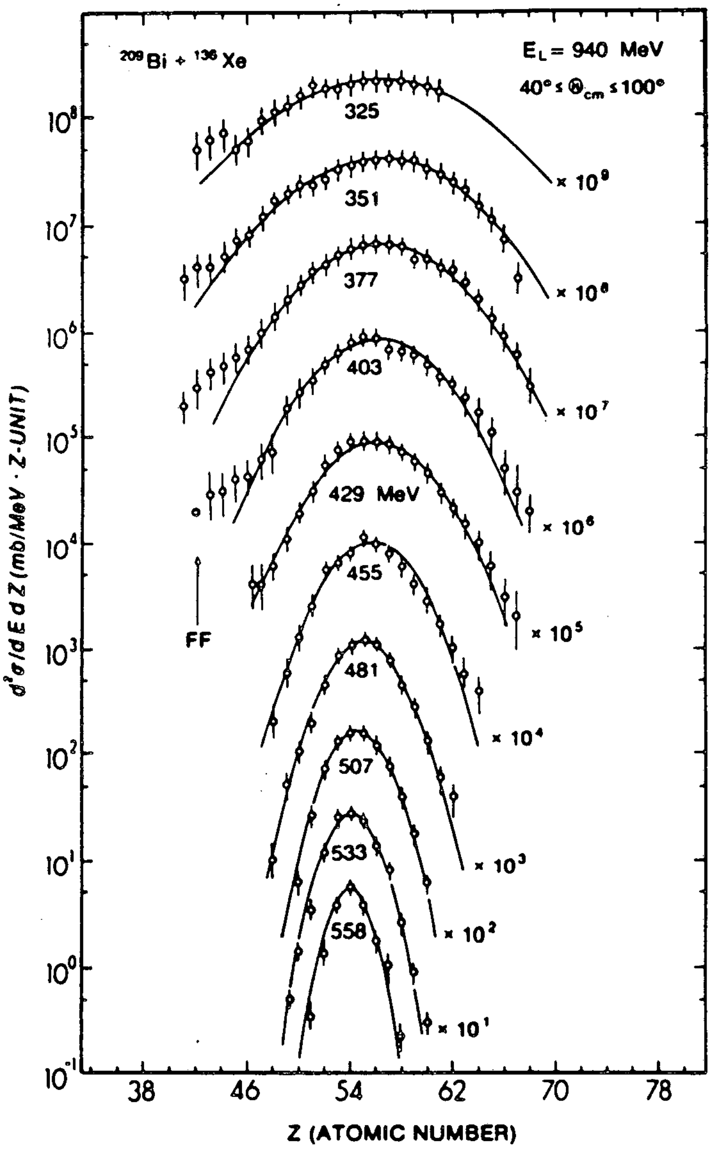


Fig.4. Distribution of elements produced in the damped reaction 940 MeV ^{136}Xe + ^{209}Bi for various values of the total kinetic energy loss.[13] The final relative kinetic energy is indicated by each curve, and gaussian fits help guide the eye. The figure is taken from ref.2.

This point usually lies off the bottom of the potential energy valley so that the local gradient will be relatively large and point approximately in the T-direction. Consequently, the system will at first develop preferentially in that direction, leading to a fairly quick relaxation of the charge-to-mass ratio. Subsequently, at a much slower rate, the system will evolve in the A-direction along the potential-energy valley, leading to a very slow change of the mean mass asymmetry. Thus, the qualitative evolution of the mean values is easily understood as a consequence of the static driving forces acting in the dinucleus, although the quantitative reproduction of the absolute drift rates requires a microscopic calculation of the associated mobility coefficients.

However, it is a general feature of the NZ distribution that the fluctuations are considerably larger than one would naively have expected by considering a standard random walk on the potential energy surface at the nuclear temperature τ. This important fact can be understood if one assumes that the changes in N and Z are due to the transfer of individual nucleons between the two dinuclear parts.[5] A single nucleon transfer generates an amount of excitation ω which is composed of two parts. One is the loss of potential energy, $F = -\Delta E_{pot}$, typically at most one MeV. The other contribution to ω arises from the relative motion between the donor and the receptor parts. The relatively large intrinsic (Fermi) momentum $\vec{p}$ of the transferred nucleon is boosted by the relative velocity $\vec{U}$ to produce an excitation $-\vec{U}\cdot\overleftarrow{p}$ which is typically several MeV and thus substantially exceeds both the static contribution F as well as the nuclear temperature τ. When the two dinuclear parts are in relative motion, the random NZ walk is then characterized by an 'effective temperature' τ^* which is considerably larger than the intrinsic nuclear temperature τ and this feature provides an understanding of the relatively large fluctuations observed. It is interesting to recall that it is this same mechanism, the exchange of nucleons, that is able to account for the large energy dissipation in the dinucleus.

