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Research Article

Plasmonic Concepts for Condensed Matter Nuclear Fusion

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Abstract

We propose and numerically investigate a scheme to provide high-density optical or electromagnetic energy to fuel materials for condensed matter nuclear fusion. Surface plasmons in metal nanoparticulates strongly interact with electromagnetic fields at their resonance, resulting in an intense focusing of the incident energy around the metal surface. It is therefore possible to take the advantage of such high energy concentration, under laser or electric power input, for instance by simply coating the conventional Pd-based fuel materials with noble-metal nanoparticles or nanoshells. This field-enhancement effect can be a powerful method to boost the fusion-triggering electromagnetic or optical energy to significantly improve the reaction rate and experimental reproducibility, and to create low-D-load fusion systems. Importantly, this enhancement scheme is applicable to both gas- and liquid-phase systems, and furthermore, not only for laser/optical power, but also for the conventional electrolysis systems due to the equivalency between light and electromagnetic fields. We also show that the conventional fusion-catalyzing metals of Pd, Ni, and Ti themselves intrinsically exhibit a certain degree of field enhancement for their nanostructured form. Therefore, we point out that this plasmonic effect may have been unknowingly produced particularly in the electrolysis-type fusion experiments reported so far. This field-enhancement phenomenon thus could be a clue to solve the mystery of the energy supplied to overcome the gigantic Coulomb barrier to produce the fusion reaction observed with visible rates, as well as a powerful tool for further technical progress.
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1. Introduction

The intensity and density of the triggering energy supplied to activate the nuclear fusion reaction are key factors to produce a smooth and reproducible initiation of the reaction. The incident electric power onto Pd samples in liquid [1,2] and gaseous [3,4] systems reported in the field of condensed matter nuclear fusion has been generally around 1 W/cm^2 or less. Note that we estimated the chemical power, instead of an electric power, from the temperature increment and heat capacity of the sample for Ref. [4]. Semiconductor or solid-state (e.g., YAG) lasers, on the other hand, are able to strike power densities several orders of magnitude greater. This approach aims an initial local ignition of nuclear fusion reaction enabling the generated heat there to trigger subsequent reactions throughout the fuel material.

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Moreover, the plasmonic field enhancement effect [5–7] induced by metal nanoparticles can concentrate the incident optical energy even further, as explained below.

2. Calculation Methods

To numerically examine the plasmonic energy focusing effect, we did the following calculations. We calculate the field-enhancement factors, which are the intensity ratios of the fields around the object to those in the absence of the object, or the original incident fields, for spherical metal nanoparticles in D_2 and D_2O. These calculations are based on the classical electromagnetic field theory in the quasistatic limit [6,7] to numerically show how much energy can be concentrated out of the incident optical or electric power. The electrostatic calculations conducted in this paper are valid for particle sizes in the range of 10–100 nm, for which the phase retardation is negligible throughout the particle, the field enhancement will be largest, and metal nanoparticles and nanoshells therefore become most applicable, as discussed in Section 3. The empirical complex dielectric functions of metals and of the surroundings on frequencies listed in [7,8] are used for the computation in this paper. The dielectric functions of D_2 and D_2O were assumed equal to those of the air and H_2O, respectively. The calculation of the field-enhancement factors was carried out for spherical nanoparticles of Pd, Ni, and Ti. The method used to calculate the field enhancement factors is described in [7]. In short, the field-enhancement factor is calculated as

$$\eta \equiv \frac{\left|\vec{E}\right|^2}{\left|\vec{E}_0\right|^2} = \left|1 + 2\frac{\varepsilon_1 - \varepsilon_m}{\varepsilon_1 + 2\varepsilon_m}\right|^2, \tag{1}$$

where $\vec{E}$ is the maximum static electric field around the metal nanoparticle, $\vec{E}_0$ is the original uniform electric field in the absence of the nanoparticle, and ε_1 and ε_m are the frequency-dependent complex permittivities or dielectric functions of the sphere and the surrounding medium, respectively. Note that this field-enhancement factor is defined as the ratio of field *intensities* and not field *magnitudes*.

We also conduct field-enhancement-factor calculations for Ag/SiO_2 nanoshells, which are subwavelength-scale heterogeneous concentric spherical particles with SiO_2 cores and Ag shells. In these calculations, we vary the diameter ratio of the inner material to the outer material, f, to understand the differences with the metal-nanoparticle case as well as the resonant-frequency dependence on f. The calculations in this part are also carried out in the quasistatic limit with the scheme described in [7]. The resulted field-enhancement factor is

$$\eta = \left|1 + 2\frac{(\varepsilon_2 - \varepsilon_m)(\varepsilon_1 + 2\varepsilon_2) + f^3(\varepsilon_1 - \varepsilon_2)(\varepsilon_m + 2\varepsilon_2)}{(\varepsilon_2 + 2\varepsilon_m)(\varepsilon_1 + 2\varepsilon_2) + f^3(2\varepsilon_2 - 2\varepsilon_m)(\varepsilon_1 - \varepsilon_2)}\right|^2, \tag{2}$$

where ε_2 is the dielectric function of the outer spherical shell. Ag has the highest electrical conductivity among the whole metal elements and therefore exhibits the highest field enhancement for its nanoshells [7,9]. Hence, we choose Ag as the nanoshell material for the calculations.

