Electromagnetic Forces in metallic nanoparticles induced by fast electron beams

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ABSTRACT

We present a study of the force induced on gold nanoparticles by fast passing electrons like those employed in transmission electron microscopes. Integrating the force over time we calculate the total momentum transferred from the electron to the particles. The calculation of the electromagnetic fields induced on the nanoparticles, which are resonant at the frequency of the localised plasmon of the system, is based on the solution of the Maxwell equations and thus the retardation effects are taken into full account. Numerical results are presented for two geometries: a pair of identical gold nanoparticles and a pair of two gold nanoparticles of different radii. The total impulse transmitted to the nanoparticle system could have a significant influence on the dynamics of the particles observed under scanning transmission electron microscopy.

INTRODUCTION AND MOTIVATION

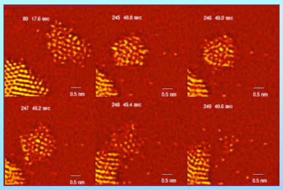


Figure 1. Sequence of images of two gold nanoparticles where they remain apart for a long time (> 50s), but then rapidly coalesce (less than 200 ms) leaving some atoms behind.

As in optical forces[1,2], where forces induced on particles by light are strong to manipulate them, the forces induced on nanoparticles by fast electrons could also move them.

A detail analysis of motion of gold nanoparticles using a transmission electron microscope has been recently published[3].

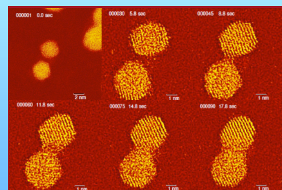


Figure 2. Sequence of images of two 2-nm gold nanoparticles. They remain apart for a long time (> 20s), but then coalesce rapidly when the current density is increase by a factor of four.

Two main behaviours are observed:

- Few atoms in the cluster → the electron probe tends to destroy the cluster.
- Big particles (>1nm in diameter) → they tend to coalesce (as shown in Figs. 1 and 2).

Images courtesy of Dr. P. E. Batson, IBM New York.

THE MODEL

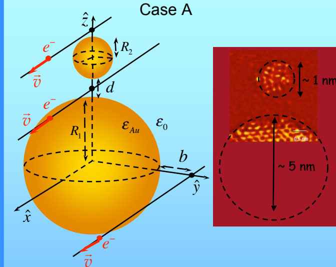


Figure 3. Model of two spheres with different radius used for the calculations of the momentum transfer.

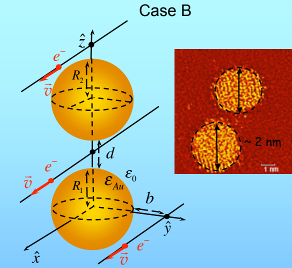


Figure 4. Model of two identical spheres used for the calculations of the momentum transfer.

Parameters of the model of Case A (Case B), see Fig. 3 (Fig. 4):

- radii → R_1=0.5nm and R_2=2.5nm (R_1=R_2=1nm)
- separated by d (varied range 1nm)
- different electron trajectories with impact parameter b
- characterized by a local[4] $\varepsilon(\omega)$
- velocity of the electron $v = c/2$

THEORY

The total momentum transfer from the electron to the particle is given by the time integral of the **equation of the conservation of momentum**[5]

$$\Delta\vec{P}_{mec} = \int_{-\infty}^{\infty}\frac{d}{dt}\vec{P}_{mec}(t)\,dt = \int_{-\infty}^{\infty}\int_S \vec{T}(\vec{r};t)\cdot d\vec{a}\,dt,$$

where the corresponding part of the electromagnetic momentum does not appear, since it does not contribute to the total momentum transfer. Identifying the time derivative of the **mechanical momentum** $\Delta\vec{P}_{mec}$ with the **mechanical force** $\vec{F}_{mec}$

$$\Delta\vec{P}_{mec} = \int_{-\infty}^{\infty}\frac{d}{dt}\vec{P}_{mec}(t)\,dt = \int_{-\infty}^{\infty}\vec{F}_{mec}(t)\,dt = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\vec{F}_{mec}(\omega)\,e^{-i\omega t}\frac{d\omega}{2\pi}dt = \vec{F}_{mec}(\omega=0).$$