5. ANGULAR MOMENTUM

The two product nuclei emerging from a damped reaction carry substantial amounts of angular momentum, typically several tens of elementary units, and it is therefore of interest to study the angular momentum dynamics in the dinucleus.

Since the total angular momentum vector $\vec{J}$ is a constant of motion, there are six degrees of freedom associated with the partition of the angular momentum among the two separate parts and their relative motion. These may be chosen as the spins $\vec{S}^A$ and $\vec{S}^B$ of the projectile-like and target-like parts, respectively; the angular momentum $\vec{L}$ associated with the relative dinuclear motion is then determined by angular momentum conservation: $\vec{S}^A + \vec{S}^B + \vec{L} = \vec{J}$. It is convenient to employ a coordinate system which is aligned with the instantaneous directions of the relative position $\vec{R} = \vec{R}^A - \vec{R}^B$ and the relative angular momentum $\vec{L} = \vec{R} \times \vec{P}$, so we choose the axes $\hat{z} = \hat{R}$, $\hat{y} = \hat{L}$, $\hat{x} = \hat{y} \times \hat{z}$. The distribution of angular momentum in a dinucleus produced in a reaction can then be characterized by two mean values, $\langle \vec{S}^F \rangle = \langle S^F_y \rangle \hat{y}$, where $F = A,B$, together with thirteen non-trivial (co)variances, $\sigma^{FG}_{ij} = \langle S^F_i S^G_j \rangle - \langle S^F_i \rangle \langle S^G_j \rangle$, where $F,G = A,B$ and $i,j = x,y,z$, with the combinations xy and yz excluded by symmetry. [These numbers may be compared with the two mean values and three (co)variances characterizing the mass and charge partition distribution.] There is thus considerable information in the angular momentum distribution, but its pursuit also presents a considerable challenge, both to experiment and theory. To date, the only comprehensive theoretical study of the dinuclear angular momentum dynamics is based on the nucleon-exchange mechanism,[14], and the following discussion will be illustrated by results from that work. Many experiments have been devoted to probing the angular momenta of damped reaction fragments and they have provided valuable information, although only certain limited aspects of the correlated six-dimensional spin distribution have been explored so far.

For the qualitative understanding of the dinuclear angular momentum dynamics, it is convenient to employ the spin variables $\vec{S}^{\ominus} = \vec{S}^{A} + \vec{S}^{B}$ and $\vec{S}^{-} = (\mathfrak{J}_B \vec{S}^{A} - \mathfrak{J}_A \vec{S}^{B})/(\mathfrak{J}_A + \mathfrak{J}_B)$, since they diagonalize the rotational Hamiltonian for the disphere and thus approximately represent the normal modes of rotation. [The individual moments of inertia are denoted $\mathfrak{J}_A$ and $\mathfrak{J}_B$ and those associated with the normal modes are $\mathfrak{J}_+ = \mathfrak{J}_A + \mathfrak{J}_B$ and $\mathfrak{J}_- = 1/(1/\mathfrak{J}_A + 1/\mathfrak{J}_B)$, in analogy with the two-particle problem.] The character of the six dinuclear rotational modes is illustrated in fig.5.

Theoretically, at least within the nucleon-exchange model, one would expect the evolution of the mean spin values to be characterized by two different relaxation times: a relatively short one t_+ associated with the growth of the positive normal spin $\langle S_y^+ \rangle$ to a value for which the two interacting nuclear surfaces no longer are sliding with respect to one another, and a relatively long one t_-, associated with the growth of the negative normal spin $\langle S_y^- \rangle$ towards the value corresponding to an overall rigid rotation of the dinucleus.[14] From the general geometry of a dinucleus one expects the two relaxation times to have the ratio $t_+/t_- \approx 4c_{ave}^2/R^2$, where $c_{ave} \approx 2\text{-}3$ fm is the mean off-axis displacement of the transfer site, while $R \approx R_A + R_B \approx 10\text{-}12$ fm is the dinuclear center separation. Thus there is about one order of magnitude difference between the two relaxation times and we expect a relatively quick braking of the initial sliding motion, followed by a fairly slow evolution from rolling toward sticking; this evolution is usually truncated by the finite reaction time before complete sticking is achieved.

