‡Also of University of Bern, Bern, Switzerland.
[1]V. W. Hughes and S. Penman, Bull. Amer. Phys. Soc. 4, 80 (1959); K. N. Huang *et al.*, Bull. Amer. Phys. Soc. 18, 1503 (1973); K. N. Huang, Ph.D. thesis, Yale University, 1974 (unpublished).
[2]K. N. Huang *et al.*, in *Fifth International Conference on High Energy Physics and Nuclear Structure,* edited by G. Tibell (North-Holland, Amsterdam, 1973), p. 312.
[3]E. W. Otten, Z. Phys. 225, 393 (1969); V. G. Varlamov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. 17, 186 (1973) [JETP Lett. 17, 132 (1973)].
[4]V. W. Hughes *et al.*, Bull. Amer. Phys. Soc. 5, 75 (1960).
[5]M. Camani, Helv. Phys. Acta 46, 47 (1973).
[6]R. A. Mann and M. E. Rose, Phys. Rev. 121, 293 (1961); I. M. Shmushkevich, Nucl. Phys. 11, 419 (1959).
[7]A. E. Ignatenko, Nucl. Phys. 23, 75 (1961).
[8]D. C. Buckle *et al.*, Phys. Rev. Lett. 20, 705 (1968).
[9]P. Souder *et al.*, in *Proceedings of the Fourth International Conference on Atomic Physics, Heidelberg, Germany, 1974. Abstracts of Contributed Papers,* edited by J. Kowalski and H. G. Weber (Heidelberg Univ. Press, Heidelberg, Germany, 1974), p. 32; R. Stambaugh, Ph.D. thesis, Yale University, 1974 (unpublished).
[10]V. W. Hughes, Annu. Rev. Nucl. Sci. 16, 445 (1966).
[11]V. W. Hughes *et al.*, Phys. Rev. Lett. 5, 63 (1960), and Phys. Rev. A 1, 595 (1970).
[12]R. L. Garwin, L. M. Lederman, and M. Weinrich, Phys. Rev. 105, 1415 (1957).
[13]Matheson-Grade helium. Matheson Gas Products, East Rutherford, N. J.
[14]Research-Grade xenon. Air Products and Chemicals, Inc., Emmaus, Pa.
[15]W. Farr and E. W. Otten, Appl. Phys. 3, 367 (1974).
[16]R. D. Stambaugh *et al.*, Phys. Rev. Lett. 33, 568 (1974).
[17]A. Placci *et al.*, Nuovo Cimento 1A, 445 (1971).
[18]H. H. Fleischmann and R. A. Young, Phys. Rev. Lett. 19, 941 (1967); W. B. Meier II, Phys. Rev. A 5, 1256 (1972).
[19]P. A. Thompson *et al.*, Phys. Rev. A 8, 86 (1973).
[20]T. D. Lee and C. S. Wu, Annu. Rev. Nucl. Sci. 15, 381 (1965).

Evidence for an Alignment Effect in the Motion of Swift Ion Clusters through Solids*

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Distributions in angle and in energy have been measured for ions transmitted through thin solid targets bombarded by various molecular-ion beams. The results, which differ markedly from those expected from simple Coulomb explosions, indicate that for the ion clusters created inside the target, the internuclear vectors tend to align with the beam direction. An explanation is suggested in terms of a wake potential generated behind each particle as it traverses the solid.

We report on measurements designed to seek evidence for the dynamic interaction between plasma oscillations in a solid and the motions of swift ion clusters. This evidence is sought in deviations from the behavior expected for such clusters undergoing simple Coulomb explosions in solids. We have measured the distributions in angle and in energy of ions transmitted through thin solid targets bombarded by beams of molecular ions. At the energies used (0.15–2.0 MeV per nucleon) one expects the electrons binding a molecule to be torn off within the first one or two

