Direct plasmon production from Thomson scattering in SuperCDMS silicon detectors

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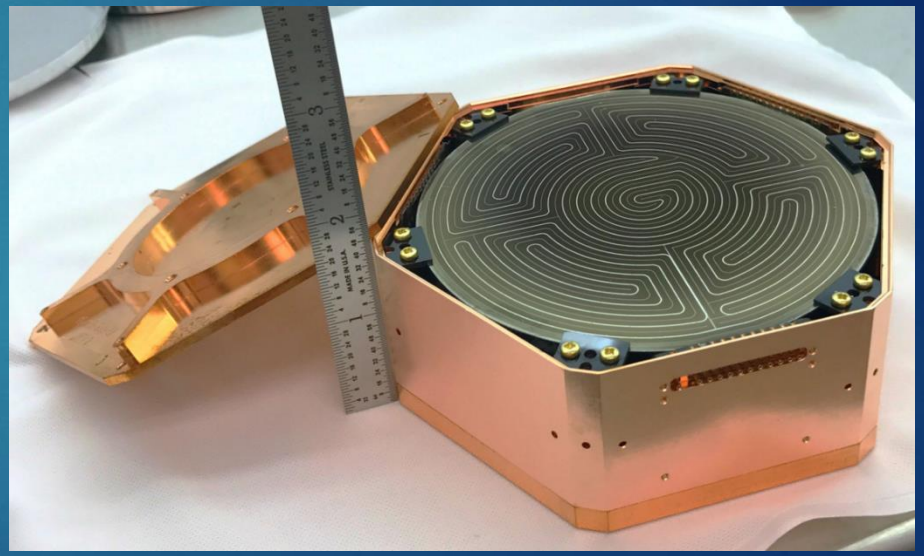
CAP Congress June 5 2019

What sparked our interest in plasmons?

SuperCDMS (Super Cryogenic Dark Matter Search) has developed high voltage g-scale calorimeters with eV-scale resolution (called CDMS HVeV) that can achieve single-charge resolution (1e-h pair)

Because of its resolution, SuperCDMS could be the first experiment to detect plasmons by measuring their electron-hole pair production

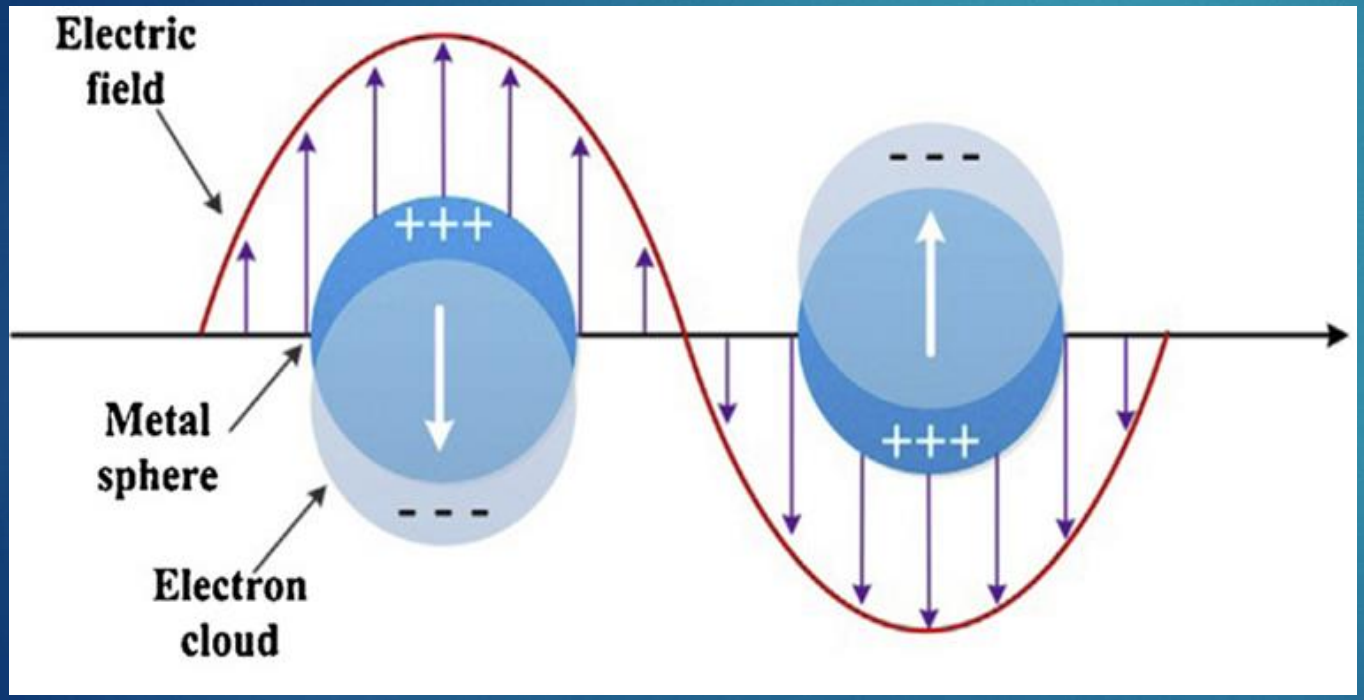
Using different approximations of the dynamic structure factor of silicon $S(\boldsymbol{q}, \omega)$, we can roughly estimate the expected volume plasmon signal in our detector



