Polarization of the Free-Free Bremsstrahlung in an Anisotropic Hot-Electron Plasma*

D. G. S. Greene, J. L. Shohet, and P. A. Raimbault
The University of Wisconsin, Madison, Wisconsin 53706
(Received 3 May 1971)

The polarization of the free-free bremsstrahlung emitted radially for an anisotropic hot-electron plasma in a magnetic mirror has been measured by means of Compton scattering. The degree of polarization was found to be exceptionally sensitive to changes in system parameters. A quantum-mechanical nonrelativistic theory has been found to agree well with the experimental results.

The intensity of the free-free bremsstrahlung in a hot-electron plasma produced in a magnetic field has previously been found to be anisotropic.[1,2] This measurement reflected the general anisotropy of the velocity distribution of the electrons in the plasma. However, the need for various geometrical and alignment corrections to the measurement of the intensity parallel and perpendicular to the field lines made the technique quite insensitive to significant variations in the plasma or machine parameters, such as impurity concentrations, mirror ratio, etc.

We present here a technique that circumvents many of the problems encountered with the previous method. The anisotropy of the electron velocity distribution can be effectively measured, at one location, by determining the degree of polarization of the free-free x-ray bremsstrahlung flux emitted in a direction perpendicular to the dc magnetic field lines.

Figure 1 shows a diagram of the experimental apparatus. The plasma is produced in helium gas at a pressure of 7×10^{-4} Torr in a magnetic mirror by means of electron cyclotron resonance heating from a 100-kW pulsed microwave source (360 2-μsec pulses per second). The bremsstrahlung is observed through a collimator window at the end of a long vacuum path. This permits removal of the effects of the walls and significant absorption by the air. The x rays are in the 5-50-keV regime.[3,4] Hence, the most efficient Compton scattering occurs in those materials that have a low Z.[5] The scatterer used here is a block of pure beryllium metal. The NaI scintilla-

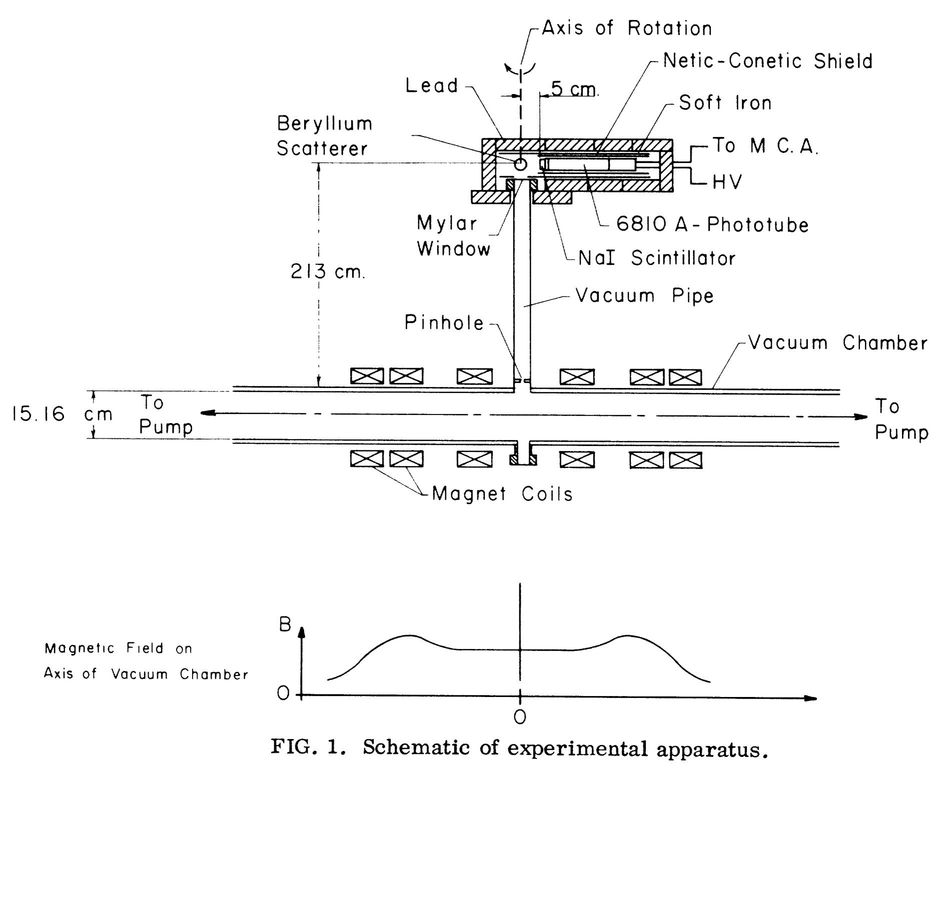

FIG. 1. Schematic of experimental apparatus.