The relaxation times are inversely proportional to the form factors which are strongly configuration dependent and, in particular, vanish for large separations. At the closest approach, calculations yield $t_+ \approx 4 \cdot 10^{-22}$ s as a typical value.[14] This is significantly shorter than a typical reaction time, while $t_- \approx 10\ t_+$ is usually longer than the reaction time. Therefore one expects that the mean positive-mode spin $\langle S_y^+ \rangle$ achieves full relaxation in a damped reaction, while the mean negative-mode spin $\langle S_y^- \rangle$ only develops a little toward equilibrium.

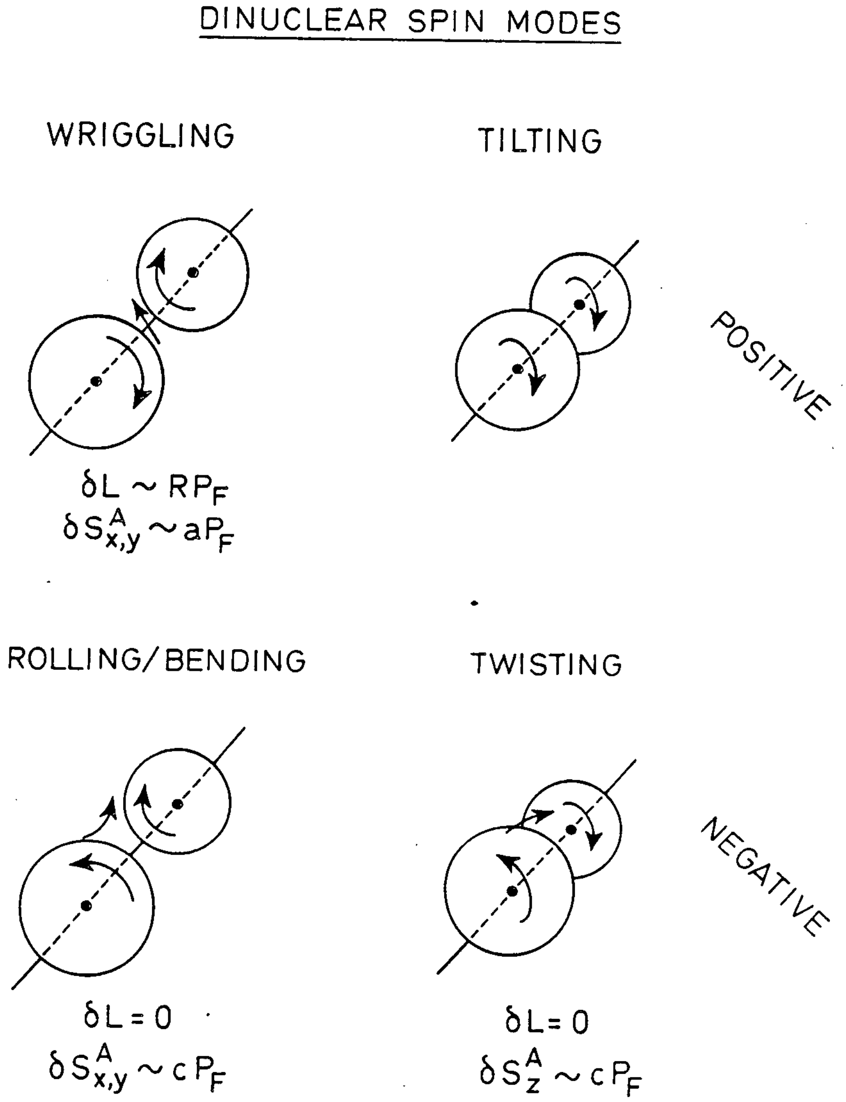


Fig.5. Illustration of the character of the six dinuclear rotational modes.

The behaviour of the dinuclear spin fluctuations is more complicated. The spin components along the instantaneous reaction normel $\hat{y}=\hat{L}$ decouple from the other cartesian components and are the simplest to treat. The in-plane x,z-components are coupled by the Coriolis force produced by the relative orbital motion and are thus more intricate. Figure 6 shows relaxation times for the variances of the various normal modes, as calculated for a symmetric dinucleus.[14] [The situation is more complicated for asymmetric systems.] This figure illustrates the very rich structure of the dinuclear angular momentum dynamics.