3. Results and Discussion

Figure 1 shows the calculated spectra of field enhancement factors around nanoparticles of Pd, Ni, and Ti, which have been conventionally used for deuterium-containing fuel materials in the field of condensed matter nuclear fusion, in D_2 (Fig. 1(a)) and D_2O (Fig. 1(b)) under the electrostatic approximation. Local energy enhancement around 10 times is seen for a wide range of optical frequencies, through visible to near infrared and beyond. These nanoparticles thus concentrate optical or electromagnetic energy in their vicinity like antennae. Among the whole metal elements,

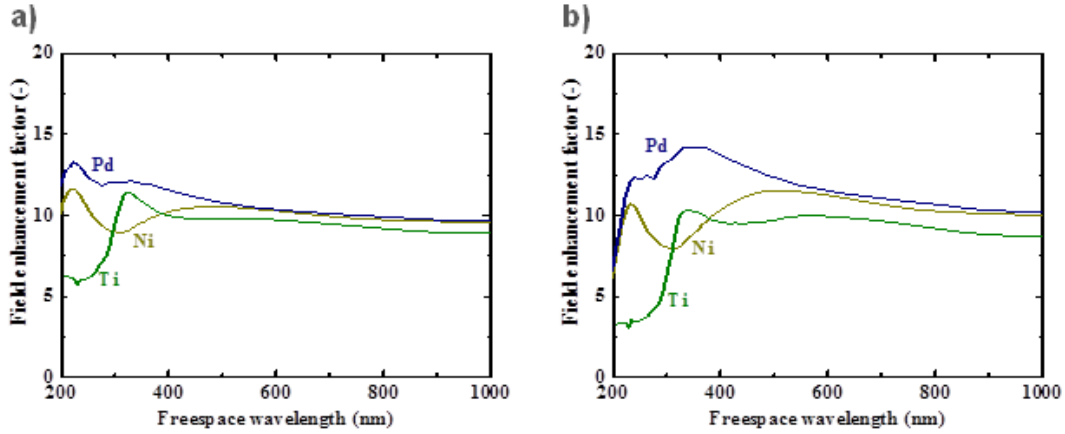

Figure 1. Electromagnetic field-enhancement factors around Pd, Ni, and Ti nanoparticles in (a) D_2 and (b) D_2O.

Al and the noble metals Ag, Au, and Cu are known to exhibit distinctively higher field enhancement factors than other metals due to their high conductivities [7,9]. A certain degree of field enhancement, however, is still attainable even for the common metals used for condensed-matter fusion, as seen in Fig. 1. Importantly, a certain number of the electrolysis-type condensed matter nuclear fusion experiments reported so far may actually have unknowingly benefited from this plasmonic local energy enhancement effect. Note that the field-enhancement-factor spectra (peak positions, intensities) are independent of particle size under the quasistatic limit but are valid for particle diameters of 10–100 nm in this calculation [7]. The peaks seen in these spectra are associated with the resonance or surface mode, characterized by internal electric fields with no radial nodes. The electrostatic calculations shown in this part and the following nanoshell part are valid for particles and shells smaller than the wavelengths at which the phase retardation is negligible throughout the objects. Also, the dielectric functions of materials used for the computation in this paper were empirical values for bulk materials, whose validity is debatable when the material sizes become smaller than 10 nm. The validity becomes problematic due to the electron mean free path limitation or scattering of conduction electrons off particle surfaces [6,10,11]. Therefore, the computation results for optical wavelengths under the quasistatic approximation are valid for metal particles and shells with diameters of 10–100 nm. Metal particles both smaller and larger than these limits exhibit broader plasmon resonances and smaller field enhancements due to surface scattering losses and radiative losses or electrodynamic damping, respectively [10,11]. The choice of particle sizes (10–100 nm) in this paper is therefore most suitable for plasmon-enhanced photonic applications due to the largest field enhancements. This size aspect should therefore be also accounted for the optimizing design of the deuterium-containing metal composite materials for condensed matter fusion.

