laser shots. In view of previously mentioned uncertainties in equipment performance, this is in good agreement with the 15 counts theoretically predicted.

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QUALITATIVE EXPLANATION OF PELLAM'S HELIUM PARADOX

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The temperature dependence of the torque on a Rayleigh disk immersed in rotating helium is explained qualitatively on the basis of superfluid dynamics. A heat-exchange torque peculiar to two-fluid mechanics arises due to the disk being bathed in ambient room-temperature radiation.

In the present note it will be shown that the apparently paradoxical results obtained for the torque on a Rayleigh disk immersed in rotating helium by Pellam[1] are explainable on the basis of heat torques due to ambient room-temperature radiation.

Using Landau's equations of superfluid dynamics,[2] the torque on the Rayleigh disk is given by

$$\vec{\tau} = \int \vec{r} \times (\overleftrightarrow{\pi} \cdot d\vec{S}), \tag{1}$$

where the integral is taken over the surface of the disk. $\vec{r}$ is the position vector of the surface element $d\vec{S}$ and $\overleftrightarrow{\pi}$ is the momentum-flux-density tensor given by

$$\overleftrightarrow{\pi} = \rho_n \vec{v}_n \vec{v}_n + \rho_s \vec{v}_s \vec{v}_s + p \overleftrightarrow{1}. \tag{2}$$

The torque is quite difficult to calculate in detail, but it is possible to examine the contributions to it due to two separate effects. To do so, we must realize the appropriate boundary conditions for the flow. In the first place, we assume that at the surface of the disk the normal fluid behaves as a viscous fluid, whence the parallel component of $\vec{v}_n$ vanishes.

The condition on the mass current density at the disk is taken to be

$$\vec{J}\cdot d\vec{S}=0=(\rho_n\vec{v}_n+\rho_s\vec{v}_s)\cdot d\vec{S}, \tag{3}$$

as usual.

Next, we suppose that the disk is a heat source and thereby realize that the energy-flux density must match the heat-flow input at the disk. In terms of the energy-flux density $\vec{Q}$,

$$\vec{Q}=(\mu+\tfrac{1}{2}v_s^2)\vec{J}+\rho sT\vec{v}_n+\rho_n\vec{v}_n[\vec{v}_n\cdot(\vec{v}_n-\vec{v}_s)], \tag{4}$$

we must have that

$$\vec{Q}\cdot d\vec{S}=\kappa dS, \tag{5}$$

where κ is the heat flow from the disk.

The torque is now given by

$$\vec{\tau}=\int\vec{r}\times\left[p\overleftrightarrow{1}\cdot d\vec{S}+\frac{\rho_n\kappa(\vec{v}_n-\vec{v}_s)dS}{\rho sT+\rho_n\vec{v}_n\cdot(\vec{v}_n-\vec{v}_s)}\right], \tag{6}$$

where the first term is the Bernoulli term which gives the usual torque expression first calculated by König.[3] It is important to realize that this Bernoulli term is relatively insensitive to the details of the flow simply because it is a pressure term. That is, in calculating the Bernoulli term one need not worry about the full Navier-Stokes equation for the helium, but may assume potential flow of a nonviscous fluid for both normal and superfluids. The resulting flow pattern would be in error only very close to the surface of the disk.

The other term in the torque expression is peculiar to superfluid dynamics and is a heat-exchange torque. It is the contention of the present author that the heat absorption of the Rayleigh disk from the surrounding room radiation, and consequent heat exchange with the superfluid, is responsible for the results of Pellam. To calculate the heat torque in detail is, in principle, exceedingly difficult, but is not difficult to see that the heat torque is capable of explaining Pellam's results.

First of all, it is obvious that the phenomenon which leads to the heat torque is peculiar to the two-fluid models and is therefore discontinuous at T_λ.

Next, let us examine some of the behavior of the heat torque. Suppose the helium is just below the λ point. Then, since ρ_s is very small, $\vec{v}_n$ nearly vanishes on the disk. In that case, we can neglect the quadratic term in the denominator of the integrand, and obtain approximately

$$\vec{\tau}_{\text{heat}}(T\cong T_\lambda)=-\int\vec{r}\times(\rho_n\kappa\vec{v}_s/\rho sT_\lambda)dS. \tag{7}$$

Now $|v_s|$ will certainly be of the order of the asymptotic velocity[1] v_0 of the flow, in terms of which the pressure is of the order of $\frac{1}{2}\rho v_0^2$. Thus the Bernoulli term and the heat-torque term will be of the same order of magnitude if

$$\rho_n\kappa v_0/\rho sT_\lambda\sim\tfrac{1}{2}\rho v_0^2 \tag{8}$$

which requires κ, the heat supplied to the disk from ambient radiation, to be of the order of 0.1 W/cm² for Pellam's experiment. In fact, a simple-minded estimate of the power given to the disk by room radiation gives

$$\kappa=\sigma T_0^4\cong0.05\ \text{W/cm}^{-2} \tag{9}$$

which lends credence to the possibility that the heat torque is comparable with the Bernoulli torque near T_λ.

