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Creating nanostars with buckyballs

Young K. Bae *

Y.K. Bae Corporation, Tustin, CA 92780, United States

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ABSTRACT

We report creating superradiant quantum nanoplasmas (nanostars) by impacting buckyballs at hypervelocities (v >100 km/s) in an innovative tabletop apparatus. The nanostars are estimated to have ~10 TPa transient pressures and convert ~35% of impact energy into soft-X-ray energy. The ultrahigh-efficiency conversion is proposed to result from Dicke Superradiance of Metastable Innershell Molecular State, originally discovered by the author and his colleagues in 1994. The usage of buckyballs and successful orders-of-magnitude scaling down of the apparatus size and complexity establish an innovative tabletop method for generating, studying, and utilizing matter in planetary or stellar interiors and open doors to numerous unprecedented applications.

1. Introduction

Investigation and understanding of materials under extreme conditions, High Energy Density Materials, as in planetary or stellar interiors are crucial for advancing a wide range of scientific and technological fields, such as astrophysics [1,2], inertial confinement fusion, [1,2] X-ray lasers [3], material science [4–7] and biological science [7]. Recently, there have been extensive researches on Warm Dense Matter, which is a non-equilibrium state of matter between solid and plasma, and is too dense to be described by weakly coupled plasma physics, yet too energetic to be described by condensed matter physics [8]. Warm Dense Matter is expected in the cores of some large planets, in the inertial confinement fusion during the solid to plasma phase transition driven by laser pulses, and other systems that start as solids and are heated to become plasmas [8].

Recent theoretical studies have predicted High Energy Density Materials and Warm Dense Matter may have rich quantum many-body characteristics [4–6], including that metals may become insulators at high pressures [5,6,9]. Atomic quantum effects that result from innershell electron excitation and ionization have been theoretically studied for many of technologically important materials, such as aluminum, silicon, and iron [10,11]. For example, the theoretical Hugoniot curve of aluminum has two density maxima corresponding to full ionization effects of the L (pressure ~30 Tpa or 300 Mbar) and K (pressure ~400 TPa or 4 Gbar) electron shells [10,11]. At shock pressures on the order of 10 TPa (100 Mbar or 10^{13} J/m^3) aluminum would have 4 times of its normal density and an energy per atom greater than 260 eV, which is sufficient enough to excite or ionize the L-shell electrons.

In addition to these atomic effects, the effects of crystalline or molecular states in such matter, of which optical transition energies are predicted to range from hundreds of eV to tens of keV, have also been theoretically investigated [4,5,9]. In their ab initio quantum calculations, Younger et al. [12] found that when an ensemble of He atoms are highly compressed, they may form tightly bound quasimolecular states. Winterberg [13] predicted an existence of quasimolecular states at pressures on the order of 10 TPa (100 Mbar) and super-intense X-ray radiations during their transition from atomic states to molecular states.

In comparison with the extensive theoretical work, experimental observations of quantum effects in High Energy Density Material and Warm Dense Matter have been very scarce. Traditionally, the focuses of experimental works on High Energy Density Material and Warm Dense Matter have been on their thermodynamic properties, such as EOS (Equation of State) and Hugoniot curves. These materials have been produced and investigated with the use of ultra-large scale experimental setups, such as underground nuclear explosions [14,15], laser fusion facilities [16], z-machines [17] and X-ray Free-Electron Lasers (XFEL) [3,6,7]. However, a definitive experimental observation of the existence of the quantum effects that were predicted by the theoretical works has been prohibited by the large uncertainties in the experimental data [10,11,14]. The reason for this lack of progress results from the extreme complexity in the experimental setup and data interpretation, which obscured the manifestation of the quantum phenomena. Therefore,

* Tel.: +1 714 838 2881; fax: +1 714 665 8829.
E-mail address: ykbae@ykbcorp.com.

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non-destructive straightforward experimental methods, which are cable of producing these materials and permitting more detailed studies on their quantum characteristics, such as spectral characteristics, have been desired.

To develop such non-destructive experimental methods, the author and his colleagues investigated the feasibility of generating and studying highly compressed matter by impacting various bio and water nanoparticle at hypervelocities ($v \sim 100$ km/s) on various targets at the Brookhaven National Lab in the early 1990s [18,19]. It was hypothesized that if the number of atoms in nanoparticles is large enough, the nanoparticle impact can generate strong shocks that can produce the highly compressed matter. One of the crucial questions was what the threshold number of atoms in the nanoparticles is to produce hydrodynamic shock characteristics. With number of atoms in nanoparticles greater than the threshold number, the pressure P_s and the density ρ_s of the shocked target material in a one-dimensional strong shock produced by the nanoparticle particle impact at a velocity v can be approximated by [18,20]:

$$P_s = \frac{4}{3}\rho_P v^2, \tag{1}$$

$$\rho_S = \frac{(\gamma+1)}{(\gamma-1)}\rho_T, \tag{2}$$

where ρ_P and ρ_T are normal densities of projectiles and targets, and γ is the adiabatic index. For example, these equations predict that at $v \sim 100$ km/s, large water nanoparticles can generate shock pressures exceeding 10 TPa (100 Mbar). If the threshold number of atoms in the nanoparticles is smaller than 1000, a principal advantage of using nanoparticles for generating such high pressure shocks for producing High Energy Density Material and Warm Dense Matter is in that they can be readily charged and accelerated to such hypervelocities greater than 100 km/s with the use of compact accelerator technologies, perhaps similar to that of dental X-ray generators.

