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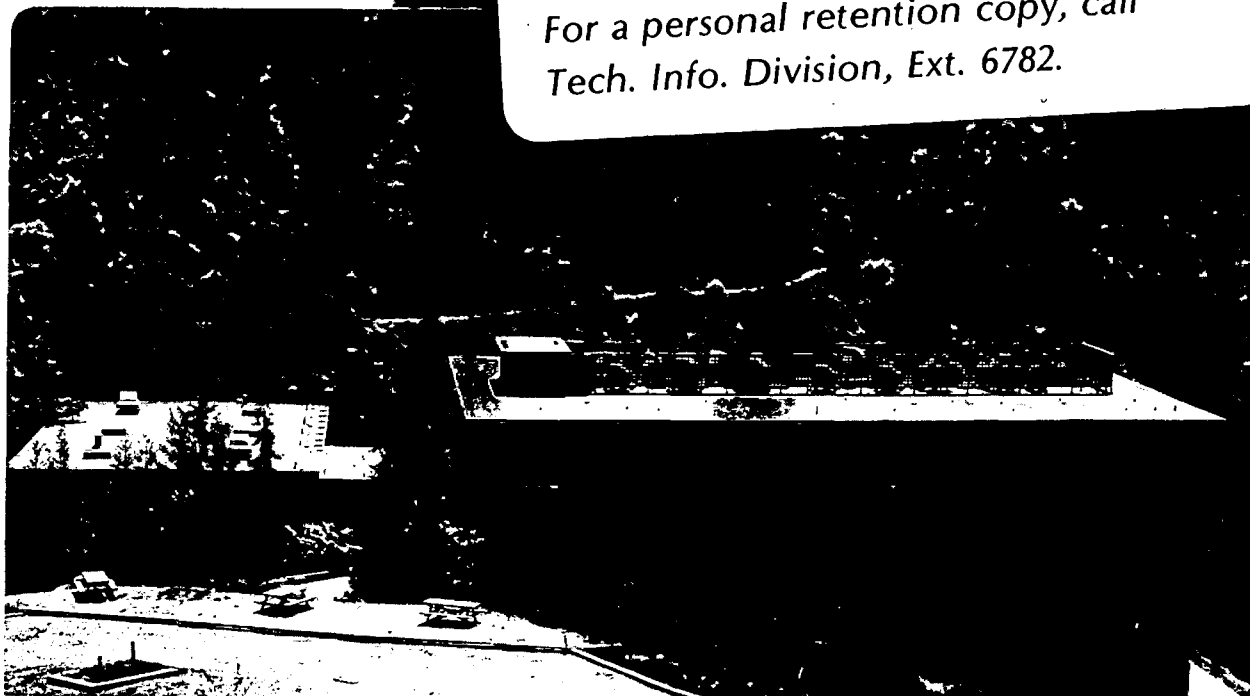
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DISCLAIMER

DENSITY DEPENDENCE OF AN ELECTRON-HOLE LIQUID

CORRELATION FACTOR IN Ge: EXPERIMENT*

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Density Dependence of an Electron-Hole Liquid Correlation Factor in Ge: Experiment

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We report the first absolute measurement of the density

dependence of the enhancement factor $g_{eh}(0)$ for the electron-

hole liquid (EHL) in Ge. This factor $g_{eh}(0)$ is a measure of

the electron-hole spatial correlation function, and provides

a valuable and sensitive test for the predictions of various

many-body approximations. A strain confined EHL-free exciton

system is used. Our data agree quantitatively with the

results of two different many-body theory approximations.

A uniquely useful physical system for testing the results of many-

body theory approximation schemes is the electron-hole liquid (EHL).