atomic layers encountered[1] and that the molecular constituents will then continue as a cluster of bare nuclei which explode apart under the influence of their mutual Coulomb repulsion. Inside the target the Coulomb repulsion can be assumed to be exponentially screened with a screening distance $a = V/\omega_p$, where V is the beam velocity and ω_p is the volume plasma frequency of the target.[2] After emergence from the target there is no screening. If v is the final c.m. velocity attained by nuclei of mass M in a Coulomb explosion, then this simple picture predicts that downstream from the target such nuclei should be confined inside a cone of half-angle $\theta_{CE} \approx v/V$ centered on the beam direction and that in the beam direction itself these nuclei should occur in two equally populated groups (corresponding to forward and to backward c.m. motion) whose energies differ by $2E_{CE} \approx 2MvV$. For example, for protons produced from 4-MeV $(^4HeH)^+$ incident on a 535-Å-thick Au target ($\hbar\omega_p = 25.8$ eV[3]), $a = 3.2$ Å, $\theta_{CE} = 0.33°$, and $2E_{CE} = 19$ keV. In the time $(4.2\times10^{-15}$ sec) to traverse the target, the internuclear separation would be expected to increase from 0.8 Å to 3.3 Å. In practice, angular-distribution measurements are complicated by nuclear multiple scattering in the target. To avoid such effects, we have used monocrystalline Au targets bombarded under planar-channeling conditions and have measured the angular distributions in a plane parallel to the channeling planes of the target. Energy distributions at 0° (i.e., in the beam direction) were measured both by channeling in Au and by employing amorphous target foils of C, Al, and Al_2O_3. We used tightly collimated beams of H^+, H_2^+, H_3^+, $(^4HeH)^+$, D^+, D_2^+, D_3^+, and $(^3HeD)^+$.

Angular distributions were measured at Argonne with a resolution of 0.08° [full width at half-maximum (fwhm)]. The movable detector assembly contained an aperture behind which lay a scattering foil. A semiconductor counter detected particles that had passed through the aperture and that had been scattered by this foil. Most of the distributions were roughly Gaussian in shape. But for protons from $(^4HeH)^+$ and deuterons from $(^3HeD)^+$ characteristic hips were seen (Fig. 1). The corresponding ^4He and ^3He distributions were too narrow (compared with the resolution) to permit analysis. By magnetic deflection of the transmitted particles it was demonstrated that the protons and deuterons were essentially all singly charged.

A similar arrangement was used at Lyon to measure energy spectra at 0°. The acceptance angle was 0.12° (fwhm) and the energy resolution

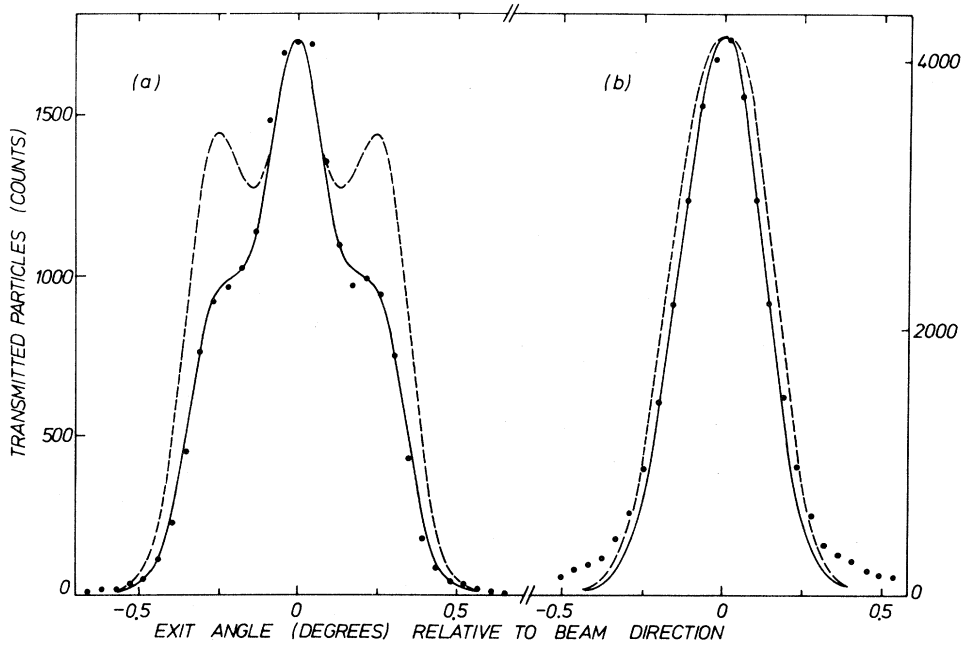

FIG. 1. Angular distributions for (a) protons from 4-MeV $(^4HeH)^+$ and (b) deuterons from 1.6-MeV D_2^+, measured under (111)-planar-channeling conditions with a 535-Å-thick Au crystal. The points are the experimental data. The curves are calculated with (solid lines) and without (dashed lines) the wake potential given in Eq. (1).

