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[1]M. A. Shifman *et al.*, Phys. Lett. 65B, 255 (1976), and 76B, 663(E) (1976), and Nucl. Phys. B136, 125, 157 (1978).

[2]J. P. Leveille and T. Weiler, Nucl. Phys. B147, 147 (1979).

[3]A. R. Clark *et al.*, Phys. Rev. Lett. 43, 187 (1979).

[4]B. Knapp *et al.*, Phys. Rev. Lett. 34, 1040 (1975); U. Camerini *et al.*, Phys. Rev. Lett. 35, 483 (1975); B. Gittleman *et al.*, Phys. Rev. Lett. 35, 1616 (1975); T. Nash *et al.*, Phys. Rev. Lett. 36, 1233 (1976); W. Y. Lee, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, 1977*, edited by F. Gutbrod (DESY, Hamburg, 1977).

[5]J. P. Leveille and T. Weiler, Phys. Lett. 86B, 377 (1979).

[6]M. Gluck and E. Reya, Phys. Lett. 83B, 98 (1979).

[7]L. M. Jones and H. W. Wyld, Phys. Rev. D 17, 759, 2332 (1978); J. Babcock *et al.*, Phys. Rev. D 18, 162 (1978); H. Fritzsch and K. H. Streng, Phys. Lett. 72B, 385 (1978); M. Gluck and E. Reya, Phys. Lett. 79B, 453 (1978); V. Barger *et al.*, Phys. Rev. D 20, 630 (1979).

[8]V. Novikov *et al.*, Phys. Rev. Lett. 38, 626 (1977).

[9]M. Mugge, in Proceedings of the SLAC Summer Institute, Stanford, California, 1979, edited by A. Mosher (unpublished); V. Korbel, *ibid.*

[10]G. R. Farrar, Nucl. Phys. B77, 429 (1974); J. F. Gunion, Phys. Rev. D 10, 242 (1974); S. J. Brodsky and J. F. Gunion, Phys. Rev. D 19, 1005 (1979).

Effect of Pauli Blocking on Exchange and Dissipation Mechanisms Operating in Heavy-Ion Reactions

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Systematic properties of dissipation and exchange mechanisms associated with damped nuclear reactions are obtained from available data, yielding results that cannot be consistently described in a classical approach. However, correlations between energy loss and the variances of the fragment A and Z distributions are understood on the basis of an exchanged-induced dissipation mechanism, if account is taken of the Pauli exclusion principle.

Although considerable progress has been made during recent years in understanding the mechanisms operating in damped nuclear reactions, several of the most characteristic features of these processes have so far escaped a consistent theoretical description. This is particularly true for the experimentally well-established correlation[1,2] between energy dissipation and nucleon exchange. Experimental evidence is in accord with the assumption of successive exchange of single nucleons proceeding simultaneously with dissipation of relative kinetic energy in many small steps. In this work, available data are examined in order to expose the systematic properties of dissipation and exchange mechanisms associated with damped nuclear reactions. It is shown that these features cannot be understood on purely classical grounds but find a natural explanation when the fermion nature of the exchanged nucleons is taken into account. A quantal model[3] is applied attributing energy dissipation to the stochastic exchange of nucleons between two Fermi-Dirac gases in relative motion, a description expected to be relevant for the modest excitations attained in damped reactions under consideration.

In a phenomenological approach described recently,[4] use was made of the microscopic time scale provided by the exchange mechanism to de-

rive a dissipation rate

$$-dE/dN_{\mathrm{exch}} \approx (m/\mu)\alpha E, \quad (1)$$

with respect to the number N_{exch} of nucleons exchanged. Here, $E = E_{\mathrm{c.m.}} - V_{\mathrm{Coul}} - E_{\mathrm{loss}}$ is the available relative kinetic energy above the Coulomb barrier V_{Coul}, m is the nucleon mass, and μ is the reduced mass of the dinuclear system. The coefficient α conveys information on the character of the dissipation mechanism. It would be unity if all dissipation were due to the recoil induced by the exchange of classical particles which are initially either at rest or have Fermi motion. Classically then, only the presence of a coacting nonexchange dissipation mechanism would lead to an increased value of α, whereas accounting for the Pauli exclusion principle yields α values considerably larger than unity for the exchange processes alone, as discussed further below.