SuperCDMS dark matter detector

What is a plasmon?

Plasmon : a plasmon is a quasiparticle that describes how a plasma oscillates.



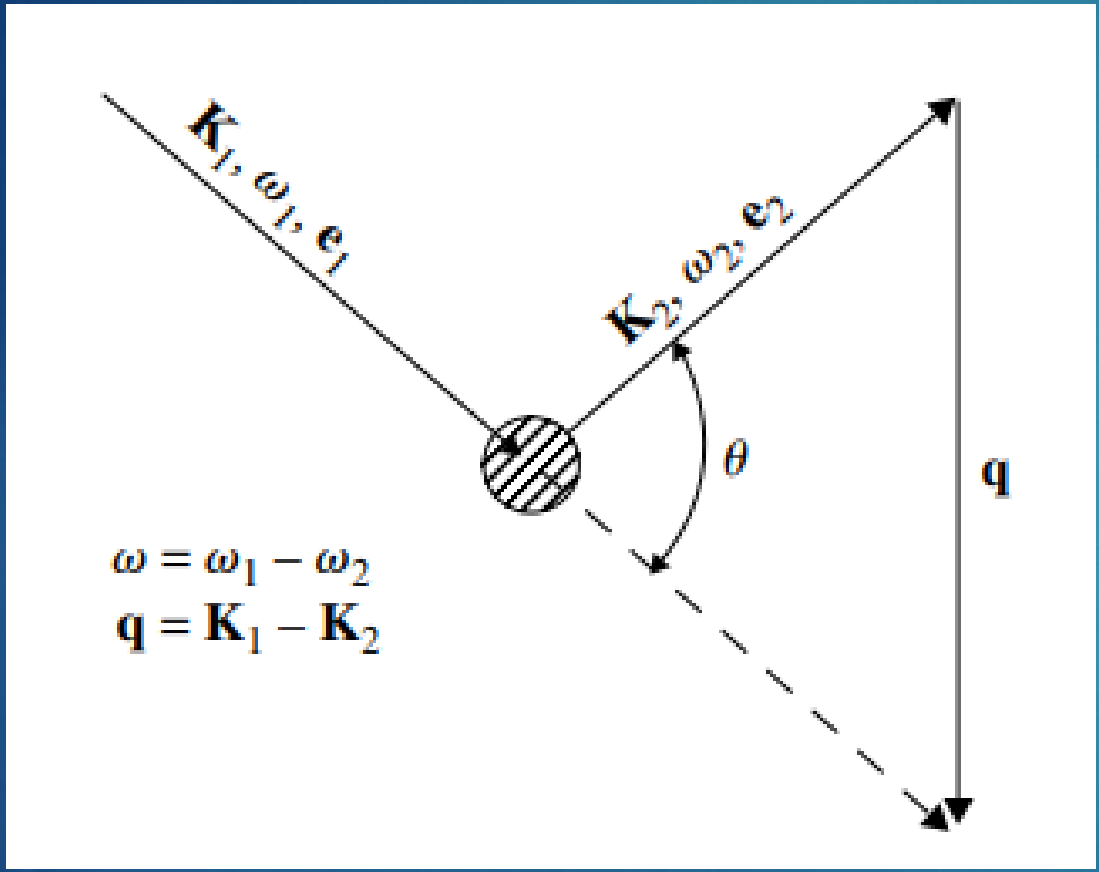
The plasmon energy is given by the plasma frequency:

