

## Comments

Comments are short papers which comment on papers of other authors previously published in the *Physical Review*. Each Comment should state clearly to which paper it refers and must be accompanied by a brief abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.

### Phonon contribution to the frequency-dependent part of the relaxation time involved in the intraband optical conductivity of noble metals

Gerardo Cisneros

*Sección de Graduados, Escuela Superior de Ingeniería Mecánica y Eléctrica,  
Instituto Politécnico Nacional, México 14, D. F., México*

J. S. Helman

*Departamento de Física, Centro de Investigación del Instituto Politécnico Nacional,  
Apartado Postal 14-740, México 14, D. F., 07000 México*

(Received 25 November 1981)

It is shown that at room temperature the phonon contribution to the frequency-dependent part of the relaxation time involved in the intraband optical conductivity of noble metals is comparable to that of the electron-electron scattering as determined from dc measurements by Parkins, Lawrence, and Christy.

The frequency dependence of the relaxation time  $\tau(\omega)$  involved in the intraband optical conductivity of the noble metals has been carefully analyzed by Parkins, Lawrence, and Christy.<sup>1</sup> For infrared photon energies  $\hbar\omega$ ,

$$\frac{1}{\tau(\omega)} \simeq \alpha + \beta \hbar^2 \omega^2, \quad (1)$$

where  $\alpha$  and  $\beta$  are adjustable parameters. The empirical values of  $\beta$  ( $\beta_{\text{expt}}$ ) for Cu, Ag, and Au are shown in Table I;  $\beta_{\text{expt}}$  seems to be temperature independent, at least in the measured range 78–425 K.

Both electron-electron scattering<sup>2</sup> and electron scattering by disordered ions<sup>3,4</sup> lead to a frequency-dependent relaxation time. The ion disorder may be due to phonons, impurities, grain boundaries, and structural disorder (liquid or amorphous phases). Parkins, Lawrence, and Christy<sup>1</sup> as well as Beach and Christy<sup>5</sup> indicated that the quadratic dependence on  $\omega$  and the temperature independence of  $\beta_{\text{expt}}$  in Eq. (1) suggest that the electron-electron scattering is the dominant effect. However, the coefficients  $\beta_{\text{expt}}$  exceed by a factor of 2 to 3 the theoretical estimates  $\beta_{e-e,\text{theor}}$  and by an order of magnitude the values  $\beta_{e-e,\text{dc}}$  inferred in a rather model-independent way from dc measure-

ments of the electrical and thermal resistivities (Table I).<sup>1</sup> Thus, the presence of some kind of structural disorder cannot be excluded as a possible explanation for the large temperature-independent values of  $\beta_{\text{expt}}$  observed.<sup>4</sup> Parkins, Lawrence, and Christy<sup>1</sup> pointed out that if this is indeed the case then, in sufficiently perfect samples,  $\beta_{\text{expt}}$  should be consistent with the dc measurements, that is, with the values  $\beta_{e-e,\text{dc}}$ .

We show here that around and above room temperature the phonon contribution to  $\beta$  ( $\beta_{\text{ph}}$ ) is comparable to  $\beta_{e-e,\text{dc}}$ , and thus  $\beta_{\text{expt}}$  should rather be consistent with the sum  $\beta_{e-e,\text{dc}} + \beta_{\text{ph}}(T)$ . We

TABLE I. Coefficient  $\beta$  in units of  $10^{13} \text{ sec}^{-1} \text{ eV}^{-2}$ .

	Cu	Ag	Au
$\beta_{\text{expt}}$ (average) <sup>a</sup>	2.1	1.4	2.4
$\beta_{e-e,\text{theor}}$ <sup>a</sup>	0.64	0.73	0.76
$\beta_{e-e,\text{dc}}$ <sup>b</sup>	0.19	0.25	~0.49
$\beta_{\text{ph}}$ (78 K)	0.06	0.08	0.04
$\beta_{\text{ph}}$ (295 K)	0.20	0.11	0.28
$\beta_{\text{ph}}$ (425 K)	0.29	0.22	0.44

<sup>a</sup>Values taken from Table IV of Ref. 1.

<sup>b</sup>Values taken from Table V and Eq. (16) of Ref. 1.

evaluated  $\beta_{\text{ph}}(T)$ , which had not been considered before in this context.