Under the assumption that α remains approximately constant during a given collision trajectory, Eq. (1) may be integrated yielding

$$E_{\mathrm{loss}} \approx (E_{\mathrm{c.m.}} - V_{\mathrm{Coul}}) \times \{1 - \exp[-(m/\mu)\alpha N_{\mathrm{exch}}]\}. \quad (2)$$

Although conceptually a different quantity, the dissipated energy E_{loss} can approximately be identified with the negative of the measured reaction Q value. However, it is not in general possible to derive a simple and unique relation between N_{exch} and experimental observables such as the variances σ_A^2 and σ_Z^2 of fragment-A and -Z distributions, because of the dynamical modification of the transition rates by the individual exchanges. Fortunately, however, knowledge of the precise relations is not essential to the present discussion, provided the same relation holds on the average for a given projectile-target combination at different bombarding energies. For simplicity, it is assumed that N_{exch} is given by $N_{\mathrm{exch}} = \sigma_A^2$ or, if only σ_Z^2 is available, by $N_{\mathrm{exch}} = (A/Z)^2\sigma_Z^2$ (Beck *et al.*[5]), where A and Z apply to the total system. It is stressed that adoption of other relations advocated[1] in the literature does not alter the conclusions to be drawn below.

Figure 1 shows the resulting fits of Eq. (2) to the experimental[4,6] correlations $\sigma_Z^2(E_{\mathrm{loss}})$ for the reaction $^{209}\mathrm{Bi} + ^{136}\mathrm{Xe}$ at 1130 and 940 MeV. As can be seen, an adequate representation of the data is provided by Eq. (2) up to energy losses close to the initially available energies $E_0 = E_{\mathrm{c.m.}} - V_{\mathrm{Coul}}$ indicated by arrows. This fact furnishes *a posteriori* justification for the assumption of a relatively constant value of α for a given experiment. However, it is observed that α decreases from

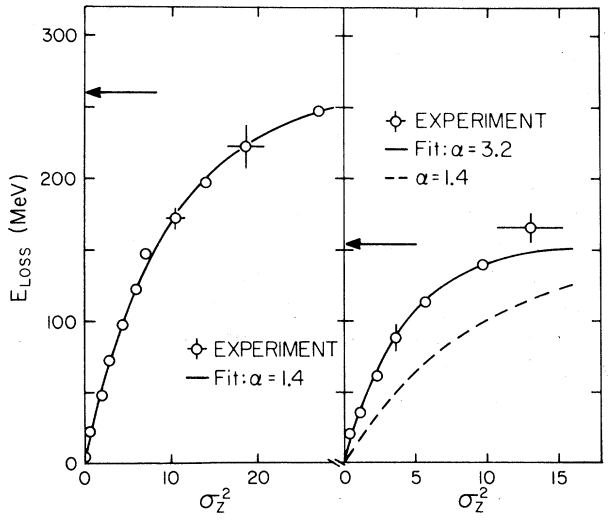

FIG. 1. Correlation between energy loss and variance of the fragment-Z distribution for the reaction $^{209}\mathrm{Bi} + ^{136}\mathrm{Xe}$ at $E_{\mathrm{Lab}} = 1130$ MeV (left) and 940 MeV (right). Arrows denote initially available kinetic energies. The curves represent predictions according to Eq. (2) with the indicated α values.

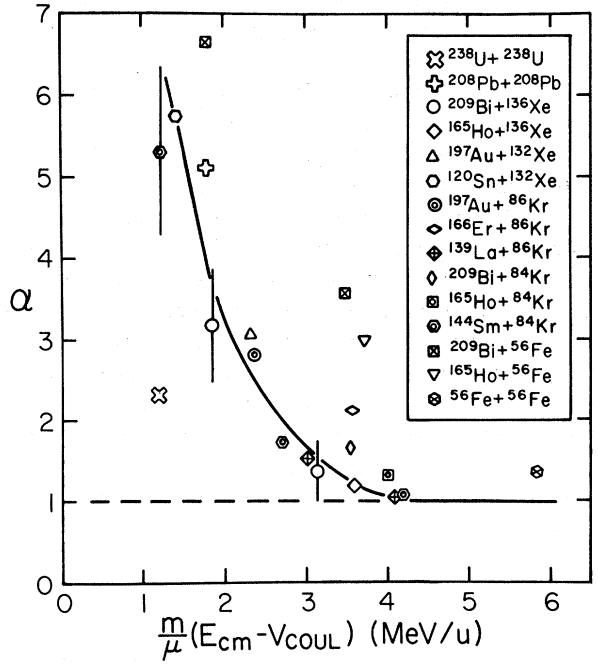

FIG. 2. Values of the parameter α obtained from fits of Eq. (2) to available data plotted vs the initially available energy per nucleon above the Coulomb barrier.