$$\omega_p = \sqrt{\frac{ne^2}{\varepsilon_0 m}}$$

With n being the valence electron density, e the electric charge, ε_0 the vacuum permittivity and m the electron mass.

$\omega_p \approx 16 - 17$ eV for Si

Plasmons can be created by electrons or X-rays



Typical X-ray inelastic scattering

Photon of energy $\hbar\omega_1$, wavevector $\mathbf{K}_1$ and polarization $\mathbf{e}_1$ is scattered by an angle Θ into a photon of energy $\hbar\omega_2$, wavevector $\mathbf{K}_2$ and polarization vector $\mathbf{e}_2$.

$\hbar\omega = \hbar\omega_1 - \hbar\omega_2$ = Energy transfered to the particle (valence electron in our case)

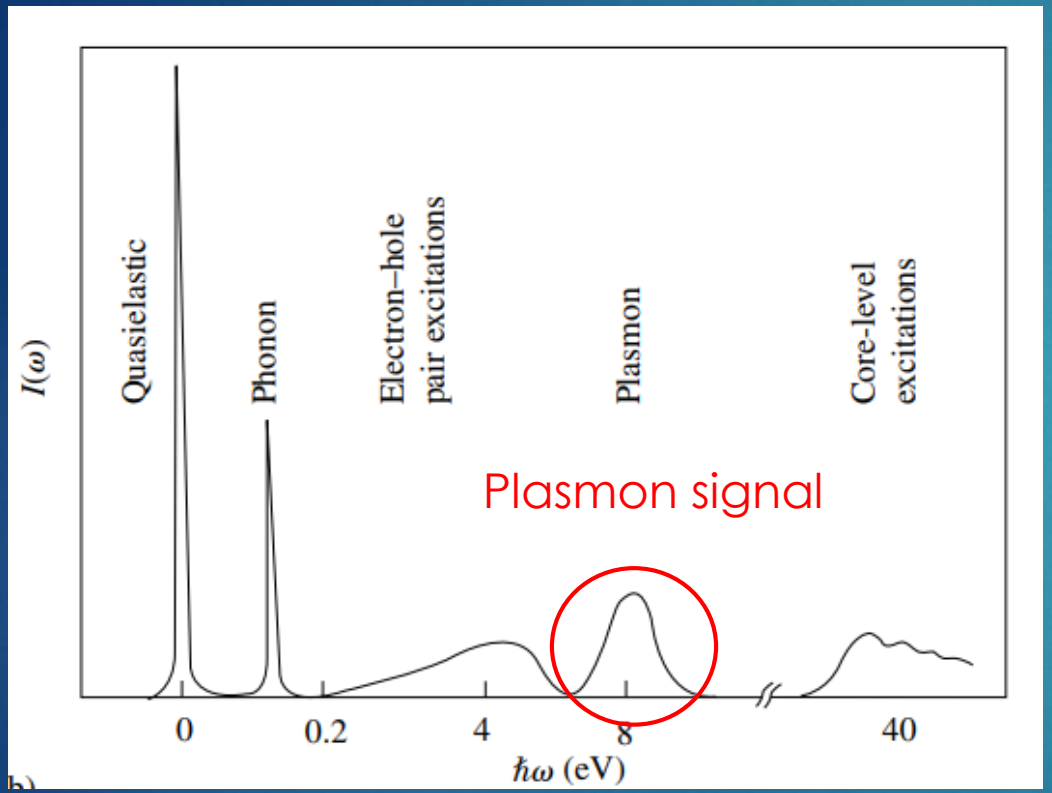
$\mathbf{q}$ = momentum transfered

$$q = (\omega_1^2 + \omega_2^2 - 2\omega_1\omega_2 \cos\theta)^{1/2}/c.$$

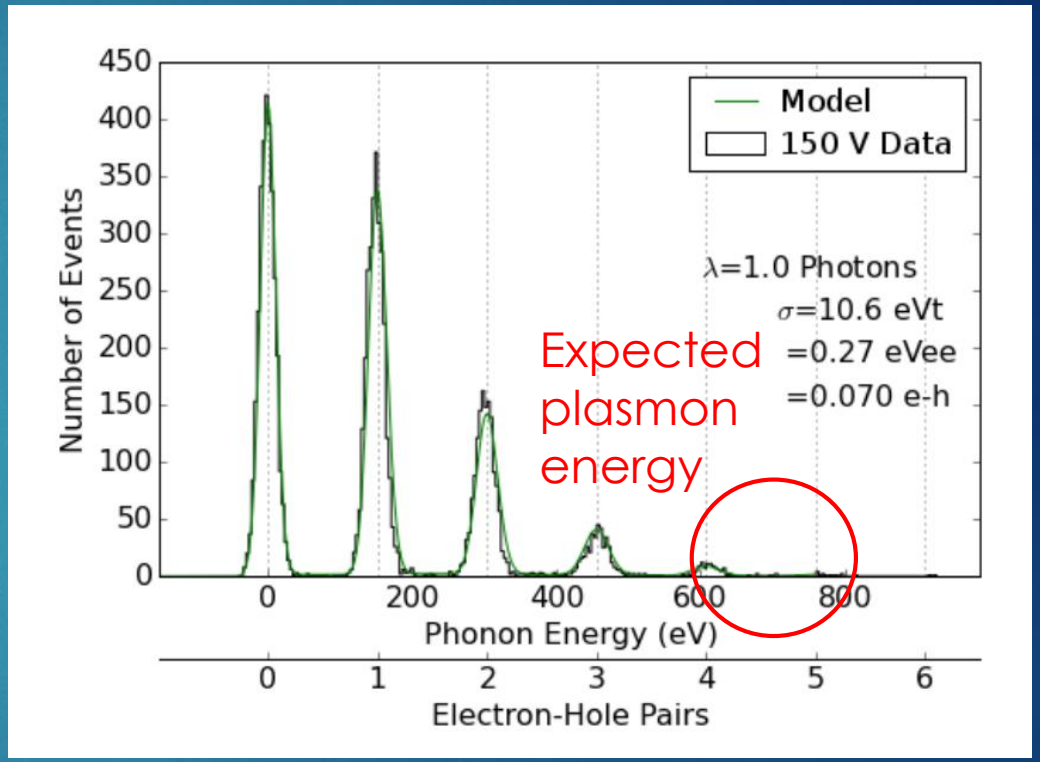
$$q \approx 2K_1 \sin(\theta/2)$$

Usually, plasmons are indirectly detected by measuring the difference in energy between the incident photon (or electron) and the scattered photon.

In SuperCDMS, we could directly detect plasmons by measuring the number of electron-hole pairs produced by the plasmon (4-5 e-h pair * 3,8 eV ≈ 16-17 eV)



Schematic of an inelastic X-ray scattering spectra



CDMS silicon HVeV detector with single e-h pair resolution. Calibration taken with 650 nm laser (1,91eV photons < plasmon energy). Ref[7]

Luke Neganov effect : $E_{\text{phonon}} = QV = charge * potential\ across\ detector$

Estimating the expected plasmon signal in our detector

The rate of plasmon production from Thomson scattering does not yet exist in the literature (to my knowledge) but can be roughly estimated to determine whether its signal would be seen over the Compton background

Number of incident photons scattered into solid angle [Ω, Ω + dΩ] with the energy transfer between [ω, ω + dω] over total incident photons