The EHL is a two-component (electron-hole) Fermi liquid existing in

optically excited semiconductors at liquid helium temperatures. Other

Fermi liquids such as neutron stars, nuclear matter, and electrons in

metals have various disadvantages when used to test many-body theory approximations: the experimenter cannot alter parameters; the number of constituent particles is small; many-body effects are small corrections; or the system's characteristics are not known accurately for the purpose of theoretical calculation. We measure the enhancement factor $g_{eh}(0)$ which is the electron-hole (e-h) spatial correlation function evaluated at zero e-h separation and normalized to the average plasma density. This measurement of the correlation function provides a sensitive and valuable test for the predictions of many-body approximation schemes. Several calculations[1-3] for the EHL have yielded varying predictions for the density dependence of $g_{eh}(0)$ while still being in reasonable agreement with experiment for EHL densities and ground state energies.

In this experiment we determine the enhancement factor of the EHL as a function of EHL density n_ℓ. A free exciton (FE) gas and at most one EHL droplet are confined to a strain induced potential well[4,5] at temperature T = 2.16K in an ultrapure Ge crystal. The EHL density is varied by stressing the crystal. The only prior experiment dealing with the density dependence of $g_{eh}(0)$ in stressed Ge is due to Chou and Wong.[6] To "estimate semiquantitatively"[6] the density dependence of a quantity proportional $g_{eh}(0)$, they assumed a model for EHL decay dependent only on EHL density n_ℓ. Work exists supporting other models.[7] At a stress and density at which they measure an EHL lifetime $\tau_\ell \simeq 0.5$ ms we measure $\tau_\ell \simeq 0.75$ ms. This runs counter to the expectations of their model.

Our method of determining $g_{eh}(0)$ has the advantage of being independent of EHL recombination models. The enhancement factor is related to the probability of an electron being at the site of a hole and thus to the

radiative decay rate. From a treatment[8] of the LA phonon assisted FE and EHL recombination rates we have

$$g_{eh}(0) = \frac{\tau_{rx}}{\tau_{r\ell}} \frac{|\psi_x(0)|^2}{n_\ell} \qquad (1)$$

where τ_{rx} and $\tau_{r\ell}$ are the LA phonon assisted FE and EHL radiative lifetimes, $\psi_x(0)$ is the FE wave function evaluated at zero e-h separation, and n_ℓ is the EHL density. Radiative lifetimes are difficult to measure so we introduce the FE and EHL radiative efficiencies $\varepsilon_{rx} = \tau_x/\tau_{rx}$ and $\varepsilon_{r\ell} = \tau_\ell/\tau_{r\ell}$ into Eq. (1):

$$g_{eh}(0) = \left(\frac{\varepsilon_{r\ell}}{\varepsilon_{rx}}\right) \frac{\tau_x}{\tau_\ell} \frac{|\psi_x(0)|^2}{n_\ell} \qquad (2)$$

All terms on the right-hand side of this equation are accessible to experiment. We obtain $|\psi_x(0)|^2$ at each stress by measuring the FE binding energy E_x and making use of the simple effective mass theory result, using s-wave wave functions, that $|\psi_x(0)|^2 = \frac{1}{\pi a_x^3}$ where $a_x = \frac{e^2}{2E_x \varepsilon}$. Here $\varepsilon = 15.36$ is the dielectric constant and a_x is the FE Bohr radius. The effective mass approximation should be valid for the Mott-Wannier exciton in Ge. The measured shift in the FE luminescence with stress is used to determine E_x in a manner similar to that used by Feldman, Chou, and Wong.[9] The lifetimes τ_x and τ_ℓ are measured from luminescence decay (see Fig. 1), the EHL density n_ℓ from luminescence lineshape fits,[10] and the ratio of radiative efficiencies from the experiment described below.