3.2 to 1.4 as the bombarding energy is increased from 940 to 1130 MeV. A similar behavior is borne out by all other reactions studied,[1,4,6-10] as demonstrated in Fig. 2 exhibiting the dependence of α on the approach energy per nucleon $(m/2)U^2 = (m/\mu)E_0$. The solid curve drawn through the data points emphasizes the average trend which is already rather well defined by the three points[7] for the reaction $^{144}\mathrm{Sm} + {}^{84}\mathrm{Kr}$. Significant deviations from the average are observed for the relatively asymmetric systems[8] associated with the ^{56}Fe projectile, as well as for the $^{238}\mathrm{U} + {}^{238}\mathrm{U}$ reaction.[9] The dependence of α on both the bombarding energy and the projectile-target combination appears to be inconsistent with the mentioned models based principally on classical kinematic considerations. For example, the constancy of α for any given experiment leads to the expectation of very little variation of α with bombarding energy. In addition, unconsidered effects of the nucleon binding energy on the determination of α, which are system dependent, are expected to be negligible for these systems, where only small drifts of the average final fragmentations from the initial ones are observed. It is then conjectured that the insufficiency of the classical model to describe the data is due to its neglect of the quantal character of the exchange and dissipation mechanisms

In the following, a recently developed model[3] is applied describing the energy dissipation associated with the exchange of nucleons between two Fermi-Dirac gases in slow relative motion characterized by a relative velocity $\vec{U}$. The two gases have a common temperature τ, and their Fermi energies T_F differ by an amount F_A which is the static driving force for the mass-asymmetry degree of freedom represented by the mass number A of the projectilelike fragment. For simplicity, the differences between neutrons and protons are neglected in the discussion, for the time being. Because, ordinarily, $|\vec{U}|$ is small compared to the Fermi velocity v_F, and $|F_A|, \tau \ll T_F$, the two gases are always nearly degenerate. It then follows from the model[3] that the rate of change of A and the dissipation rate can be expressed as

$$dA/dt = F_A N'(\epsilon_F), \quad dE_{\mathrm{loss}}/dt = \langle \omega^2 \rangle_F N'(\epsilon_F). \quad (3)$$

Here $N'(\epsilon_F) = \partial N(\epsilon_F)/\partial T_F$ is the differential current of nucleons exchanged between the gases calculated with neglect of the Pauli blocking effect. This form factor governs the overall intensity of the interaction and depends delicately on the details of the interaction zone. The quantity $\omega = F_A - \vec{U}\cdot\vec{p}$ is the amount of intrinsic excitation produced by the exchange of a nucleon with the intrinsic momentum $\vec{p}$, and the brackets denote an average over the orbitals in the Fermi surface, the only ones participating. The two quantities in Eq. (3) can both be represented in terms of one-body operators and may, therefore, be calculated without taking explicit account of the Pauli exclusion principle.

This, however, is not true for the particle-number dispersion $\sigma_A{}^2$, a quantity depending explicitly on the correlations present, such as those imposed by the Fermi-Dirac statistics of the nucleons. The rate of growth of $\sigma_A{}^2$ is, in this model, equal to the total rate of actual exchanges, as long as the system has not evolved too far towards equilibrium. It is given by

$$d\sigma_A{}^2/dt = 2\tau^* N'(\epsilon_F). \quad (4)$$

Here, $\tau^* = \langle \frac{1}{2}\omega \coth(\omega/2\tau)\rangle_F$ is a measure of the energy interval around the Fermi level contributing to exchange processes. In the limit $|\omega| \ll \tau$, it approaches the nuclear temperature $\tau^* \approx \tau$, whereas in the case $|\omega| \gg \tau$, $\tau^* \approx \frac{1}{2}\langle|\omega|\rangle_F$ may be considerably larger than τ, because of a larger relative displacement of the two Fermi spheres. In any case, the appearance of τ^* in Eq. (4) ensures that proper account is taken of the quantum statistics at all temperatures.

Inspection of the general behavior of the coefficient α is particularly simple for symmetric systems ($F_A \approx 0$) and peripheral collisions, where $\vec{U}$ is almost tangential. Then $\langle \omega^2 \rangle_F \approx \frac{1}{4} p_F{}^2 U^2 = \frac{1}{2} m U^2 T_F$, and from Eqs. (3) and (4) follows

$$\alpha = (\mu/mE) dE_{\mathrm{loss}}/d\sigma_A{}^2 \approx T_F/2\tau^*. \quad (5)$$

By contrast, a classical treatment neglecting the Pauli blocking effect would result in the replacement $\tau^* \to T_F/2$ and yield $\alpha \approx 1$. The above simple estimate suggests that α should typically be substantially larger than unity and decrease as the bombarding energy is increased. Furthermore, according to Eq. (5), a certain degree of universality is expected for α: The α values for different projectile-target combinations with similar values F_A should lie on the same "universal" curve when plotted against $\frac{1}{2}mU^2$ essentially determining τ^*. It is striking to observe that these general features, absent in a classical picture, are indeed borne out by the experimental results shown in Fig. 2.