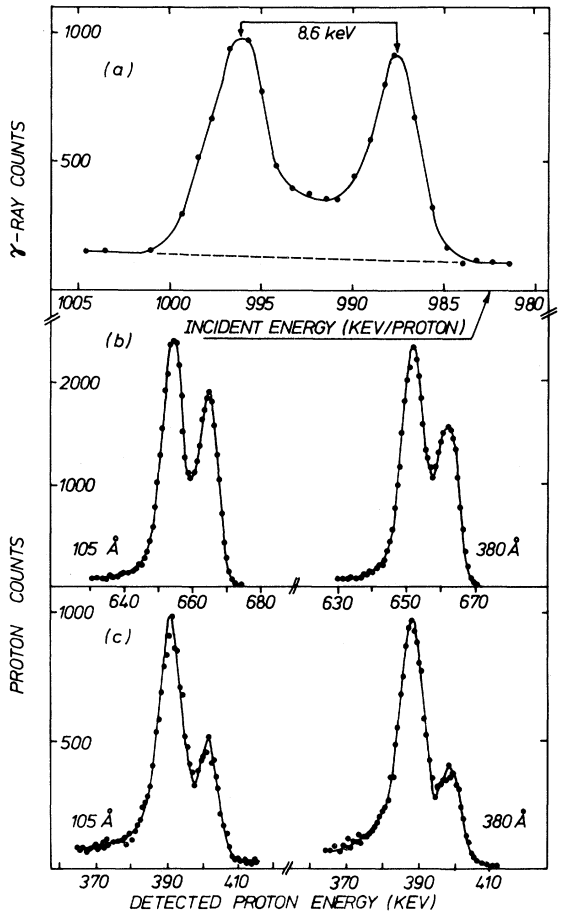

FIG. 2. (a) Yield curve for γ rays from the reaction $^{27}\mathrm{Al}(p,\gamma)$ induced by protons transmitted at 0° through a 100-Å-thick C foil bombarded with H_2^+. (b), (c) Proton energy spectra measured at 0° for protons transmitted through C foils with thicknesses of 105 and 380 Å, bombarded by 2-MeV beams of H_3^+ and $(^4\mathrm{HeH})^+$, respectively.

was 5 keV (fwhm). The scattering foil in the detection system consisted of 10 μg/cm^2 of C with 30 Å of Au evaporated on the front surface. The spectra exhibited two peaks as expected, but the low-energy peak was always more intense than the high-energy one and the separation was always somewhat less than $2E_{CE}$. These departures from the results expected from a simple screened-Coulomb explosion increased with foil thickness (Fig. 2). Almost identical results were obtained in Rehovot with a different technique. Here protons emerging from the target inside a cone of half-angle 0.09° centered on the beam direction were incident on thin secondary targets of either Al or CaF_2. The γ-ray yield from the reaction $^{27}\mathrm{Al}(p,\gamma)$ or $^{19}\mathrm{F}(p,\alpha\gamma)$ was measured as the bombarding energy was varied over a small range so as to excite a narrow nuclear resonance (Fig. 2). Both measurement techniques indicated that the detailed shapes of the energy spectra depended not only on the thickness but also on the composition of the target foil.

In Munich the channeling experiments were computer simulated by calculating, for several thousand randomly oriented incident molecules, the trajectories of the individual bare nuclei assumed created on entering the target. The initial internuclear separations were assumed to have a Gaussian distribution.[4] At first the particle motions were calculated with use of only a screened-Coulomb repulsion and a continuum channeling potential.[5] The influence of the target's stopping power on the trajectories is small and was neglected. Similarly, the small effects due to multiple scattering (almost entirely electronic) were not calculated microscopically but were taken into account (together with the angular resolution of the apparatus) by smearing the calculated angular distributions with Gaussians whose widths were those measured with monatomic beams. The widths of the angular distributions thus calculated were always too large and the shapes often differed markedly from the measured ones (see Fig. 1, dashed lines). We were unable to fit the experimental data by assuming larger initial internuclear separations or lower ionic charge states inside the solid.

Before smearing, the calculated angular distributions exhibited a central peak and two peaks located at $\pm\theta_{CE}$. Contributions to the central peak come mainly from incident molecules whose internuclear vectors lie close to the normal plane (i.e., a plane that is perpendicular to the channeling planes of the crystal and that contains the beam direction). The relative height of this central peak is increased when one introduces into the calculations an additional force corresponding to a wake potential assumed to trail behind each particle as it traverses the solid. Good fits (examples are shown by the solid curves in Fig. 1) to a wide range of data were obtained with a wake potential of the form

$$\phi(s,\rho) = -(2Ze/a)\sin(s/a)K_0(\rho/a)S(s), \qquad (1)$$

where Ze is the particle's charge, s and ρ are distances from the particle measured antiparallel to and perpendicular to the particle's velocity vector, respectively, K_0 denotes the zero-order modified Bessel function of the second kind, and

$S(s)$ is the unit step function. The wakes of leading particles in a cluster influence the motions of trailing particles so that the internuclear vectors tend towards alignment with the normal plane.