We perform a steady state experiment measuring the combined FE and EHL luminescence intensity, I_x plus I_ℓ, as a function of e-h pair generation rate G (see Fig. 2). Below the EHL threshold the number of free excitons N_x is determined by the steady state equation $G = N_x/\tau_x$. The

measured FE luminescence intensity is related to N_x by $I_x = (N_x/\tau_{rx})\epsilon_{cx}$ where the FE collection efficiency ϵ_{cx} is the ratio of the luminescence detected to that emitted. An EHL collection efficiency $\epsilon_{c\ell}$ is similarly defined. Combining equations, the slope dI/dG below EHL threshold is $\epsilon_{rx}\epsilon_{cx}$. <u>Above the EHL threshold</u> both FE and EHL exist, and the number of e-h pairs N_x in FE and N_ℓ in the EHL are related to the generation rate G by the steady state equation $G = N_x/\tau_x + N_\ell/\tau_\ell$. In a manner similar to the FE case, $I_\ell = (N_\ell/\tau_{r\ell})\epsilon_{c\ell}$. Combining equations and using the experimental observation (see Figs. 1 and 2) that $N_x \approx$ constant just above the EHL threshold, we find the slope dI/dG just above threshold is $\epsilon_{r\ell}\epsilon_{c\ell}$. Taking the ratio of the slope just above to that just below threshold we have

$$\frac{(dI/dG)_{above}}{(dI/dG)_{below}} = \left(\frac{\epsilon_{r\ell}}{\epsilon_{rx}}\right)\left(\frac{\epsilon_{c\ell}}{\epsilon_{cx}}\right) \tag{3}$$

An optical hysteresis in EHL droplet formation which would complicate the above discussion has not been observed for the strain confined FE-EHL system we use. Upon separately measuring the ratio of the FE and EHL collection efficiencies, we obtain the desired ratio of radiative efficiencies. A pumping efficiency relating excitation power to e-h pair generation rate G has been found to be constant over the range of excitation powers used and is thus neglected in the above discussion.

An assumption inherent in the use of both steady state and decay measurements for the terms in Eq. (2) is the existence of a thermodynamic quasi-equilibrium (i.e. thermal and spatial) within the FE-EHL system. To compare steady state and decay measurements, these measurements must be made on the same physical system. To ensure quasi-equilibrium three

criteria must be satisfied: (a) The e-h pairs in the EHL must be in thermodynamic equilibrium. (b) The FE gas must be in thermodynamic equilibrium with itself. (c) The FE gas must be in thermodynamic equilibrium with the EHL droplet. If any of these conditions is not met, then equilibrium thermodynamics is not appropriate, and a more general transport picture must be considered.

Given a carrier-phonon scattering time $\tau_p \sim 1$ ns the FE-EHL system is well characterized by the lattice temperature for the low excitation powers (μW) and long time scales (ms) of this experiment. The parameters characterizing the speed of response of the EHL to perturbations which are the plasma frequency, and the inter- and intra-band relaxation times[11] all correspond to time scales shorter than 1 ps. This assures that the electrons and holes in the EHL are to a good approximation in quasi-equilibrium for the time scales of this experiment. For the FE gas to be in spatial equilibrium with itself, the FE diffusion length $L_x = \sqrt{D_x \tau_x}$ must be large compared to the spatial extent of the FE gas. If we approximate the bottom of the strain induced potential well with a parabola $U = \alpha r^2$, the spatial extent of the FE gas is characterized by $\alpha(\Delta r)^2 = k_B T$ or $\Delta r = \sqrt{k_B T/\alpha}$. Taking worst case values of α and τ_x from our data, we find $L_x/\Delta r \gtrsim 14$ so the FE gas is in spatial equilibrium with itself to a very good approximation.

To ensure thermodynamic equilibrium between the EHL droplet and the FE gas, the net flux of FE out of (for decays) or into (for steady state) the EHL droplet must be small compared to the equilibrium flux of e-h pairs back and forth across the EHL droplet surface. Simple thermodynamic and kinetic arguments[12] give this equilibrium flux $J_\infty = \gamma S(4\pi m_x/h^3)(k_B T)^2 \exp(-\phi/k_B T)$

