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Plasmaron excitation in a 2D electron gas

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Abstract

Plasmaron excitation in a two-dimensional electron gas leads to a staircase-like density of states with three steps. The renormalization of the chemical potential is smaller than that of the edge of the density of states if the full dynamical spectral function is used.

Plasmaron excitation was identified by B.I. Lundquist [1] for a three-dimensional electron gas. They showed that, aside from the usual quasi-particle peak, the spectral function presents a second peak associated with the resonant scattering of a plasmon with a hole in the Fermi sea.

In three dimensions, plasmaron excitation leads to a satellite peak below the non-interacting electron density of states (DOS) that provides an explanation for the low-energy tail in the soft X-ray emission spectra of light metals and makes a significant contribution to cohesive energy [1].

In two dimensions, the plasmaron excitation has not yet been described. For the evaluation of the band renormalization, several approximations in addition to the random phase approximation (RPA) are usually made. The shift of the chemical potential is often calculated by neglecting the imaginary part of the self-energy, solving the Dyson equation in the lowest order approximation and using the chemical potential of the non-interacting electron gas for the evaluation of the self-energy [2,3]. The shift of the band is assumed to be rigid and hence the shift of the edge of the DOS is taken to be equal to that of the chemical potential.

This paper describes the plasmaron excitation in a two-dimensional electron gas and the renormalization of the chemical potential and of the edge of the DOS calculated with the full dynamical spectral function.

The spectral function is given by the following expression:

$$A(k, E) = \frac{-2S_I(k, E)}{(E - \xi(k) - S_R(k, E))^2 + S_I^2(k, E)} \tag{1}$$

where $\xi(k)$ is the kinetic energy of the non-interacting electron measured from the chemical potential. The real (S_R) and imaginary (S_I) part of the self-energy are calculated using the standard RPA.

Figure 1 displays the DOS given by the sum over the momentum of the spectral function. The electron effective mass is $m = 0.07m_0$ and the background dielectric constant is $\varepsilon_r = 12$. The first two steps are associated with the two peaks in the spectral function at $k = 0$. The third step is due to the steep decrease of the quasi-particle width and to an increase of the effective mass near the Fermi momentum. It is interesting to note that, whereas in three dimensions the satellite peak in the DOS is stronger at high electron density, in two dimensions the steps are steeper at low density.

The electron density, n_S, for a given chemical potential, μ, is given by the integral over the energy of the DOS times the Fermi distribution function. The corresponding chemical potential for a non-interacting electron gas is $\mu^{(0)} = \hbar^2 n_S \pi / m$. The resulting renormalization of the chemical potential, $\Delta^{(\mu)} = \mu - \mu^{(0)}$, is presented in Fig. 2.

The edge of the DOS, $\Delta^{(DOS)}$, is determined by the low-energy solution, $E^{(QP)}(0)$, of the Dyson equation at $k = 0$

$$E^{(QP)}(0) - \xi(0) - S_R(0, E^{(QP)}(0)) = 0. \tag{2}$$

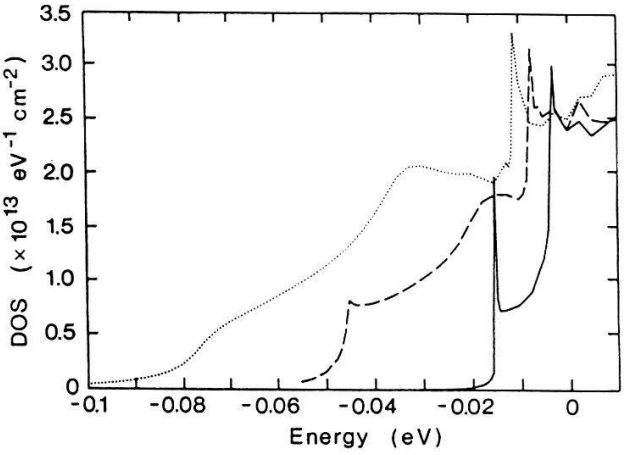

Figure 1: Density of states of a 2D electron gas at $T = 0$ K; solid line: $n_S = 2.2 \times 10^{11}$ cm^{-2}, dashed line: $n_S = 7.1 \times 10^{11}$ cm^{-2}, dotted line: $n_S = 1.2 \times 10^{12}$ cm^{-2}.

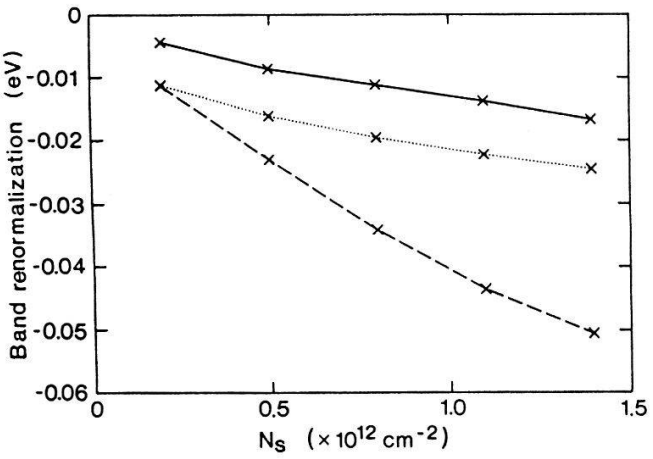

Figure 2: Band renormalization for a 2D electron gas at $T = 0$ K; solid line: shift of the chemical potential (full RPA), dashed line: shift of the edge of the DOS (full RPA), dotted line: lowest order approximation.

The shift of the edge of the DOS, also displayed in Fig. 2, is then given by $\Delta^{(DOS)} = E^{(QP)}(0) + \mu$.

We observe that the shift of the chemical potential is smaller than that of the edge of the DOS. This is explained by the shape of the DOS which is very different from that for the non-interacting electron gas and in particular by the contribution of the imaginary part of the self-energy. Figure 1 shows that this behavior is even accentuated at higher electron density, which explains why the shift of the edge of the DOS increases faster with increasing density than the shift of the chemical potential does.

In the literature, the band renormalization is often calculated using a different procedure [3]. The electron density, n_S, is given and the self-energy is calculated using the chemical potential of the non-interacting electron gas, $\mu^{(0)}$. The chemical potential of the interacting electron gas, μ, is obtained from the solution of the Dyson equation in the lowest order approximation

$$\mu = \mu^{(0)} + S_R(k_F, 0) \tag{3}$$

where $k_F = 2\pi n_S$ is the Fermi momentum. With the assumption that the DOS has the same shape for the interacting and for the non-interacting electron gas (rigid shift approximation), the shift of the edge of the DOS is taken to be equal to that of the chemical potential. Figure 2 shows that the resulting renormalization stays between the shift of the chemical potential and that of the edge of the DOS calculated with the full dynamical spectral function.

In conclusion, I feel that Fig. 2 clearly shows the importance of performing the full calculation when quantitatively comparing experimental and theoretical band renormalization. This is true in particular for the interpretation of optical data where the edge of the DOS is important.

References

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