The fluctuations of the negative normal spin $\vec{S}^-$ are isotropic in space. Their relaxation time is half of that associated with the corresponding mean value, time.[14] Since the orbital rotation is relatively slow, the tilting relaxation time is expected to be fairly long, as seen from fig.6.

Experimental information on the excitation of the tilting mode in a nuclear reaction can be obtained from the behaviour of the differential cross section near the beam, which is expected to have a dip whose width is proportional to K_0/J, where K_0 is the appropriate effective K-value.[16] This effect is illustrated in fig.7. In order to exploit this effect, it is necessary to measure yields within a few degrees of the beam. This is quite feasible in practice and such data would yield rather direct evidence on the tilting mode. It would be of particular interest to perform such a measurement for a quasi-fission reaction, in which the dinuclear complex lives substantially longer than in an ordinary damped reaction; the time evolution of the tilting relaxation process might then be extracted. Such efforts are currently under way.[17]

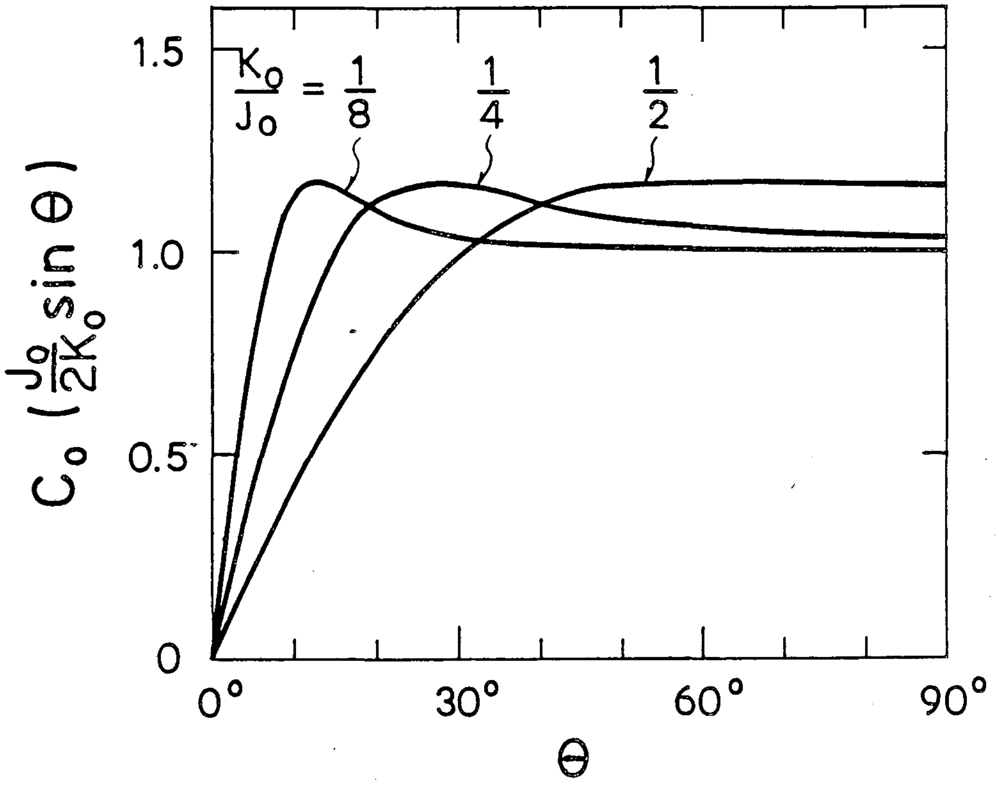


Fig.7. The tilting correction factor $C_0(J_0/2K_0 \sin\theta)$ by which the uncorrected differential cross section $d\sigma/d\theta$ should be multiplied near the beam. From ref.16.

