broadening of the ensemble mentioned above. By comparison, the polarization theory[11] values for these mean intervals are 6.07 and 1.38 GHz, respectively. At fields around 40 G, magnetic mixing of F states of different J brings out weak 7^1D_2-$7F$ Zeeman transitions leading to the pure triplet zero-field states. However, no accurate data on these have been taken.

We have also seen resonances with unequivocal assignments in several other helium singlet and triplet states between $n=6$ and $n=11$. Precise results for these will be presented in future publications. It will be interesting to see both how low and how high in n the method will reach; in the former case the limitation is the high microwave frequency required, and in the latter it is the weakness of the signal and the effects of external perturbations.

It should be noted that we are by no means limited to helium, and that in fact other systems should require very little change in experimental technique. Thus, the microwave-optical resonance method appears to be widely applicable to the study of atomic and molecular Rydberg states.

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Comments on "Demonstration of Collisionless Interactions Between Interstreaming Ions in a Laser-Produced–Plasma Experiment"*

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It is shown that the results of a recent laser-produced–plasma interaction experiment by Dean *et al.* can be explained by collisional processes.

On the basis of the long mean free path of laser-produced ions in the background gas, Dean *et al.*[1] have concluded that a collisionless interaction occurs between the expanding laser plasma and the background ions. They apparently have failed to consider the fact that, in the region where their measurements were taken (distances less than 2 cm from the target), the laser-produced plasma density is high enough to collisionally snowplow up the background plasma. Indeed, Koopman[2] performed his measurements at radii greater than 10 cm to insure the collisionless nature of the laser-produced plasma.

To demonstrate that the data of Dean *et al.* can be explained by atomic collision processes, the mean free path for background ions in the laser-produced plasma is calculated at various stages in the expansion. The nitrogen atoms are assumed to be streaming into the laser-created plasma at a velocity of 2×10^7 cm/sec. The total scattering cross section can be estimated as follows: From the range-energy formulas verified by Cano and Dressel,[3] it is possible to define an effective collision cross section for atoms of mass M_1, atomic number Z_1, and velocity v incident on target atoms of mass M_2, atomic number Z_2, and density n:

$$\sigma_{\text{eff}}=\frac{2\pi a(M_1+M_2)Z_1Z_2e^2}{2.718M_1M_2v^2}+\frac{8\pi a(M_1+M_2)^2Z_1^{7/6}Z_2e^2}{M_1^2M_2(Z_1^{2/3}+Z_2^{2/3})vv_0},$$

where $v_0=e^2/\hbar$ is the Bohr velocity, and the Bohr radius with a shielding factor is given by

$$a=\frac{\hbar^2/e^2m_e}{(Z_1^{2/3}+Z_2^{2/3})^{1/2}}.$$

This cross section is the sum of the usual elastic scattering cross section and an inelastic term attributable to electronic excitation. From numerical comparisons it can be shown that, for a uniform density of scattering centers, the range of the incident particle is about two or three mean free paths as calculated from this effective collision cross section. From the above expression, the following cross sections are obtained:

$$\sigma_{\text{O}}=1.86\times10^{-17}\ \text{cm}^2\ (\text{N}\rightarrow\text{O}),$$

$$\sigma_{\text{H}}=1.94\times10^{-17}\ \text{cm}^2\ (\text{N}\rightarrow\text{H}),$$

$$\sigma_{\text{C}}=1.43\times10^{-17}\ \text{cm}^2\ (\text{N}\rightarrow\text{C}).$$

There appear to be few data available for total scattering cross sections for the species and velocities found in this experiment. However, from comparison with data for helium in the right velocity range[4] and argon in the right energy range[5] (2–3 keV), it appears that the total scattering cross section may be at least an order of magnitude larger than given by the values calculated above. These cross sections will tend to give upper bounds on the calculated mean free paths. The cross sections for charge exchange are large, but this merely results in the rearrangement of charge states and has little effect on momentum transfer.

The density of the laser-produced plasma is obtained through two simplifying assumptions: The $C_5H_8O_2$ target is assumed to be a sphere of 0.25 mm diam, and the plasma density is assumed to be uniform inside the leading edge of the laser-produced plasma. The latter assumption is a generous one, since the sweeping up of background ions produces a shell of greater than average density at the edge of the laser-produced plasma for expansion radii greater than a few millimeters. There can be no doubt that this enhanced-density shell exists, since it is identified in the shadowgraph of Ref. 1. This shell will produce momentum coupling for times longer than calculated by the simple model used here.