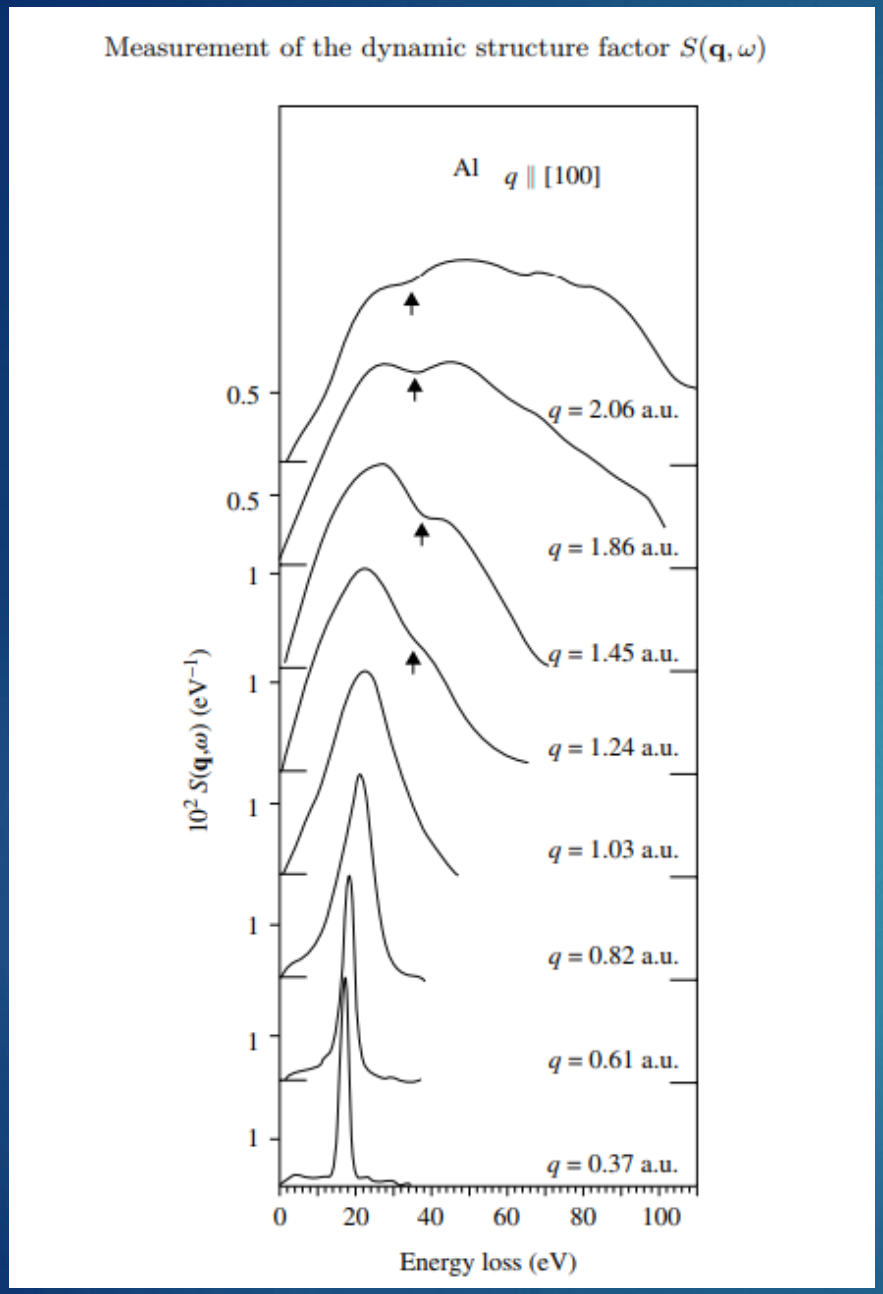
$$\frac{d^2\sigma}{d\Omega d\omega} = \left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{Th} S(\boldsymbol{q},\omega)$$

Th stands for Thomson scatterring

S(**q**, ω) is the dynamic structure factor, a mathematical function which describes how a material scatters incident photons

-The cross section depends on the dynamic structure factor S(q,w)
-at low q, the dynamic structure factor is dominated by plasmons

Dynamic structure factor S(**q**, ω)



Real data of S(**q**, ω) of aluminium for different q

With increasing q (momentum transfered), the peak of the dynamic structure factor moves to the right and loses its sharpness.