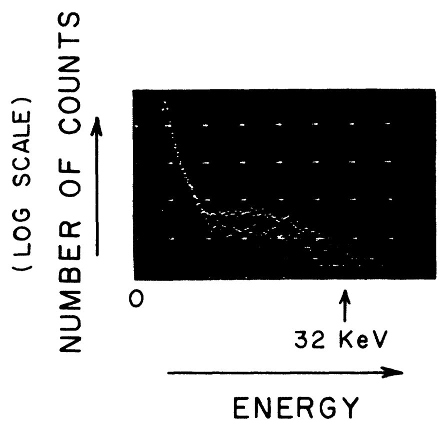

FIG. 2. Overlapping display of scattered flux. The upper trace is produced by those photons whose electric vectors are perpendicular to the magnetic field lines; the lower, parallel.

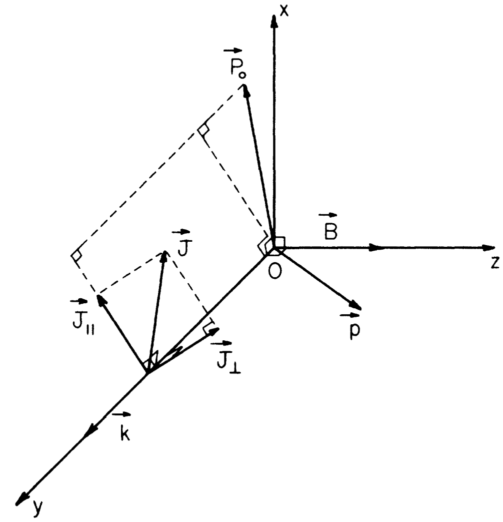

FIG. 3. Coordinate representation.

tor-photomultiplier detector can be oriented so as to measure the polarization of the bremsstrahlung parallel to or perpendicular to the field lines. The orientation shown in Fig. 1 measures the flux polarized perpendicular to B. The scintillator-photomultiplier assembly is turned 90° about the axis of rotation shown in the figure so that it can measure the flux polarized parallel to the field.

Figure 2 shows the results for 100-min counts of the scattered flux measuring the polarization in both the parallel and perpendicular directions, respectively. Since the x rays appeared only within the first 500 μsec after each heating pulse, the system was gated on only during that time to improve its noise characteristics. The detection device was shielded from the magnetic field and produced identical spectra in the two orientations when an unpolarized radioactive source was used for calibration. From Fig. 2 it can be seen that there is a greater flux of photons whose electric vectors are perpendicular to the magnetic field lines. The anisotropy in the fluxes is about 4 to 1, yielding a polarization of 0.6.

The degree of polarization is a function of impurity-gas pressure. The normal base pressure of the system is about 5×10^{-7} Torr. When the pumping rate was deliberately slowed down to produce a base pressure of 3×10^{-6} Torr which increased the impurity concentration, the polarization at the same *operating* pressure was decreased to about 0.3 along with a fourfold decrease in total flux because of the resultant increase in collision cross section. The shape of the profiles remained the same, however.

The degree of polarization was also found to be a function of the mirror ratio. The original mirror ratio was 1.19 to 1. When the ratio was *decreased* to 1.02 to 1, the degree of polarization *increased* and the absolute flux decreased as to be expected since the confinement time is lowered with the smaller value of mirror ratio.

To examine the validity of these results, we consider the quantum-mechanical nonrelativistic theory of free-free bremsstrahlung polarization[6,7] from a particle with momentum $\vec{p}_0$ deflected by a fixed scattering center. Figure 3 is a coordinate representation used to describe the problem. Its origin is at the scattering center. The magnetic field is in the z direction; and $\vec{k}$, the propagation vector of the photon in the direction of observation, is in the y direction. $\vec{p}_0$ is the momentum vector of the electron before the collision, and $\vec{p}$ is its momentum after the collision. The polarization vector $\vec{J}$ (parallel to the photon's electric field) is always perpendicular to $\vec{k}$. Thus, for the directions shown, the polarization vector is in the x-z plane.

The degree of polarization, A, is given by[6]

$$A=\frac{J_\parallel-J_\perp}{J_\parallel+J_\perp}=\left[(1-3D^2)\ln\left(\frac{1+D}{1-D}\right)+6D\right]\times\left[(3-D^2)\ln\left(\frac{1+D}{1-D}\right)+2D\right]^{-1}, \quad (1)$$

where $|p|/|p_0|=D$. The subscripts $\parallel$ and $\perp$ refer to directions parallel and perpendicular to the plane of the incident momentum vector $\vec{p}_0$ and $\vec{k}$ (not to the direction of the magnetic field lines). A graph of this function is shown in Fig. 4 as a