Important information about the angular momentum dynamics is contained in the correlations between the two fragment spins. It follows from the discussion in

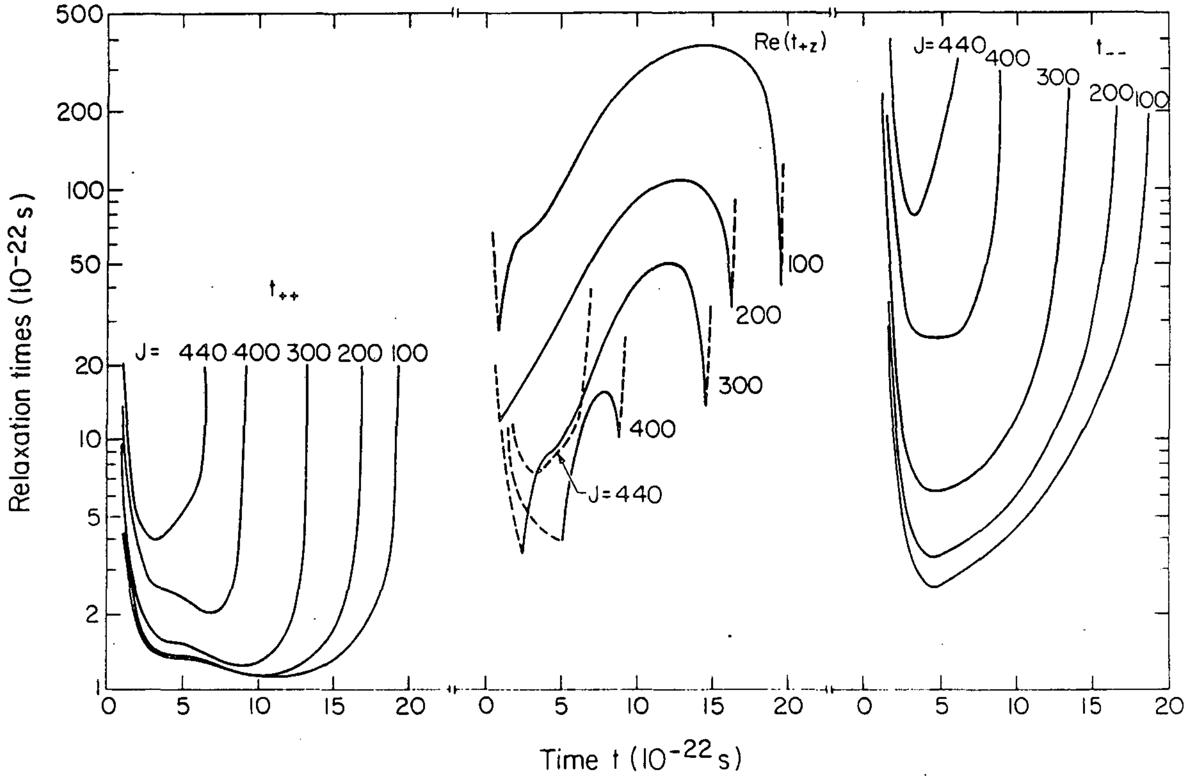


Fig.6. Calculated instantaneous relaxation times for the reaction 1400 MeV ^{165}Ho + ^{165}Ho for various values of the total angular momentum J. The relaxation times for the two positive transverse modes (wriggling) are denoted t_{++}, while that for the positive longitudinal mode (tilting) is denoted t_{+z}. The relaxation time for the three negative modes (bending and twisting) is denoted t_{--}. From ref.14.

$t_{--} = \frac{1}{2}t_{-}$. This is also a fairly long time, so only partial relaxation is expected to occur in a damped reaction.

The fluctuations of the positive normal spin $\vec{S}^{+}$ are isotropic in the xy-plane perpendicular to the dinuclear axis $\hat{z} = \hat{R}$. The fluctuations in this transverse plane have a relaxation time $t_{++} = \frac{1}{2}t_{+}$ and are therefore expected to develop a far way toward their equilibrium values.

The component of the positive normal spin on the dinuclear axis, S_z^{+}, is analogous to the K-value used in discussions of nuclear fission. It is often denoted the tilting mode, since $\vec{J}$ can only have a component K along the dinuclear axis if this axis is tilted out of the impact plane which is perpendicular to $\vec{J}$. This mode is not directly excitable by angular momentum exchange between the two dinuclear parts, except for recoil corrections of relative order 1/A, and its activation is due to the orbital rotation. Indeed, its relaxation time is found to be inversely proportional to the square of the angular frequency ω, insofar as the evolution of this mode can be characterized simply by a single relaxation connection with fig.6 that in the transverse xy-plane the spin dynamics is expected to be dominated by the positive modes. Therefore, the fluctuations of these spin components in the individual reaction products will tend to be positively correlated, with this tendency diminishing for larger energy losses where the longer reaction time allows the partial excitation of the negative modes, thus counteracting the positive correlation. For the axial spin components, the situation is nearly the opposite since the positive mode is here the tilting which has a relaxation time which is typically even longer than that characterizing the negative modes. The situation is illustrated in fig.8. Thus a very intricate correlation pattern is expected and its experimental measurement would clearly add qualitatively to our information about the angular momentum dynamics in the dinucleus.