Since the rough estimate represented by Eq. (5) relies on a number of idealizations, a more re-

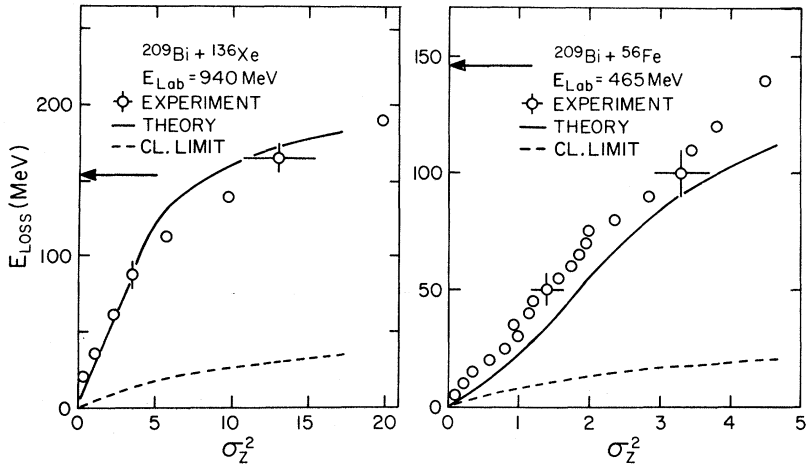

FIG. 3. Comparison of model predictions for the correlation $E_{loss}(\sigma_Z^2)$ with data for the reactions ^{209}Bi + ^{136}Xe (left) and ^{209}Bi + ^{56}Fe (right). The dashed curves represent the classical limits of the full calculations (full curves).

fined approach is taken in this work by performing dynamical calculations of collision trajectories in a coordinate space including the fragment-mass and -charge asymmetries. The dinuclear complex is parametrized by two spherical nuclei joined by a cylindrical neck. Conservative forces are calculated from droplet-model masses, the Coulomb repulsion, and the surface and proximity energies of the neck region. Energy dissipation is provided by the nucleon-exchange mechanism [cf. Eq. (3)], together with the damping due to the neck motion approximated by a wall-type dissipation formula. Inertial forces are calculated for two sharp rigid spheres. Energy loss and the accumulated variances σ_A^2 and σ_Z^2 are obtained from integrating along the trajectory the dissipation function and the diffusion coefficients, respectively, as given by the model. The various aspects of the dynamical model are discussed in detail elsewhere.[3,11,12]

Typical results of the calculations (full curves) are compared to experiment in Fig. 3 for the reactions ^{309}Bi + ^{136}Xe (Wilcke *et al.*[6]) and ^{209}Bi + ^{56}Fe (Breuer *et al.*[8]) at E_{lab} = 940 and 465 MeV, respectively, that are associated with α values far in excess of the classical limit. A good reproduction of the data is achieved for ^{209}Bi + ^{136}Xe at 940 MeV, and also for the 1130-MeV data for energy losses up to about 150 MeV. For systems such as ^{209}Bi + ^{56}Fe also depicted in Fig. 3, where the static driving force is no longer negligible, satisfactory agreement with experiment is also obtained with respect to the correlations $\sigma_Z^2(E_{loss})$ and $\sigma_A^2(E_{loss})$. As is illustrated by the dashed curves in Fig. 3 representing the dynamical calculations in the classical limit, the Pauli principle is essential to the good agreement between data and the quantal model. For relatively high energy losses ($E_{loss} > 100-150$ MeV), predictions of the quantal model deviate somewhat from the data, as is expected from the simplifications made in the model. Only for the reaction ^{238}U + ^{238}U, for which dominating sequential fission of both reaction partners prevents direct measurement of primary Z or A distributions,[9] the model results in a poor description of the data.

In summary, the good agreement between data and model predictions found in general demonstrates that energy dissipation in damped reactions can be consistently understood in terms of a nucleon exchange mechanism in which the Pauli exclusion principle plays a crucial role.

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[1]W. U. Schröder and J. R. Huizenga, Annu. Rev. Nucl. Sci. 27, 465 (1977).