for the infinite lifetime limit where $J_{in} = J_{out} = J_{\infty}$. Here m_x is the FE translational mass; ϕ is the EHL ground state binding energy per e-h pair; γ is the FE ground state degeneracy; and S is the absorption probability for a FE incident on the EHL droplet. For decays the EHL droplet acts as a FE source which keeps the number of FE approximately constant for small drop sizes. Thus $4\pi R_\ell^2 (J_{out} - J_{in}) = N_x/\tau_x$ where R_ℓ is the droplet radius. For steady state excitation a FE flux inward compensates the droplet's bulk recombination loss of carriers. Thus $4\pi R_\ell^2 (J_{in} - J_{out}) = (4/3\pi R_\ell^3 n_\ell/\tau_\ell$. For these systems to be in quasi-equilibrium, we must have $|(J_{out} - J_{in})/J_{\infty}|$ << 1. Worst case steady state and decay parameters from our data yield $|(J_{out} - J_{in})/J_{\infty}| \leq 5 \times 10^{-3}$ which justifies the use of decay and steady state measurements together in Eq. (2) for $g_{eh}(0)$.

Finally, we note that the $g_{eh}(0)$ measured here are not altered by the compression[13] of the EHL in the strain well since a worst case (highest stress) estimate yields a 5% average compression, and most cases are much better. The compressional stresses[14] used fall in the range 6.3 kgf/mm^2 $\leq -\sigma \leq 14.6$ kgf/mm^2 where 1 kgf = 9.80665 N. To ensure that all measurements for a given stress were performed on the same physical system (strain well), all such measurements were made in the same day.

The enhancement factors determined from our data are plotted with error bars in Fig. 3 as a function of r_s where $r_s = [3/(4\pi n_\ell)]^{1/3}/a_x$, a_x being the high stress FE Bohr radius. The curves are the results of several many-body approximations[2,3] for a model system assuming isotropic electron and hole bands and equal electron and hole masses. The legitimacy of such model systems for use in $g_{eh}(0)$ calculations is suggested by the following: The exchange-correlation energy of the EHL has been shown

to be independent of different band characteristics of semiconductors.[15] The lower two curves show the Hubbard and RPA predictions. The upper two curves are the result of more sophisticated approximations. The FSC approximation[2] takes into account multiple scattering between the plasma components to infinite order in an approximate way. The dashed curve[3] is the result of a variational calculation as opposed to the solid curves which are the results of perturbative methods. Within experimental error our data agree quantitatively with the results of the FSC approximation and also with the Jastrow variational calculation.[3] The Jastrow variational calculation $g_{eh}(0)$ are claimed to always lie lower than they should.[3] Our $g_{eh}(0)$ tend to be larger than the variational $g_{eh}(0)$.

In summary, our experiment provides the first absolute determination of the density dependence of $g_{eh}(0)$. Our $g_{eh}(0)$ are in good agreement with the most sophisticated theoretical predictions[2,3] and do not agree with the HA and RPA predictions.

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FIGURE CAPTIONS

Fig. 1.   Luminescence intensity is plotted semilog vs time for the
electron-hole liquid droplet (a), free exciton gas (b), and
total luminescence (c). The electron-hole liquid has disappeared
by 4 ms. Curve (a) shows a transition from bulk to surface
decay for the droplet. Typically the GaAs laser was pulsed at
lower than a 100 Hz rate with pulse energies less than 2 µJ.

Fig. 2.   Luminescence intensity is plotted vs excitation power for the
electron-hole liquid droplet (a), free exciton gas (b), and the
total luminescence (c). The electron-hole liquid threshold is
clearly visible in (a) and (b). All curves are scaled vertically
to have the same height at 10 µW. No hysteresis in electron-
hole liquid formation is seen within experimental resolution.