In our study at Brookhaven National Lab [18,19], the author and his colleagues proved the feasibility of generating the 10 TPa (100 Mbar) shocks and discovered anomalous signals, when the nanoparticles were directly impacted on and detected by Si particle detectors with windows sufficiently thick enough to block the penetration of the nanoparticles completely. With the use of the anomalous signals as functions of nanoparticle kinetic energy, the amounts of energy deposition through thin films were measured [18,19]. In these experiments, it was observed that the energy deposition of nanoparticles was very different from that of atoms. The deposited energy of individual atoms was flat over the investigated impact velocity range, on the other hand that of nanoparticles was proportional to v^2 as in Eq. (1). The observed v-square dependence of the energy deposition was used to prove the feasibility that the nanoparticles can be used to generate strong shocks [18]. The amount of the energy density in the thin film deposited by the nanoparticle impact was measured to be on the order of 10^{13} J/m^3, which is equivalent a pressure of 10 TPa (100 Mbar), in qualitative agreement with the pressure obtained with Eq. (1) [18]. However, the nature and production mechanism of the anomalous signals had been unresolved over 14 years [18,19].

In 2008, inspired by the theoretical proposition by Winterberg [13], the author reanalyzed the BNL data and concluded the anomalous signals resulted from soft X-ray photons from the optical decay of Metastable Innershell Molecular State in highly compressed matter generated by the nanoparticle impact [20]. By reinterpreting the Brookhaven National Lab data, the author found that the photon energy from the optical decay was in the range of 75–100 eV for Si targets. One surprising aspect of the discovery was that the conversion efficiency of the nanoparticle kinetic energy to photon energy was as high as ∼38% [20]. Such a high energy conversion efficiency indicates that the overall optical decay process of Metastable Innershell Molecular State in the nanoplasma is faster than non-radiative decay processes, which are typically orders of magnitude faster than the former in non-compressed solids. Since the size of the impact generated nanoplasmas are typically smaller than or on the order of the wavelength of radiation involved, the author proposed [20] that the Dicke Superradiance [21] mechanism speeds up the radiative process by orders of magnitude and permits efficient optical probing of the transient states in the time scale of tens of fs.

We report here creating the superradiant quantum nanoplasmas, which are defined here as nanostars, by impacting buckyball ions (C_{60}^+) on Al at hypervelocities ($v > 100$ km/s) in an innovative tabletop apparatus. The nanostars are estimated to have ∼10 TPa (100 Mbar) transient pressures and measured to convert ∼35% of impact kinetic energy into soft-X-ray energy, which is similar to the one observed (∼38%) at Brookhaven National Lab for Si. The present paper reports experimental generation of Dicke Superradiance of Metastable Innershell Molecular State in highly compressed materials, such as High Energy Density Material or Warm Dense Matter, in a table-top non-destructive apparatus that is completely different from and orders of magnitude smaller than that at BNL [18,19].

2. Metastable Innershell Molecular State

The theoretical Hugoniot curves related to High Energy Density Material and Warm Dense Matter of many elements, such as aluminum, silicon, and iron, show quantum effects of inner-shell excitation and ionization near or above pressures of 100 Mbar (10 TPa) [10,11]. Intuitively, innershell electrons of these atoms can be modeled to the first order as the closed outershell electrons similar to that of rare gas atoms. It is now well established that when the closed outershell electrons of the rare gas atoms are excited or ionized, they can readily form transient molecules, excimers, with a pairing ground state atom. In this paper, the author proposes that Metastable Innershell Molecular State can be modeled as an analogue to the excimer state.

A realistic theoretical picture of the Metastable Innershell Molecular State requires full blown ab initio calculations that can handle molecular orbits; however, the barriers to such ab initio calculations are formidable owing to the extreme computational difficulty in solving the relevant many-body problem [10–12]. Consequently, such quantum plasmas have been theoretically described by atoms with electronic structures in terms of statistical models, such as Thomas–Fermi model, Spherical Cells or Jellium of Charges. Many EOS models rely on the Thomas–Fermi (TF) model of dense matter [10,11]. These approaches provide only semi-classical descriptions of electrons, and are valid over a limited range of conditions. At intermediate shock pressures, when the material becomes electronically excited or partially ionized, the EOS depends on the precise quantum-mechanical state of the matter, i.e. on the electronic shell structure. Recently Pain applied a quantum self-consistent-field (QSCF) EOS model, in which potential energies and bound-electron wave functions are determined by solving Schroedinger equations with a self-consistent procedure in the density functional theory using a finite-temperature exchange-correlation potential [10,11]. Hugoniot curves of variety of materials were calculated and the results showed quantum innershell effects clearly. On the other hand, the effects of molecular orbitals of innershell electrons have been unincorporated into these models.

The potential existence of tightly bound transient quasimolecular states, similar to Metastable Innershell Molecular State, in highly compressed plasma with relatively low ion temperatures was numerically investigated and predicted by Younger et al.