A quantum-theoretical treatment of the dielectric function  $\epsilon(\omega)$  of an electron gas interacting with disordered ions leads to<sup>3</sup>

$$\epsilon(\omega) = 1 - \left[ \frac{\omega_p}{\omega} \right]^2 [1 - \gamma(\omega) + i\xi(\omega)/\omega]^{-1}, \quad (2)$$

where  $\omega_p$  is the plasma frequency of the free-electron gas and  $\gamma(\omega) - i\xi(\omega)/\omega$  is a complex function of  $\omega$  that is expressed in terms of an integral over the scattering momentum transfer  $q$ , and whose integrand involves, besides some phase factors, the electron-ion pseudopotential  $V_q$  and the structure factor  $S(q)$  of the ions in the metal.

At infrared energies the relaxation frequency  $\xi(\omega)$ , which is to be identified with  $\tau^{-1}(\omega)$ , can be approximated by

$$\xi(\omega) = \alpha_{\text{ph}} + \beta_{\text{ph}} \hbar^2 \omega^2, \quad (3)$$

where  $\alpha_{\text{ph}}$  coincides with  $\alpha$  if the static electron-electron and impurity scattering are negligible. We calculated  $\beta_{\text{ph}}$  for Cu, Ag, and Au at room temperature with the use of pseudopotentials reported

by Moriarty<sup>6</sup> and a model structure factor  $S(q)$  in the one-phonon approximation with Einstein dispersion  $\omega_q = k_B T_E / \hbar$ .<sup>7</sup> The Einstein temperature  $T_E$  was adjusted to reproduce the empirical static resistivity (or  $\alpha_{\text{ph}}$ ) at room temperature. The results are shown in Table I. The values of  $\beta_{\text{ph}}$  reported at 78 and 425 K in Table I were obtained under the assumption that  $\beta_{\text{ph}}$  is proportional<sup>8</sup> to  $\alpha_{\text{ph}}$ ; the corresponding experimental values of  $\alpha_{\text{ph}}$  were taken from Table III of Ref. 1.

In conclusion, it is apparent from Table I that the temperature-dependent contribution of phonon scattering to the coefficient  $\beta$  in Eq. (1) is significant, and that already at room temperature it becomes comparable to that of electron-electron scattering as determined from dc measurements.

The work of G. C. was partially supported by Comision de Fomento de Actividades Académicas—Instituto Politécnico Nacional (COFAA-IPN). J. S. H. acknowledges the partial support of the Organization of American States (OAS), Secretaría de Patrimonio y Fomento Industrial (SEPAFIN, Mexico) and Consejo Nacional de Ciencia y Tecnología (CONACyT, Mexico).

<sup>1</sup>G. R. Parkins, W. E. Lawrence, and R. W. Christy, Phys. Rev. B **23**, 6408 (1981).

<sup>2</sup>R. N. Gurzhi, Zh. Eksp. Teor. Fiz. **35**, 965 (1958) [Sov. Phys.—JETP **8**, 673 (1959)].

<sup>3</sup>J. S. Helman and W. Baltensperger, Phys. Kondens. Mater. **5**, 60 (1966); **15**, 346 (1973); Phys. Rev. B **17**, 2427 (1978).

<sup>4</sup>S. R. Nagel and S. E. Schnatterly, Phys. Rev. B **9**, 1299 (1974).

<sup>5</sup>R. T. Beach and R. W. Christy, Phys. Rev. B **16**, 5277 (1977).

<sup>6</sup>J. A. Moriarty, Phys. Rev. B **6**, 1239 (1972).

<sup>7</sup>J. S. Helman and R. A. B. Devine, Phys. Rev. B **6**, 1607 (1972).

<sup>8</sup>This proportionality is exact within the Einstein approximation for the phonon dispersion and we conjecture that it should be very approximate in general for the solid. However, this relation between  $\beta_{\text{ph}}$  and  $\alpha_{\text{ph}}$  cannot be extrapolated from the solid to the liquid or amorphous state; this may lead to the overestimation of  $\beta_{\text{ph}}$  by an order of magnitude. In the liquid state  $\beta_{e-e}$  is negligible compared with the contribution to  $\beta$  ( $\sim 5 - 10 \times 10^{13} \text{ sec}^{-1} \text{ eV}^{-2}$ ) coming from the structural disorder.