Equation (1) is identical with the (undamped) oscillatory part of the potential derived by Neufeld and Ritchie[6] in considering the passage of charged particles through a plasma. The wake potential results from electron-density oscillations generated by the projectiles. (It has recently been suggested[7] that charged particles could become trapped into bound states in such a wake potential.) The data on plasmon energies[3] and also the results presented here indicate that about eight electrons per Au atom contribute to the plasma oscillations. Channeling offers a unique opportunity for studying interactions with such a dense electron gas over usefully long interaction times without the disturbing influence of nuclear multiple scattering. Since in our experiments, the clusters remain compact during traversal of the target, our measurements do not test the detailed form of the oscillatory part of Eq. (1). However, the fits are quite sensitive to the value chosen for the plasma frequency and also to the functional form chosen for the radial part of Eq. (1). Because of the compactness of the clusters, plasmon damping (even at the fast rate known to exist for Au) does not play a role here.

The unequal populations of the peaks observed in the energy spectra may be qualitatively understood by noting that trailing particles in a cluster experience a force tending to align their velocities with the beam direction, whereas leading particles experience no such force. Consider, for example, those protons arising from the breakup of $(^4\mathrm{HeH})^+$ molecules whose initial internuclear vectors lie close to the beam direction. Protons emitted forwards at some small angle φ in the c.m. frame may miss a detector placed on the beam axis and having a restricted acceptance angle ($\sim \pm 0.06°$ in our experiments). Protons emitted backwards (initially at an angle $\pi - \varphi$ in the c.m. frame) would also miss the detector were it not for the force exerted by the wake of the α particle. This force reduces the angle between the proton velocity and the beam direction so that the proton may now strike the detector. A crude order-of-magnitude estimate of the extent to which the wake force can alter the laboratory angle for trailing particles emitted in the breakup of a diatomic cluster with nuclear charges Z_1e and Z_2e is given by

$$\Delta\theta = (Z_1 Z_2 e^2 d/a^2 E) \sin(\bar{s}/a) K_1(\bar{\rho}/a), \qquad (2)$$

where d is the target thickness, E is the laboratory kinetic energy of the trailing particle, K_1 denotes the first-order modified Bessel function of the second kind, and $\bar{s}$ and $\bar{\rho}$ are average separations between the two nuclei while inside the solid, measured parallel to and perpendicular to the beam direction, respectively. For a case like the one depicted in Fig. 2(c) [protons from 2-MeV $(^4\mathrm{HeH})^+$ incident on 380-Å-thick carbon, $\hbar\omega_p = 22$ eV, dwell time in the target $= 4.2 \times 10^{-15}$ sec], Eq. (2) yields $\Delta\theta \approx 0.3°$ if we take $\bar{s} = 1.7$ Å and $\bar{\rho} = 1.0$ Å (corresponding to a c.m. angle $\varphi \approx 30°$). By way of comparison, the laboratory angle expected for these protons in the absence of a wake force is $\theta \approx 0.25°$. The longer the dwell time in the target, the longer the wake force can operate and the greater will be the disparity in the peak intensities in the 0° energy spectra. This is in accord with our experimental results. Thus, for 2-MeV H_2^+ incident on C foils of 2, 10, and 14 μg/cm^2, we observe the high-energy proton peak to be less intense than the low-energy one by 7%, 15%, and 20%, respectively.[8] Similarly, as the bombarding energy is raised, the peaks become more nearly equally populated. Differences between energy spectra observed for various foil materials may reflect differences in the plasma frequencies involved. Calculations taking into account nuclear multiple scattering are currently in progress in an attempt to reduce the detailed shapes of the energy spectra.

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[1]From cross sections derived, for example, by N. Bohr, Kgl. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 18, No. 8 (1948), one can estimate that the mean free path for electron loss in the target is always less than 10 Å for the ions considered here.

[2]For a recent discussion, see W. Brandt, in *Atomic Collisions in Solids*, edited by S. Datz, B. R. Appleton, and C. D. Moak (Plenum, New York, 1975), p. 261.

[3]M. Glicksman, in *Solid State Physics*, edited by H. Ehrenreich, F. Seitz, and D. Turnbull (Academic,

New York, 1971), Vol. 26, p. 338.