It's because at low q, the dynamic structure factor is dominated by nearly-undamped plasmons.

At higher q, plasmons become strongly damped because they can decay into particle-hole excitations which now dominate the dynamic structure factor.

The plasmon energy goes up with q

$$\omega_p = \omega_p(q)$$

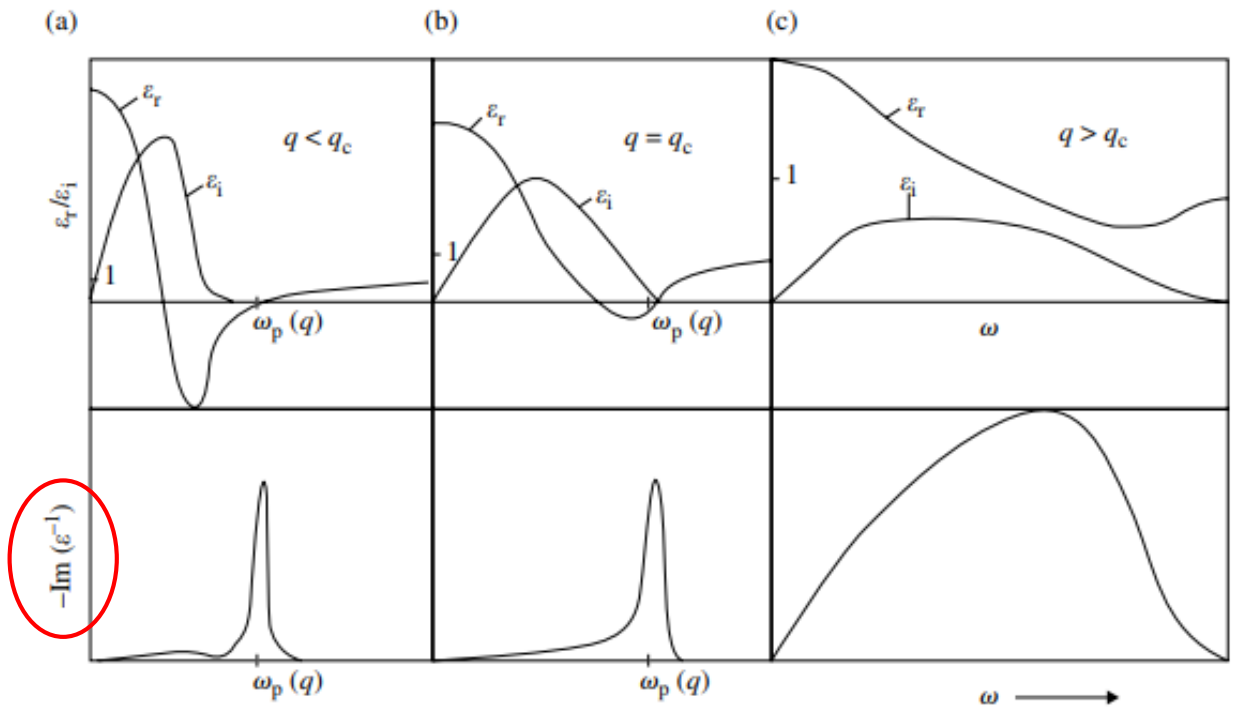


Fig. 2.14. Upper row: real part ε_r and imaginary part ε_i of the free electron RPA dielectric function $\varepsilon(\mathbf{q},\omega)$ (including weak damping the particle–hole excitations) for (a) $q < q_c$ (q_c = plasmon cut-off wave vector); (b) $q = q_c$, and (c) $q > q_c$. Lower row: RPA free-electron response function $-\mathrm{Im}\,\varepsilon^{-1}(\mathbf{q},\omega)$ (including weak damping of the plasmon excitation) (a) $q < q_c$; (b) $q = q_c$, and (c) $q > q_c$.

2 conditions for nearly-undamped plasma excitations :

1) Im (ε) = 0
2) Re (ε) goes from negative to positive

Where ε is the dielectric function (describes the polarisation of a material when put under an exterior electric field.)