Fig. 3.   The enhancement factor $g_{eh}(0)$ is plotted vs r_s where $r_s =$
$[3/(4\pi n_\ell)]^{1/3}/a_x$, a_x being the high stress limit free exciton
Bohr radius and n_ℓ the electron-hole liquid density. Our data
are plotted with error bars. The solid curves are theoretical
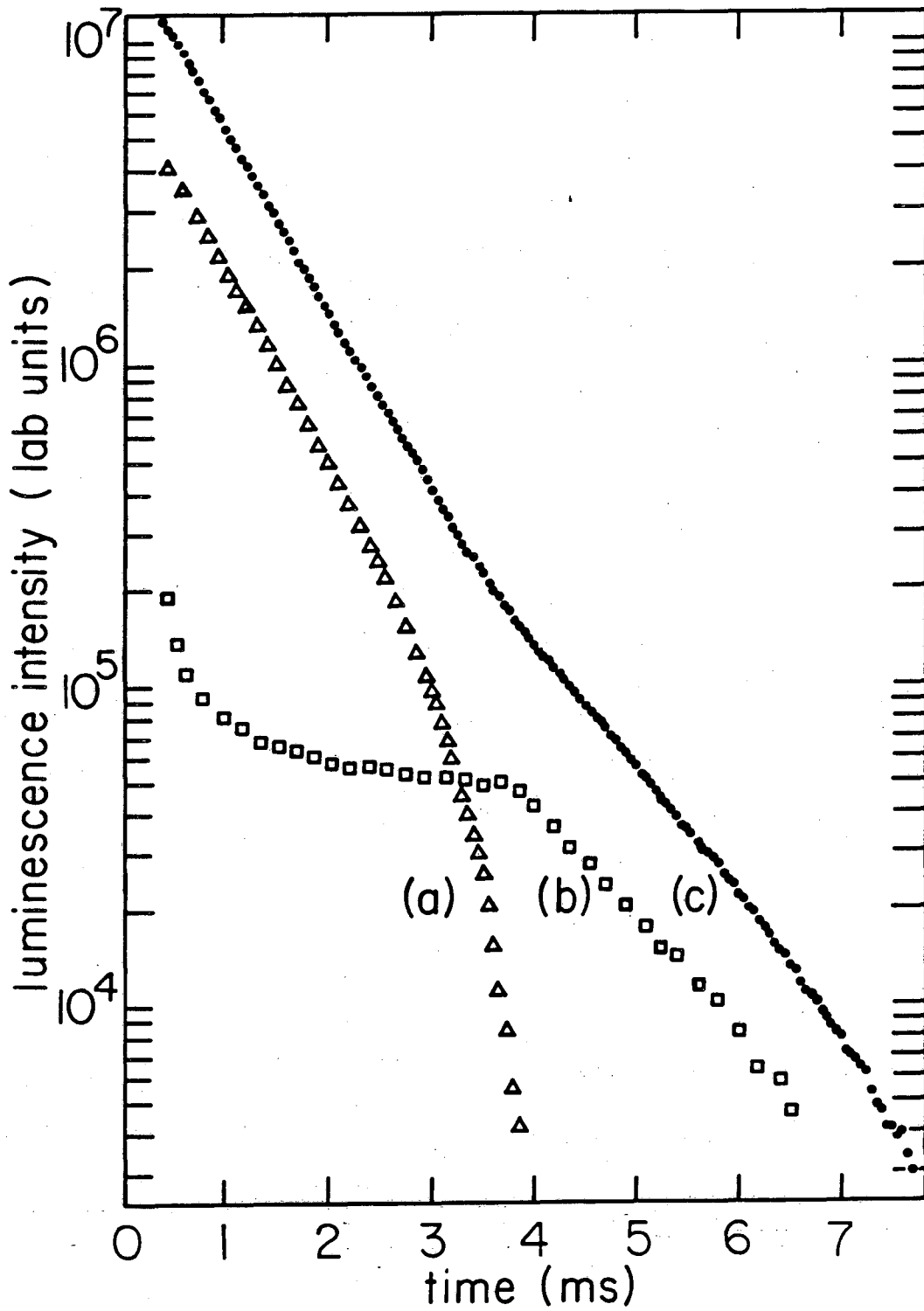results from Ref. 2. The dashed curve is a theoretical result
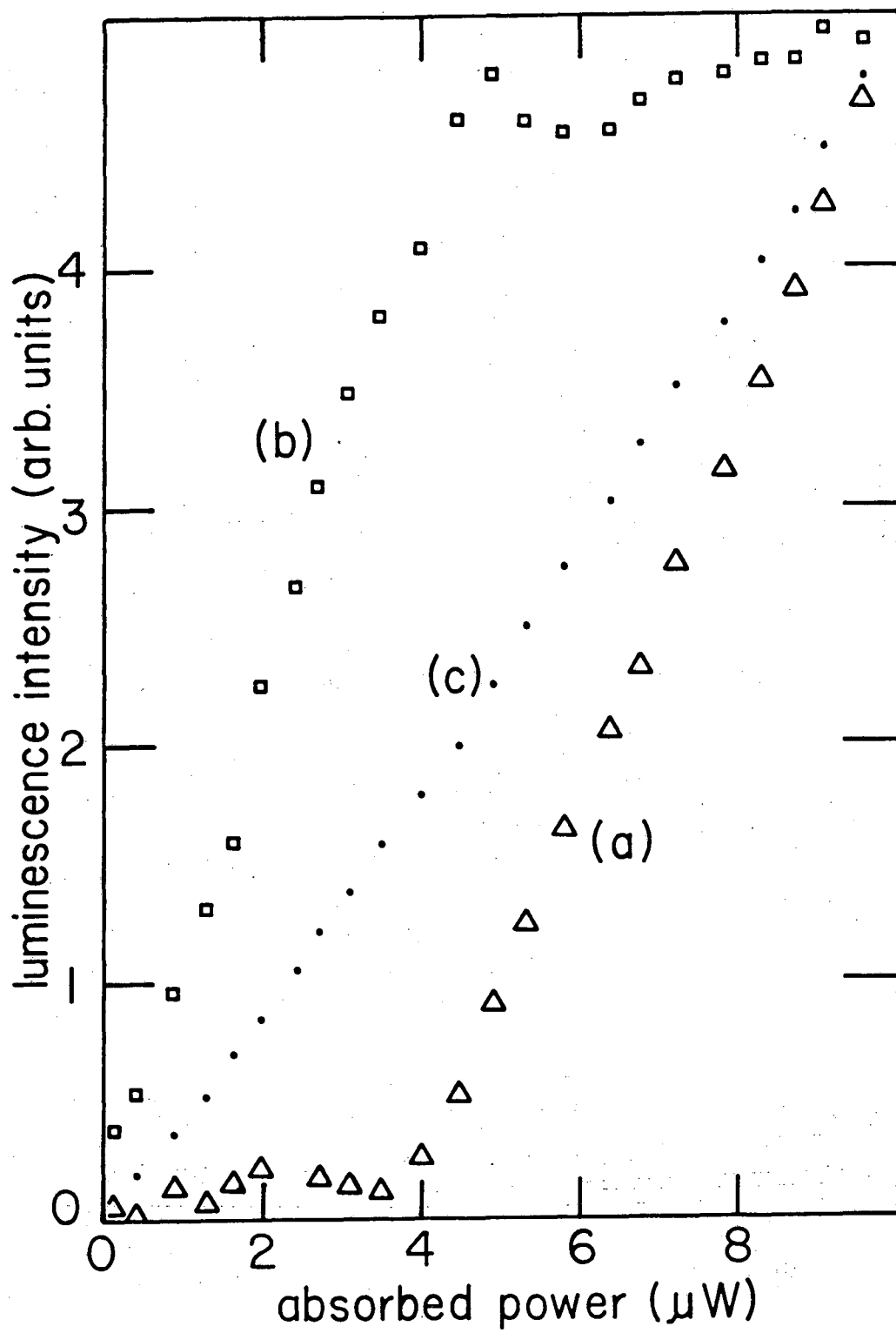from Ref. 3.