From the Fourier transform in ω space of the **Maxwell Stress Tensor** (MST), one can identify that the integral on time of the MST corresponds to

$$\int_{-\infty}^{\infty}\vec{T}(\vec{r};t)\,dt = \vec{T}(\vec{r};\omega=0).$$

Since the components of the MST are products of fields (electric or magnetic), and using the Fourier transform in ω space for each field component, one can write for each product

$$\int_{-\infty}^{\infty}\vec{E}(\vec{r};t)\vec{E}(\vec{r};t)\,dt = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\vec{E}(\vec{r};\omega')e^{-i\omega' t}\frac{d\omega'}{2\pi}\int_{-\infty}^{\infty}\vec{E}(\vec{r};\omega'')e^{-i\omega'' t}\frac{d\omega''}{2\pi}dt$$
$$= \frac{1}{2\pi}\int_{-\infty}^{\infty}\vec{E}(\vec{r};\omega')\vec{E}(\vec{r};-\omega')\,d\omega' = \frac{1}{2\pi}\int_{-\infty}^{\infty}\vec{E}(\vec{r};\omega)\vec{E}^{*}(\vec{r};\omega)\,d\omega.$$

Performing the same steps for each integral on time of the product of fields in the MST, one can write that the **total momentum transfer** is given by

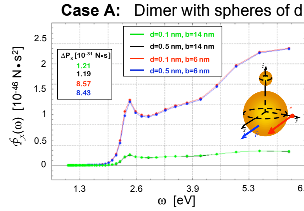
$$\Delta\vec{P}_{mec} = \frac{1}{4\pi^2}\int_0^{\infty}\vec{\mathcal{P}}(\omega)\,d\omega,$$

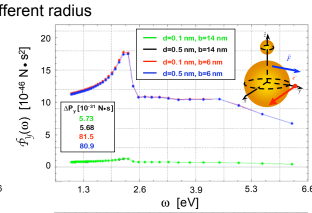
with

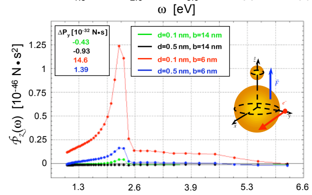
$$\vec{\mathcal{P}}(\omega) = \int_S d\vec{a}\cdot\left\{\vec{E}(\vec{r};\omega)\vec{E}^{*}(\vec{r};\omega) + \vec{B}(\vec{r};\omega)\vec{B}^{*}(\vec{r};\omega) - \frac{1}{2}\vec{I}\left[\vec{E}(\vec{r};\omega)\cdot\vec{E}(\vec{r};\omega) + \vec{B}(\vec{r};\omega)\cdot\vec{B}(\vec{r};\omega)\right]\right\}$$

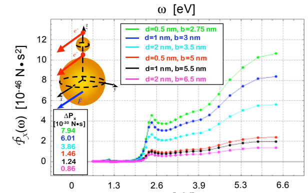
NUMERICAL RESULTS

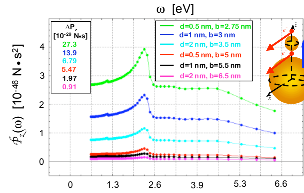
Case A: Dimer with spheres of different radius





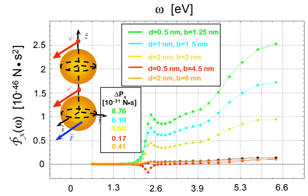


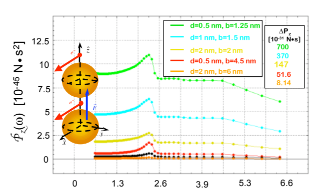




CASE A: First geometry,
$\Delta P_y > \Delta P_x > \Delta P_z$
Second geometry,
$\Delta P_z > \Delta P_x$
CASE B:
$\Delta P_z > \Delta P_x$

Case B: Dimer with identical spheres





SUMMARY

- Electromagnetic fields and forces induced on pairs of nanoparticles are calculated.
- Systematic calculation of momentum transfer from electrons to nanoparticles for different electron trajectories and separation of particles.
- Calculations of force on nanoparticle pairs reveal different behaviour for different electron trajectories and separation of the particles.
- We observe different magnitudes in the induced forces on a dimer than in the case of one single sphere[6].

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