When these two conditions are met, it produces a sharp peak at frequency ω_p.

$$S(\mathbf{q},\omega) = \left(\frac{1}{1-\exp(-\hbar\omega/k_B T)}\right)\left(\frac{q^2}{4\pi^2 e^2}\right)\mathrm{Im}\left[\frac{-1}{\varepsilon(\mathbf{q},\omega)}\right].$$

When q > qc (plasmon cut-off momentum transfer), these two conditions can no longer be met and there is no more sharp peak. The dynamic structure factor is then dominated by particle-hole excitations.

Approximation of the dynamic structure factor S(**q**, ω)

$$S(\mathbf{q},\omega) = \left(\frac{1}{1-\exp(-\hbar\omega/k_{\mathrm{B}}T)}\right)\left(\frac{q^2}{4\pi^2 e^2}\right)\mathrm{Im}\left[\frac{-1}{\varepsilon(\mathbf{q},\omega)}\right].$$

$$\varepsilon_{\mathrm{M}}(\mathbf{q},\omega) = \frac{1 - v(\mathbf{q})(1-\widetilde{G}(\mathbf{q},\omega)\chi_0(\mathbf{q},\omega)}{1+\widetilde{G}(\mathbf{q},\omega)v(\mathbf{q})\chi_0(\mathbf{q},\omega)}.$$

$$v(\mathbf{q}) = \frac{4\pi e^2}{q^2}$$

K_f and E_f are Fermi wavevector and energy

G(q,w) is called the local field correction. There exist a lot of different G(q,w) in the litterature, the simplest being G(q,w) = 0. We used a few different ones for our calculations

$$\chi_0(\mathbf{q},\omega) = \chi_{\mathrm{L}}(\mathbf{q},\omega) = -\left[\frac{3q^2}{512\pi\gamma^2 Z^3 e^2}\right]\left\{4Z + [1-(U-Z)^2]\,\mathrm{In}\frac{U-Z-1}{U-Z+1} - \left[1-(U+Z)^2\,\mathrm{In}\frac{U+Z-1}{U+Z+1}\right]\right\}$$

$$Z = \left|\frac{q}{2k_{\mathrm{F}}}\right|, \quad U = \frac{\hbar\omega}{4ZE_{\mathrm{F}}}, \quad E_{\mathrm{F}} = \frac{\hbar^2 k_{\mathrm{F}}^2}{2m}, \quad \gamma = \frac{E_{\mathrm{F}}}{\hbar\omega_{\mathrm{p}}}.$$

Lindhard Polarisation Function

Evaluating the double differential cross section

$$q \approx 2K_1 \sin\frac{\theta}{2}$$

$E=\hbar\omega$

$$\frac{d^2\sigma}{d\Omega d\omega} = \left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{Th} S(\boldsymbol{q},\omega)$$

$$\frac{d^2\sigma}{dqdE} = \left(\frac{d^2\sigma}{dqdE}\right)_{Th} S(\boldsymbol{q},\omega)$$

$$\int \frac{d^2\sigma}{dqdE} dq = \int \left(\frac{d^2\sigma}{dqdE}\right)_{Th} S(\boldsymbol{q},\omega) dq$$