Figure 1

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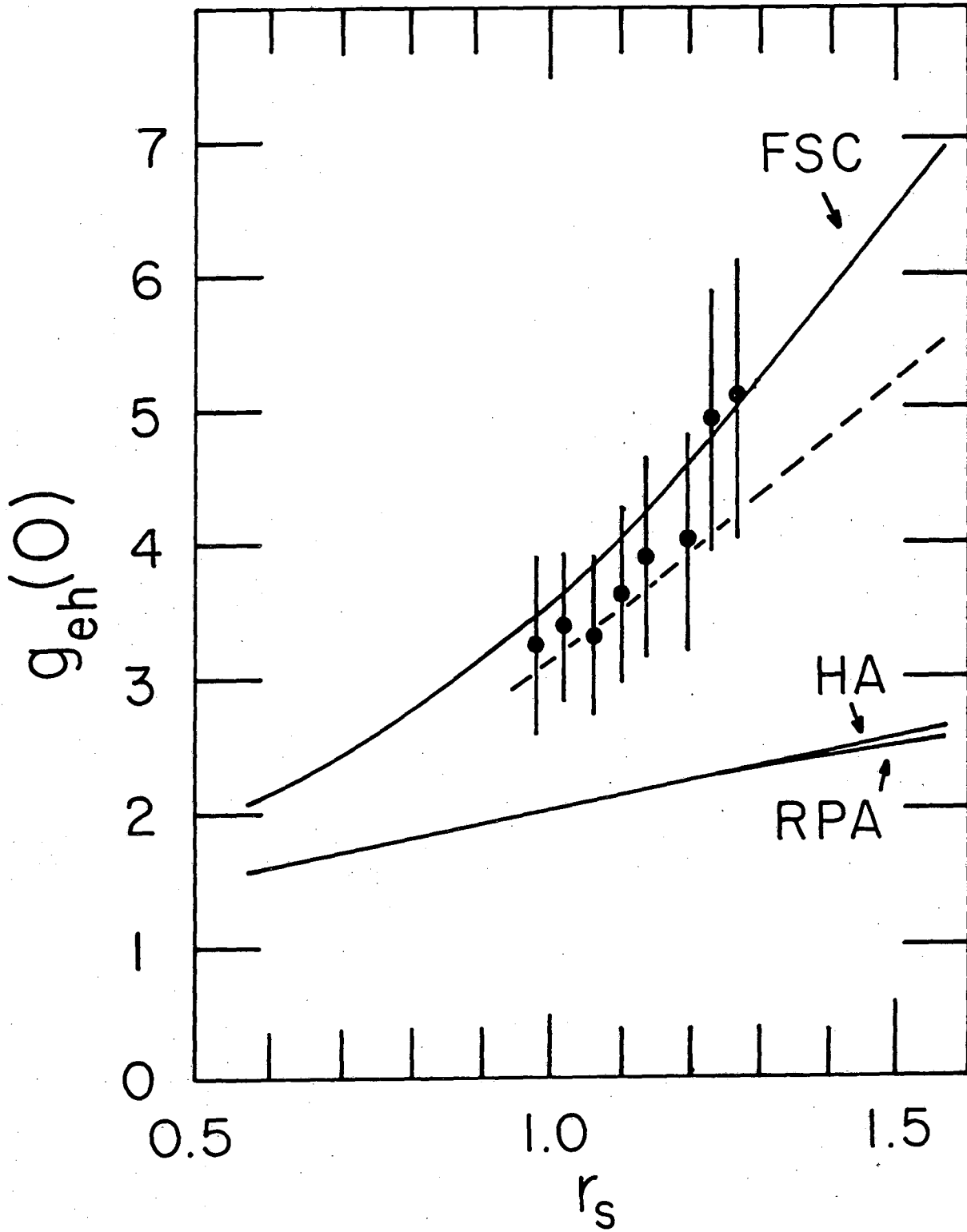Figure 2   XBL 8112-12786

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Figure 3

XBL 825-9954