[4]One expects the molecules to be incident on the target in various excited states primarily determined by conditions in the accelerator ion source. The average internuclear separation $\bar{r}_0$ will therefore differ slightly from the value for the molecular ground state. The curves shown in Fig. 1 were calculated with $\bar{r}_0 = 0.8$ and 1.1 Å and with Gaussian widths (fwhm) of 0.5 and 0.7 Å for $(^4HeH)^+$ and D_2^+, respectively. For further details, see the discussion by J. Remillieux, in Proceedings of the Fifth International Radiation Congress, Seattle, Washington, 1974 (to be published).

[5]W. M. Gibson and J. Golovchenko, Phys. Rev. Lett. 28, 1301 (1972).

[6]J. Neufeld and R. H. Ritchie, Phys. Rev. 98, 1632 (1955).

[7]V. N. Neelavathi, R. H. Ritchie, and W. Brandt, Phys. Rev. Lett. 33, 302 (1974).

[8]Similar measurements using 2-$\mu g/cm^2$ C foils have been reported by J. Golovchenko and E. Laegsgaard, Phys. Rev. A 9, 1215 (1974). Although these authors fit their energy spectra with a symmetric calculated curve, the data themselves display an asymmetry in agreement with that which we observe.

NMR in A-^{3}He and B-^{3}He: The Intrinsic Relaxation Mechanism

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A previously developed theory of NMR in superfluid ^{3}He is generalized to include relaxation effects. The physical mechanism envisaged is the relaxation of nonequilibrium Cooper-pair concentrations in the different spin bands. The results should describe both linear and nonlinear phenomena for all frequency regimes. The results for continuous-wave linewidths disagree with those of Combescot and Ebisawa as to temperature dependence.

If we assume, as is by now conventional, that the A phase of liquid ^{3}He is the ABM (Anderson-Brinkman-Morel) state[1] and the B phase the BW (Balian-Werthamer) state,[2] then most of the gross features of the dynamic nuclear magnetism in both phases[3] can be understood in terms of the equations derived previously[4] from a Born-Oppenheimer type of approximation. These equations are equations of motion for the total spin $\vec{S}$ and the vector $\vec{T}(\hat{n})$ [or $\vec{d}(\hat{n})$] which describes the amplitude and axis of spin quantization of the Cooper pairs at point $\hat{n}$ on the Fermi surface:

$$d\vec{S}/dt = \gamma \vec{S} \times \vec{\mathcal{H}}(t) + \vec{R}_D\{\vec{T}(\hat{n})\}, \tag{1}$$

$$d\vec{T}(\hat{n})/dt = \vec{T}(\hat{n}) \times \vec{H}. \tag{2}$$

Here $\vec{\mathcal{H}}(t)$ is the external magnetic field (including the radio-frequency field, if any) and $\vec{R}_D$ is the "dipole torque" and is a bilinear function of $\vec{T}(\hat{n})$ and $\vec{T}^\dagger(\hat{n})$ for whose specific form we refer to Ref. 4. $\vec{H}$ is defined as $-(\partial E/\partial \vec{S})$; in particular, in the case of longitudinal resonance, it is the difference of the up- and down-spin chemical potentials. To get a closed set of equations we need to supplement Eqs. (1) and (2) with an expression for $\vec{H}$ in terms of $\vec{S}$ and $\vec{\mathcal{H}}$. In the zeroth-order adiabatic approximation used in Ref. 4 the system is taken to be always in equilibrium for the given values of $\vec{S}$ and $\vec{T}(\hat{n})$; then (neglecting for the moment the question of "susceptibility anisotropy") the requisite relation is

$$\vec{H} = \gamma \vec{\mathcal{H}}(t) - \gamma^2 \chi^{-1} \vec{S}. \tag{3}$$

The theory based on Eqs. (1)–(3) seems to be reasonably successful in accounting for a variety of phenomena observed in the dynamic nuclear magnetism of the new phases.[3-6] However, it has the major defect that there is no point at which relaxation is introduced. Experimentally, on the other hand, very substantial effects of damping and relaxation are seen, although it is not always easy to disentangle intrinsic effects from those which may be due to inhomogeneity of sample orientation and/or rf field. A theory of the damping of the cw resonance has been given by Combescot and Ebisawa[7] on the basis of a kinetic-equation approach; however, the generalization to nonlinear phenomena, though possible,[8] is not trivial, and there may be, therefore, some value in an attempt to set up a more intuitive, less mathematically complex approach to the problem.

In this Letter we attempt to generalize Eq. (3)