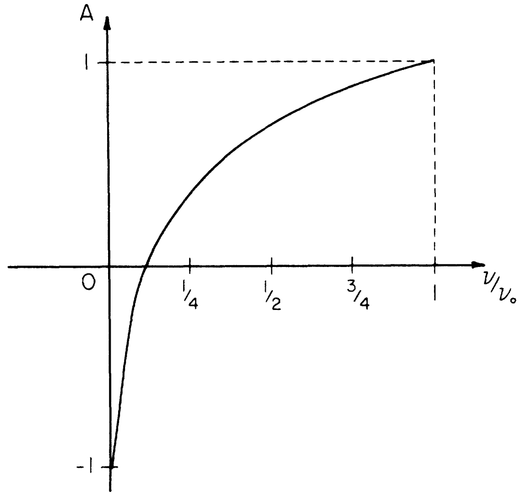

FIG. 4. The degree of polarization as a function of v/v_0.

function of ν/ν_0, where ν is the photon frequency and ν_0 is the highest photon frequency obtainable from an electron of momentum p_0. The conditions under which the x rays are emitted in this system correspond to this high-frequency limit (that is, the photon energy is comparable to the electron energy[4]). The degree of polarization should approach the value 1. Thus, in the y direction more photons are emitted with polarization in the x direction if the electron is incident in the x direction.

For a plasma whose electron velocity distribution is anisotropic so that most of the electrons are in the x-y plane, we conclude that $\vec{J}$ tends to be in the direction perpendicular to the magnetic field lines. Electron cyclotron resonance heating does produce anisotropic velocity distributions of this type,[1,2] and the results are in excellent agreement with both theory and experiment. Integration over the velocity distribution can be performed, but it will not change the basic results.

The authors would like to express their thanks to A. C. England for his advice and continued encouragement.

*Work supported by the U. S. Atomic Energy Commission.

[1]M. C. Becker, R. A. Dandl, H. O. Eason, A. C. England, R. J. Kerr, and W. B. Ard, Nucl. Fusion Suppl. P. 1, 345 (1962).

[2]J. L. Shohet and S. J. Gitomer, Phys. Fluids 10, 1359 (1967).

[3]S. J. Gitomer and J. L. Shohet, Phys. Fluids 13, 413 (1970).

[4]J. L. Shohet, Phys. Fluids 11, 1065 (1968).

[5]R. D. Evans, *The Atomic Nucleus* (McGraw-Hill, New York, 1955), Chap. 23.

[6]H. A. Bethe and E. E. Salpeter, in *Handbuch der Physik*, edited by S. Flügge (Springer, Berlin, 1957), Vol. 35, p. 409.

[7]A. Sommerfeld, Atombau und Spektrallinen (Viewig, Braunschweig, Germany, 1931), Vol. 2.

New Theoretical Interpretation of the Kapitza Resistance of a Nonmagnetic Liquid-He^3-Solid Interface

M. J. Rice*
General Electric Corporate Research and Development, Schenectady, New York 12301
(Received 11 May 1971)

In contrast to the acoustic mismatch theory of Bekarevich and Khalatnikov, it is suggested that the origin of the ultralow-temperature Kapitza resistance of a nonmagnetic liquid-He^3–solid interface is the inelastic scattering of *single-quasiparticle excitations* from the surface atoms of the solid boundary.

The currently accepted theoretical interpretation of the ultralow-temperature Kapitza resistance[1] of a nonmagnetic liquid-He^3–solid interface is based on the original work of Bekarevich and Khalatnikov.[2] These authors considered sound energy from the solid to be transferred at the interface to the collective zero-sound[3] modes of the Fermi liquid. Although the theoretical formula for the Kapitza resistance based on this acoustic mismatch theory correctly predicts the observed[4] limiting low-temperature dependence, $R \propto T^{-3}$, it seriously fails[4,5,1] to predict the correct order of magnitude of R and the observed dependence[4] of R on liquid-He^3 density.

It is the purpose of the present note to suggest a new theoretical interpretation of the nonmag-

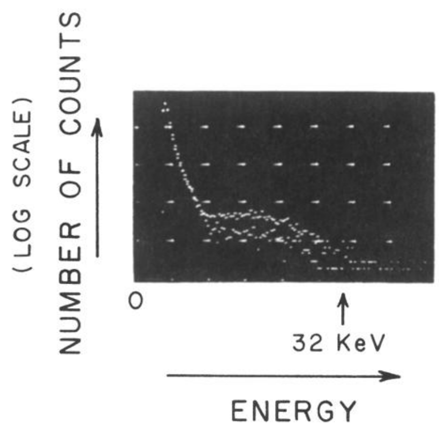

FIG. 2. Overlapping display of scattered flux. The upper trace is produced by those photons whose electric vectors are perpendicular to the magnetic field lines; the lower, parallel.