[2]W. U. Schröder *et al.*, in *Proceedings of the Conference on Growth Properties of Nuclear Excitations, 1978*, edited by H. Von Grotte, AED-CONF. 1978-007-022 (Institut für Kernphysik, Darmstadt, West Germany, 1978).

[3]J. Randrup, Nucl. Phys. A307, 319 (1978), and A327, 490 (1979).

[4]W. U. Schröder *et al.*, Phys. Lett. 71B, 283 (1977), and Phys. Rep. 45, 301 (1978).

[5]F. Beck *et al.*, Z. Phys. A 289, 113 (1978).
[6]W. W. Wilcke *et al.*, to be published.
[7]A. C. Mignerey *et al.*, to be published.
[8]H. Breuer *et al.*, Phys. Rev. Lett. 43, 191 (1979).
[9]K. D. Hildenbrand *et al.*, Phys. Rev. Lett. 39, 1065 (1977).
[10]H. Sann *et al.*, in *Proceedings of the Topical Conference on Heavy Ion Collisions, Fall Creek Falls State Park, Pikeville, Tennessee, 1977*, CONF-770602 (Oak Ridge National Laboratory, Oak Ridge, Tenn., 1977).
R. Vandenbosch *et al.*, Phys. Rev. C 17, 1672 (1978).
[11]W. J. Swiatecki, Lawrence Berkeley Laboratory Report No. LBL-8950, 1979 (unpublished).
[12]J. Randrup *et al.*, to be published.

Explanation of Nuclear Quadrupole Interaction in ^{14}N "Spherical" Atomic Ground State

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The explicit incorporation of the Breit interaction in relativistic many-body perturbation theory provides an explanation of the recent experimental value of 1.27 ± 0.10 Hz for the nuclear quadrupole interaction constant in the spherical ^{14}N atom. The theoretical value including the Breit and other mechanisms is 1.7 Hz.

Recently, through the advent of new experimental techniques capable of remarkable precision, hyperfine interactions have been measured in systems in which they were believed to be vanishingly small if not exactly zero. The most noteworthy of such measurements is the quadrupole interaction in half-filled S-state atoms[1-3] in free state, and similar ions in solids at sites of cubic symmetry.[4] The origin of these interactions poses a formidable challenge to qualitative and quantitative theoretical analysis. Of the S-state atoms, nitrogen has remained refractory[1,2] for about a decade. The latest value of the quadrupole coupling constant of ^{14}N was measured by Hirsch, Zimmerman, Larson, and Ramsey,[1] in its ground state, to be 1.27 ± 0.10 Hz with an ingenious technique involving spin exchange between hydrogen and nitrogen atoms.

Sandars and Beck[5] have proposed two mechanisms referred to in the literature as Casimir and breakdown of LS coupling (BDLSC) in order to explain the origin of quadrupole interaction in relatively heavy S-state atoms and ions such as manganese and europium, and an approximate treatment[5] of these mechanisms provided a reasonable explanation of the experimental data. A detailed treatment of these mechanisms including many-body effects has been carried out recently[6] for Gd^{3+}. In contrast to this encouraging situation in transition-metal and rare-earth systems the net contribution from Casimir and BDLSC mechanisms for nitrogen[7] is in sharp disagreement with experiment yielding a contribution of -19.1 Hz, compared with the very small positive experimental value.

In the present work, we demonstrate that the influence of the Breit interaction[8] between the electrons is critical for the problem at hand and that its incorporation within the framework of relativistic many-body perturbation theory (RMBPT) is necessary to provide the balance to reach satisfactory agreement with the experimental ^{14}N quadrupole coupling constant.[1] While the influence of the Breit interaction on two-electron systems has been considered before,[9] to our knowledge this is the first treatment of its influence on the ground state of a multi-electron system in many-body theory.

Before discussing the procedure and results for the Breit-interaction contribution to the quadrupole coupling, we shall briefly discuss the contribution from the Casimir and BDLSC mechanisms as well as from the small pseudo quadrupole interaction. These mechanisms can also be handled in the framework of RMBPT, as has been done in earlier work in Gd^{3+} ion. Thus, the relativistic ls coupling[6] used for the one-electron rls states occurring in the zeroth-order (unperturbed) many-electron wave function Φ_0 of RMBPT preserves the nonrelativistic LS composition of the configuration, ^4S in the present problem of the nitrogen atom. The expectation value of the quadrupole Hamiltonian with respect to Φ_0, referred to later as the (0,0) term in RMBPT, gives a zero result. The finite contributions from the Casimir and BDLSC mechanisms depend on