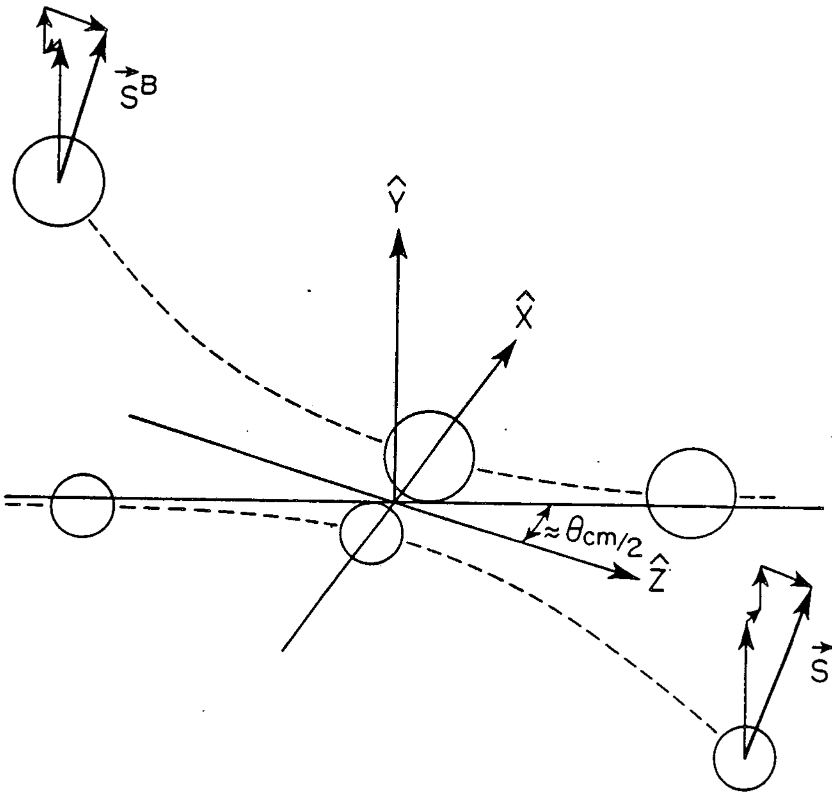


Fig.8. Illustration of the composition of the correlated spins in the two reaction products: Both mean spins point perpendicular to the reaction plane. Furthermore, the fluctuations along the reaction normal, as well as along that in-plane direction which is perpendicular to (the dominant direction of) the dinuclear axis, are large and mainly positively correlated, while the fluctuations in the direction of the dinuclear axis are small and mainly negatively correlated. The dominant direction of the dinucleus corresponds to the closest approach when the system is about half way through the reaction process.

While certainly more complicated, such spin-correlation experiments are in fact practically feasible. For example, Lazzarini[18] has suggested that one considers a damped reaction between fissile nuclei and detects all four fission fragments; their angular correlations are then directly related to the correlated spin-spin distribution.[15] Such an experiment has already been carried out, but unfortunately the data analysis has not been completed.[19] One may hope that this pioneering effort will be followed by others so that this novel kind of information can be uncovered.

6. CONCLUDING REMARKS

This contribution has dealt with the physics of the dinucleus and has described the dynamical characteristics of its most important macroscopic degrees of freedom; the relative motion, the heat partition, the mass and charge partition, and the angular momentum.

The dinucleus presents a special manifestation of the nuclear many-body system which is so far from the more ordinary mononuclear configurations that it is characterized by different macroscopic degrees of freedom. These degrees of freedom have unique dynamical properties which can be probed experimentally, particularly by means of damped nuclear reactions. Such experiments have greatly increased our knowledge about the dinucleus, but there is a need for still more refined measurements if we are to fully uncover the intricate dinuclear dynamics.