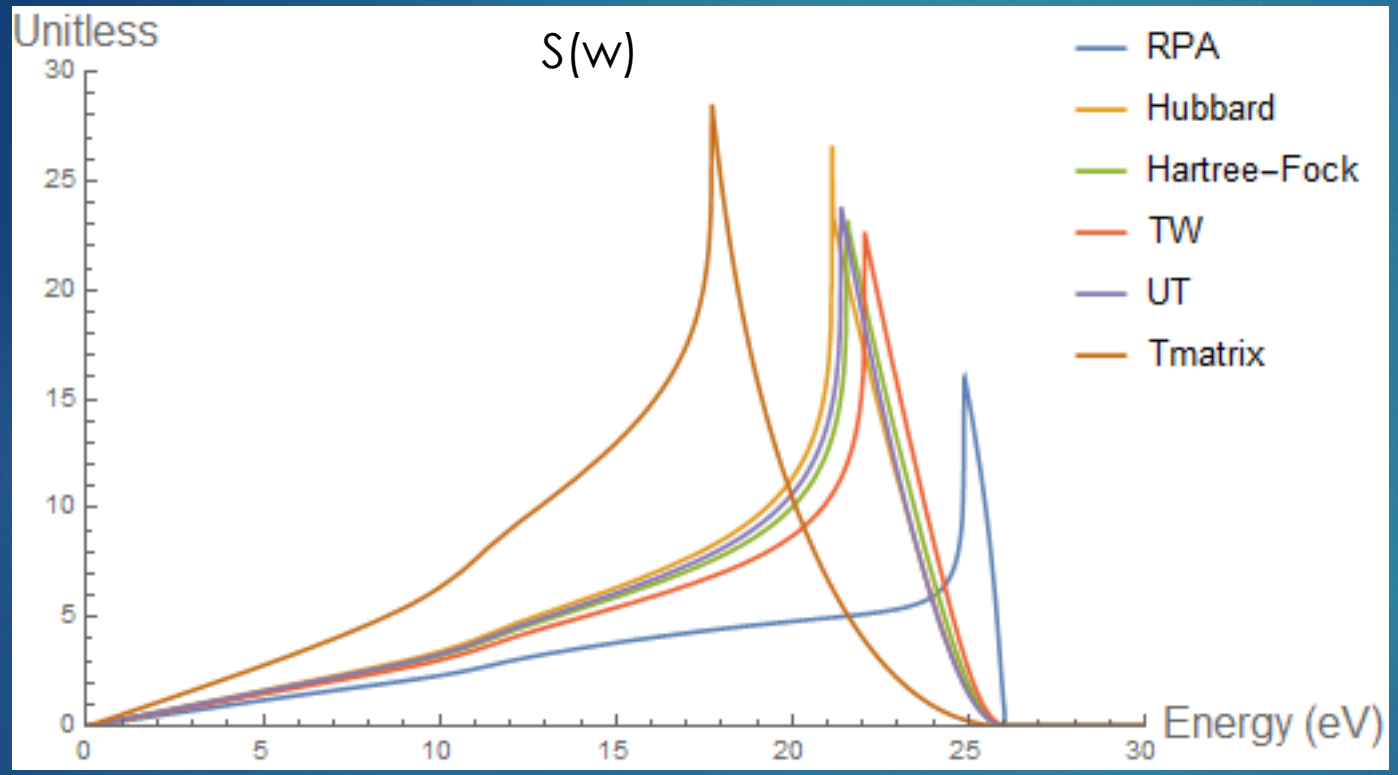
$$\frac{d\sigma}{dE} = \left(\frac{d\sigma}{dE}\right)_{Th} S(\omega)$$

$$\frac{\frac{d\sigma}{dE}}{\left(\frac{d\sigma}{dE}\right)_{Th}} = S(\omega)$$

We integrate from 0 to qc (plasmon cut-off vector)

By integrating S(q,w) over q, we end up with S(w) which is the ratio between Thomson scattering on an atom's valence electrons and on free electrons

S(w) as a function of energy transfered by the incident photon



The different plots represent different approximations of S(q,w) (different local field corrections G(q,w)

We see that near the plasmon frequency, S(w) goes as high as 25; which means the Compton differential cross section on silicon valence electrons is around 25 times the differential cross section on free electrons.

At these low q, S(w) is dominated by plasmons, and we should therefore see a peak above the compton scattering background caused by plasmon production.

What we learned

-Volume plasmons are quasi particles excited by electrons or X-rays

-The plasmon cross section has been roughly estimated to be almost 25x that of the Compton cross section near the plasma frequency.

-Not negligible!

-Only indirect detection of plasmons have been observed so far by looking at the difference in energy between the incident photon (or electron) and the scattered photon

-SuperCDMS could be the first experiment to directly detect plasmons by measuring their electron-hole pair production (~ 4-5 e-h pairs → ~16-17 eV).

-We expect to be able to measure this effect this year!

References

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QUESTIONS?