The behavior of the heat torque near $T=0$ is easily assessed by realizing that the boundary condition of $\vec{J}$ gives

$$v_n=-\rho_s/\rho_nv_s \tag{10}$$

for the normal component, while the parallel v_n component remains zero. The heat torque is then of the order of magnitude

$$\vec{\tau}_{\text{heat}}(T=0)=-\int\frac{\vec{r}\times(\rho_s\kappa\vec{v}_s)dS}{\rho sT+\rho_nv_n^2}$$
$$=-\int\frac{\vec{r}\times(\rho_n\rho_s\kappa\vec{v}_s)}{\rho\rho_nsT+\rho_s^2v_s^2}dS, \tag{11}$$

which vanishes as ρ_n as T approaches absolute zero.

Lastly, we need remark that the heat torque is directed opposite to the Bernoulli torque. To see this without too much detail, recall that the Bernoulli torque is such as to turn the disk perpendicular to the flow. Indeed, the angular dependence of the Bernoulli torque can easily be seen to be proportional to $\sin2\theta$, where θ is the angle of attack. That result follows simply by realizing, on the basis of symmetry, that the equilibrium position must be either parallel or perpendicular to the flow. The same considerations dictate that the angular dependence of the heat torque should be proportional to either $\sin2\theta$ or $\cos2\theta$. One needs merely to examine the two equilibrium possibilities to decide which is stable. The heat torque tends to turn the disk to be parallel to the flow, hence opposing the Bernoulli torque.

To see the truth of the last statement, look at the torque expression near T_λ whence the element of torque goes like $-\vec{r}\times\vec{v}_s$. If we imagine the disk parallel to the flow, then turn the disk slightly, the velocity of the flow will be greater at the "top" of the leading edge than at the "bottom," as with an airfoil. The torque will therefore tend to decrease the angle of attack.

In conclusion, we have shown that for superfluid dynamics there exists a heat-exchange torque which is of sufficient magnitude to counter the Bernoulli torque at T_λ. Indeed, it would seem extremely fortuitous that the heat supplied to the disk by ambient room temperature radiation be very close to the value necessary to compensate for the Bernoulli torque at T_λ. Nonetheless, the existence of such a heat-exchange torque seems indisputable, and there seems little doubt, in spite of a lack of detailed hydrodynamics, that the heat torque exhibits the required temperature dependence to account for the "paradoxical" results of Pellam.

The present analysis is consistent with the results of Pellam and probably also with the results of Tsakadze and Shanshiashvili,[4] who performed a variation of the experiment with two disks. In the Tsakadze-Shanshiashvili experiment, the torque on the disk was independent of T when the disk immersed in the liquid helium was not illuminated, but the torque exhibited the same behavior as in Pellam's experiment when the disk in the liquid helium was illuminated. The duplication of the Pellam results needs no explanation, but it is necessary to assume that when Tsakadze and Shanshiashvili used the upper disk to measure the deflections, they deliberately or inadvertently masked the immersed disk from the ambient room radiation. It is difficult to judge whether this was the case.

One obvious way to check the present theory would be to change the emissivity of the disk material or the ambient temperature. Such a change should vary the amount by which the torque decreases at T_λ. Some further consequences of the existence of such a heat torque will be reported later.

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EXTREME-ULTRAVIOLET CONTINUUM ABSORPTION BY A LASER-GENERATED ALUMINUM PLASMA

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A strong absorption of extreme uv radiation by a laser-generated ionized metallic plasma has been observed. A discussion is made about the mechanisms likely to be responsible for this absorption. Attention is paid to photoionization and, overall, to the inverse bremsstrahlung process.

We describe here an experiment in which the absorption of extreme-uv radiation by an ionized metallic plasma has been observed. The uv source and the absorbing plasma are constituted by two plasma bursts produced by the focusing of two Nd laser beams (CGE type VD 160 laser) on the surface of aluminum rods. Up to now, the study of such plasmas has been achieved only by emission spectroscopy.[1-4]

The experimental design is shown in Fig. 1. A target I is placed at a fixed distance from the entrance axis of an extreme-uv spectrograph. This distance, about 0.5 mm, is chosen to obtain maximum illumination of the spectrograph by the continuous radiation emitted by the plasma formed near the target.[1] Between target I and the spectrograph entrance slit, another target II is found whose distance from the spectrograph entrance axis can be varied. The plasma II forms the "sample" to be studied with the target-I plasma radiation. As shown in the figure, the spectrograph slits delimit the observed "sample" zone. It is therefore possible to explore the different plasma regions by the way they absorb the target-I radiation. Furthermore, time exploration can be obtained by using optical delay variations in