On the theoretical side there is also work to do. Any satisfactory model must be able to address all the different dinuclear observables. The only such comprehensive model developed incorporates (nearly) only one single dissipation mechanism, namely incoherent nucleon exchange, and so far it exists only in a rather crude implementation (for example with respect to the shape parametrization).[2,9,14] It is highly desirable to improve this situation. In particular, it would be very valuable to derive the dinuclear dissipation from a more fundamental basis, so that the role of the different possible mechanisms can be more confidently assessed.

On balance, though, it must be said that great advances have been made since the study of the dinucleus gained momentum about a decade ago after the discovery of damped reactions. Thanks to extensive experimental efforts, we have now a rather detailed insight into the associated phenomena. On the theoretical side, good progress has been made with regard to both the development of phenomenological models and the more fundamental understanding of the physical mechanisms.

The dinucleus presents a small quantal many-body system far from equilibrium and the problem of understanding its dynamical behaviour, including its dissipative properties, is of interest beyond the narrow context of nuclear physics.

In general, one would expect that the excitation energy is initially deposited fairly equally in the two reaction partners, since the energy exchange intrumental for the dissipation occurs locally in the interaction zone, so that the actual sizes of the two bulks are unimportant. Thus, the smaller dinuclear part will initially get hotter than the larger one. Subsequently, one expects the onset of a regulatory feedback mechanism which will act towards establishing an eventual overall thermalization where the intrinsic temperature is the same throughout the system. In a damped reaction, one consequently expects a systematic evolution with energy loss from about equal excitation in the two reaction products to about equal temperature.

In view of the generality of the above arguments, it was puzzling that early measurements of neutron spectra and multiplicities seemed to indicate a practically complete thermal relaxation at all energy losses.[6,7] However, more recent experiments indicate a significant temperature difference at modest energy losses. Figure 3 shows the results obtained by Vandenbosch et al. by exploiting the temperature dependence of the mass asymmetry in fission.[8]

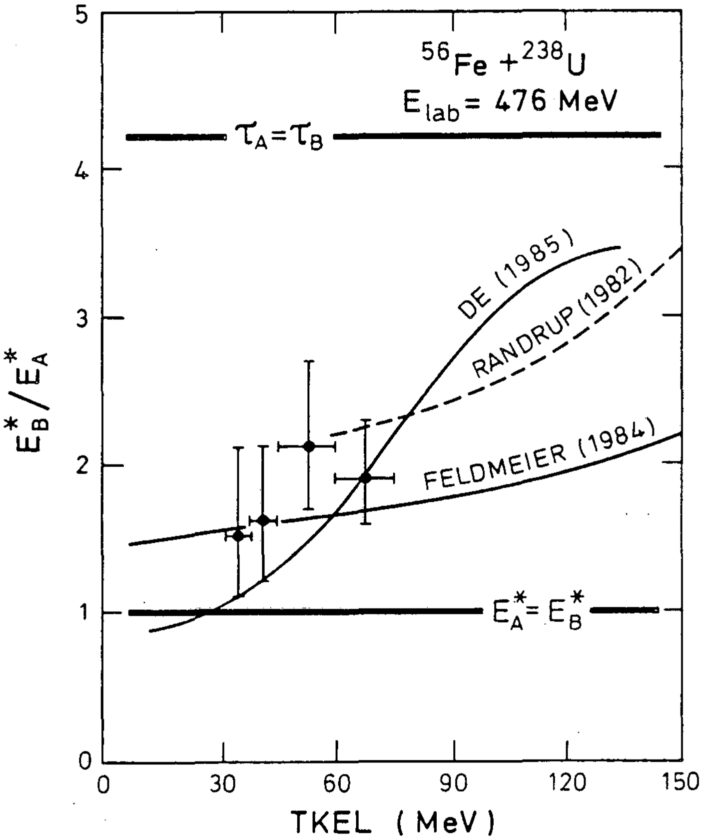


Fig.3. The partition of excitation energy on the two products in the damped reaction 476 MeV ^{56}Fe + ^{238}U as a function of the total kinetic energy loss TKEL. The data points are those obtained by Vandenbosch et al. by exploiting the temperature dependence of the mass asymmetry in the subsequent fission of the heavy reaction product.[8] Calculations based on the incoherent nucleon-exchange mechanism are also indicated.[9-11]

In principle, all the different possible dissipation mechanisms give definite predictions about the heat partition. However, so far this observable has been studied only for the incoherent nucleon-exchange mechanism and these results are included in fig.3.[9-11] The nucleon-exchange mechanism yields a relaxation time of $t_{\Delta\tau} \approx 5 \cdot 10^{-22}$ s for the heat partition in the dinucleus, which is in good accordance with the (so far rather limited) experimental data.