With the particle size and composition specified, it is easy to determine that there are approximately 3×10^{17} carbon atoms, 4.7×10^{17} hydrogen atoms, and 1.2×10^{17} oxygen atoms in the pellet. Number densities of the various species in the laser-produced plasma at a given expansion radius are given by

$$n^{(s)}=3N_s/4\pi r^3=n_0^{(s)}(R_0/r)^3,$$

where N_s is the number of atoms of species s in the pellet radius, and $n_0^{(s)}$ is the initial density of the species s:

$$n_0^{(\text{C})}=\tfrac{1}{3}n_0,\quad n_0^{(\text{O})}=\tfrac{2}{15}n_0,\quad n_0^{(\text{H})}=\tfrac{8}{15}n_0,$$

$$n_0=1.1\times10^{23}\ \text{cm}^{-3}.$$

The effective mean free path of a nitrogen atom in the laser-produced plasma is given by

$$\lambda_{\text{N}}^{-1}=\lambda_{\text{NO}}^{-1}+\lambda_{\text{NH}}^{-1}+\lambda_{\text{NC}}^{-1}=(R_0/r)^3[\tfrac{8}{15}\sigma_{\text{H}}+\tfrac{2}{15}\sigma_{\text{O}}+\tfrac{1}{3}\sigma_{\text{C}}]n_0.$$

Substituting numerical values into this expression gives

$$\lambda_{\text{N}}=0.52(r/1.25)^3\ \text{cm}$$

for r in centimeters. Therefore, at an expansion radius of 1 cm (approximately that in the shadowgraph[1]), the upper bound on the collision mean free path as calculated by this simple model is 2.7 mm. Since the collision cross section used appears to be a strong underestimate and the enhanced density shell is not accounted for in this calculation, it appears that the results of Dean *et al.* can be explained by collisional coupling alone. Thus it is not surprising that their results are consistent with classical radiation-driven detonation and blast-wave models.

An alternative method of estimating the mass of the laser-produced plasma is to fit a blast-wave model to Fig. 1 of Ref. 1. This results in a mean free path $\lambda \sim 3r$ which falls in the region between clearly collisionless and collision dominated. Since the laser energy was only 8 J in this case, the calculation serves to show the trend toward a collisionless regime when smaller targets and laser energies produce less plasma.

It should also be noted that under somewhat similar experimental conditions, Paul *et al.*[6] have not observed any momentum coupling between the laser-produced and background plasma. Their laser energy and target size are both smaller than in the work of Dean *et al.*, and a calculation for the experiment of Paul *et al.* gives a mean free path of background ions in the laser-produced plasma which is greater than the expansion radius r of the plasma for $r > 4$ mm. Therefore, it is possible to surmise that the different results in the two experiments arise from the fact that the work of Dean *et al.* is collision dominated, while that of Paul *et al.* is collisionless.

In conclusion, it appears that the results of Dean *et al.* can be explained by collisional processes, and that more convincing data must be presented if a collisionless interaction is to be believed. Moreover, the argument that observed interaction distances are apparently less than a mean free path (which is not true in this experiment) was shown to be insufficient by Grad[7] when he demonstrated that a classical, collision-dominated, steady-shock profile can be thin compared to the mean free path, and can also be oscillatory.

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Cross-Field Ion-Acoustic Instability Observed in a Turbulent-Heating Experiment*

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A high-frequency ($\omega_{ci} \ll \omega \simeq \omega_{pi}$) electrostatic instability observed in a toroidal turbulent-heating device has been interpreted in terms of ion-acoustic waves excited by a radial, electron temperature gradient across a toroidal magnetic field. The waves have been found to propagate across the field, in the direction opposite to the electron diamagnetic velocity. Observed anomalous electron thermal transport has been explained by the instability.

It is known that high-frequency ($\omega \gg \omega_{ci}$) ion-acoustic waves can propagate in a hot electron ($T_e \gg T_i$) plasma at almost any angle with respect to an external magnetic field.[1,2] Electric currents, either parallel or perpendicular to the magnetic field, can make the waves unstable if they are above some critical value.[3] In general, the critical drift velocity for the onset of the instability is on the order of the ion-acoustic speed when the drift velocity is in the direction of propagation of the ion-acoustic wave.

In the present Letter, we report an experimental observation of ion-acoustic instability in a toroidal, turbulent-heating machine, a schematic diagram of which is shown in Fig. 1(a). An electric field ($E \lesssim 40$ V/cm) is inductively applied to a preionized argon plasma ($n \lesssim 10^{12}$ cm^{-3}) along the quasistationary toroidal magnetic field ($B \lesssim 2$ kG). In Fig. 1(b) measured plasma parameters are shown as functions of time. Our inves-