Figure 2 shows the spectra of field-enhancement factors around Ag nanoshells with SiO_2 cores with varied f in D_2 and D_2O. We can take advantage of such gigantic energy concentration and resonant-frequency tunability with f, for instance by simply coating the conventional Pd-based fuel materials with metal nanoshells. Once an initial nuclear fusion reaction occurs in the energetic highly concentrated "hot spot" region around a metallic nanoparticulate, a gigantic amount of heat locally generated by the nuclear reaction induces subsequent reactions around the region by supplying the activation energy, and thus effectively initiates heat-mediated chain reactions to spread throughout the fuel material. The local energy focusing scheme we propose in this paper thus significantly increases the probability of the initial nuclear reaction even if the total power irradiated into the fuel material is the same, and therefore may

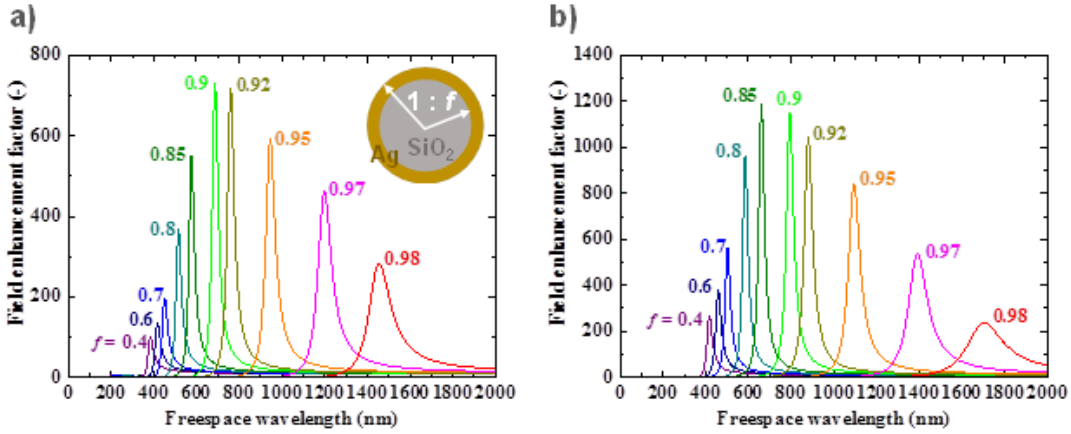

Figure 2. Electromagnetic field-enhancement factors around Ag/SiO_2 nanoshells in (a) D_2 and (b) D_2O.

effectively reduce the threshold input power. This enhancement approach may enable fusion with significantly lower deuterium loading than reported so far. Note that this metal-nanoparticle/shell-induced energy focusing scheme is applicable not only with lasers but also to the conventional electrolysis-type condensed-matter fusion, since the electromagnetic field enhancement is equivalent for both systems. Our approach may be also beneficial for laser fusion [9]. This sort of optical or electromagnetic model, incidentally, is simple and flexible to connect to other models, and may construct a comprehensive model by combining with transport and reaction submodels [12], for instance. The wide tunability of the resonant frequency to f seen in Fig. 2 allowing it to be matched with the wavelength of the incident laser or electric field offers a significant advantage in the use of nanoshells over solid nanoparticles. This tunability as well as the large field enhancement can be understood to be a result of the strong interaction between the plasmons for a metal sphere and a metal-dielectric hollow cavity, whose hybridization forms a metal shell [13,14]. Some of the plots in this paper incidentally coincide with those in [7] due to the assumed equivalency in the dielectric functions between D_2 and the air, and between D_2O and H_2O. The reproduction permission has been granted by the American Chemical Society; copyright 2008. This paper aims to give a conceptual understanding of the nature of the concentration of electromagnetic fields around nanoparticles/nanoshells, so we assumed that the case for a single stand-alone spherical nanoparticle/nanoshell geometry with high symmetry is suitable, due to its relatively straightforward computation and analysis. Therefore, in the present work, we show calculations only for spherical nanoparticles and nanoshells for the sake of simplicity in a preliminary investigation, but ellipsoidal ones would provide even higher field enhancement factors around their tips, because the sharper curvature of the metal/dielectric interfaces allows the electromagnetic field to concentrate further. This is known as the "lightning-rod effect" [6,15,16]. Also, surface plasmons located in between multiple metal nanostructures, or the so-called "gap plasmons," are known to have distinctive characteristics [17,18]. The shape and interparticle/shell effects will be discussed elsewhere.

4. Conclusion

In this work, we have proposed and numerically investigated a scheme to provide high-density optical or electromagnetic energy to fuel materials for condensed matter nuclear fusion. Plasmonic metal-nanoparticle field enhancement can be utilized by combining with laser or electric power input, for instance, by simply coating the conventional

Pd-based fuel materials with noble-metal nanoparticles or nanoshells. This field-enhancement effect can be a powerful method to boost the fusion-triggering electromagnetic or optical energy to significantly improve the reaction rate and experimental reproducibility as well as create low-D-load fusion systems. Importantly, this enhancement scheme is applicable both for gas- and liquid-phase systems, and furthermore, not only for laser/optical power, but also for the conventional electrolysis systems due to the equivalency between light and electromagnetic fields. We have also shown that the conventional fusion-catalyzing metals of Pd, Ni, and Ti themselves intrinsically exhibit a certain degree of field enhancement for their nanostructured form. Therefore, we point out that this plasmonic effect may have been unknowingly applied, particularly in the electrolysis-type fusion experiments reported so far. This field-enhancement phenomenon thus could be a clue to solve the mystery of the energy supplied to overcome the gigantic Coulomb barrier to produce the fusion reaction observed with visible rates, as well as a powerful tool for further technical progress.

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