4. PARTITION OF MASS AND CHARGE

The partition of the total mass and charge among the two dinuclear parts represents important macroscopic degrees of freedom in the dinucleus. The mass partition, or mass asymmetry, is conveniently specified by the number of nucleons A in the projectile-like part. When both mass and charge is measured, it is convenient to use the number of neutrons N and the number of protons Z in the projectile-like part as the two independent degrees of freedom representing the mass and charge partition. These degrees of freedom have been the focus of much activity, theoretical as well as experimental, through the last decade, and a recent review is given in ref.12.

It is a general and characteristic feature of the experimental data that the mean mass and charge partitions change remarkably little in a damped reaction, while the associated fluctuations in particle number increase steadily with energy loss and acquire substantial values at the largest energy losses. This is illustrated in fig.4 which shows the measured element distribution for various energy losses in the damped reaction 1130 MeV ^{136}Xe + ^{209}Bi.[13] The large fluctuations present a fairly universal feature of damped reactions, also present in other observables, and no theory of the dinucleus can be satisfactory without incorporating this characteristic feature.

In order to discuss the qualitative behaviour of the mass and charge partition, it is instructive to consider the potential energy of the dinucleus as a function of N and Z. Due to the relatively strong symmetry energy in nuclei, which is responsible for the existence of the β-stability valley, the contours of the dinuclear potential energy is rather steep in the isospin direction, so that the energy surface appears as a narrow, gently sloping valley approximately aligned with the A-direction. Of course, the potential energy surface changes in time since it depends on the dynamical state of the dinucleus, particularly on its total angular momentum.

The time evolution of the mass and charge partition can be described phenomenologically and understood theoretically as a transport process in the macroscopic variables N and Z. Initially, the distribution function is sharply peaked at the injection point where N and Z have the values of the projectile nucleus.

REFERENCES

1) M.C. Weiss, LLNL report UCRL-89145 (1983).

2) W.U. Schröder and J.R. Huizenga, Treatise on Heavy-Ion Science, ed. D.A. Bromley (Plenum Press, New York, 1984) p.115.

3) S. Bjørnholm, preceding contribution to this conference.

4) R.A. Broglia, C.H. Dasso and A. Winther, Proc. of the Int. School of Physics Enrico Fermi: LXXVII, eds. R.A. Broglia, R.A. Ricci and C.H. Dasso (North-Holland, Amsterdam, 1981) p.327.

5) J. Randrup, Nucl. Phys. A327(1979)490.

6) D. Hilscher, J.R. Birkelund, A.D. Hoover, W.U. Schröder, W.W. Wilcke, J.R. Huizenga, A.C. Mignerey, K.L. Wolf, H.F. Breuer and V.E. Viola, Phys. Rev. C20(1979)576.

7) J.R. Huizenga, W.U. Schröder, J.R. Birkelund and W.W. Wilcke, Nucl. Phys. A387(1982)2576.

8) R. Vandenbosch, A. Lazzarini, D. Leach, D.K. Lock, A. Ray and A. Seamster, Phys. Rev. Lett. 52(1984)1964.

9) J. Randrup, Nucl. Phys. A383(1982)468.

10) H. Feldmeier and H. Spangenberger, Nucl. Phys. A428(1984)2236.

11) S.K. Samaddar, J.N. De and K. Krishan, Phys. Rec. C31(1985)1053.

12) H. Freiesleben and J.V. Kratz, Phys. Rep. 106(1984)1.

13) W.W. Wilcke, J.R. Birkelund, A.D. Hoover, J.R. Huizenga, W.U. Schröder, V.E. Viola, K.L. Wolf and A.C. Mignerey, Phys. Rev. C22(1980)128.

14) T. Døssing and J. Randrup, Nucl. Phys. A433(1985)215.

15) T. Døssing and J. Randrup, Nucl. Phys. A433(1985)280.

16) T. Døssing and J. Randrup, Phys. Lett. 155B(1985)333.

17) K. Lützenkirschen et al. Z. Phys. A320(1985)529.

18) A. Lazzarini, private communication (1982).

19) A. Lazzarini, private communication (1984).

*This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720