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EXPLOITATION OF NEW MATERIALS PROCESSING IN A MEGA-GRAVITY FIELD†

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Abstract—A strong acceleration field (mega-gravity) can cause the sedimentation of even atoms and is expected to create an unique one-dimensional crystal strain state, i.e. an instability in molecular or crystalline state in multi-component condensed matter. However, materials science research under the mega-gravity field has now remained unexploited, while microgravity has been much used in many fields. We developed a self-consistent theory for sedimentation of atoms in condensed matter, and an ultracentrifuge apparatus to generate an acceleration of over 1 million $(1 \times 10^6)g$ at high temperature. Recently, we for the first time formed an atomic-scale-graded structure by the sedimentation of atoms, and observed crystal growth in an alloy under a mega-gravity field. It is expected that the availability of mega-gravity may offer us new and powerful options in materials processing in terms of controlling compositions even of isotopes, of forming atomic-scale-graded structure or nonstoichiometric structure, and of controlling the ordering of atoms or molecules.

1. INTRODUCTION

Gravity fields that exist in nature are very weak, while we sometimes experience strong accelerations in case of earthquake, explosion or impacts. The value of gravity on planets is less than several g ($1g = 9.8$ m/s^2), and even on the sun it is at most $30g$. Figure Fig. 1 shows the degrees of acceleration that exist in nature or are artificially generated. In nature, strong gravity fields of over $10,000g$ may exist only at degenerate stars or neutron stars. On the other hand, microgravity can be obtained in space, while it is difficult realize on earth. Well, what phenomena at the atomic level happen in solids at very strong acceleration? We know that sedimentation of macro-particles arises even at earth's gravity ($1g$), and that Brownian particles in a liquid can be concentrated by using a conventional ultracentrifuge machine. A mega-gravity field may cause the sedimentation of even atoms, and would be expected to create an unbalanced crystal state due to one-dimensional displacement of atoms, i.e. an instability in molecular or crystalline state in multi-component condensed matter.

Pressure or temperature can be easily controlled, but it is much harder to control the composition in condensed matter. Sedimentation of atoms in condensed matter can be used to control composition based on differences in atomic weight and volume, while electromigration is based on differences in electric charge. Sedimentation might also be used for concentrating elements or isotopes and for controlling impurity and density distributions. However, sedimentation of atoms is very difficult to realize in solids or liquids, because an atom's chemical potential is usually much greater than the mechanical energy. Our previous analyses based on a self-consistent theory [1,2] revealed that the concentrations of component atoms in an alloy or compound can be changed, often remarkably, and mostly at an acceleration field above that where the external energy stays in harmony with the thermal energy.

No sedimentation of component atoms in a solid (alloy or compound) had been reported, while sedimentation macro-particles in liquids is used in biochemistry (e.g. [3,4]). There had been only a few experiments on sedimentation of Au isotopes in some elemental metals with low melting temperatures [5–7]. In these experiments, the concentrations of the isotope were at an impurity level, and the achieved concentration changes were small. The main reason for the difficulty of such

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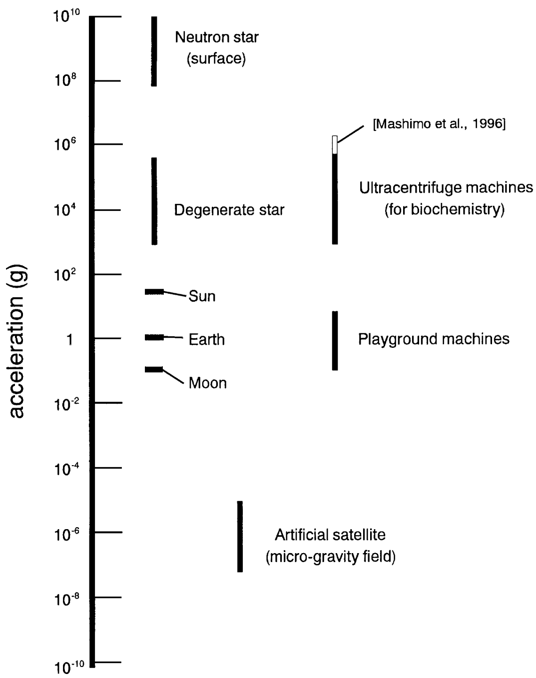

Fig. 1. Acceleration fields that exist in nature or are artificially generated.

experiments in solids has been that there was no ultracentrifuge machine that simultaneously generated on the order of $10^6 g$ and operated at high temperature. If such ultracentrifuge technology were established, it is expected that a new extreme-conditions science of strong acceleration fields in condensed matter and related application research would be started in many fields.

In 1996, we developed an ultracentrifuge apparatus that can generate acceleration fields of over $10^6 g$ at temperatures of several hundreds °C for several days [8]. Recently, we succeeded in forming composition distributions due to sedimentation of component atoms in an alloy [9]. In the present paper, the history and the recent progress of studies under a strong acceleration field are reviewed. The effect of a strong acceleration field on atoms, molecules and crystals in condensed matter, along with possible applications, are discussed on the basis of the theoretical and experimental results.

2. GENERATION OF A MEGA-GRAVITY FIELD IN CONDENSED MATTER

We developed a new ultracentrifuge capable of generating very high accelerations. Ultracentrifuges were developed and much improved before 1940 for studies of sedimentation and concentration of micro-particles and macromolecules especially in biochemistry. The machines developed up to 1940 and the present conventional ones of highest acceleration fields are shown in Table 1. In the 1920s, Svedberg and his collaborators first developed an ultracentrifuge, which generated an acceleration field of $5000g$ for convection-free sedimentation of macro-particles in liquids. They developed two kinds of ultracentrifuges: an electrical motor-driven-type with ball bearings (500 $-15,000g$) and an oil turbine-driven-type (15,000 $-750,000g$) for sedimentation equilibrium measurements in liquid solutions of very high molecular weight compounds and for observing the setting of particles [3,10]. Then, air-driven ultracentrifuge machines were put in use [4]. Henriot and Huguenard constructed a simple air turbine, which was both driven and supported by a system of directed air jets [11]. This turbine could achieve a very high rotation rates but temperature control was difficult. Beams *et al.* developed a self-balancing ultracentrifuge to overcome the difficulties of the above machines [12]. The electrical motor-driven ultracentrifuge machine also has progressed [13].

The capability of the present conventional ultracentrifuges for liquids in biochemistry are as follows: the maximum rotation rate for an 70–150 mm inner diameter is 10,000–150,000 rpm, so that the maximum acceleration is $(8\text{–}9) \times 10^5 g$. However, no ultracentrifuge for high temperatures has been developed, probably because the rotation support or the strength of the rotor might fail at high temperature.

In order to realize the sedimentation of atoms at high concentration (even a component of an alloy or a compound), or to examine the changes in molecular or crystalline state under strong acceleration, an acceleration of $10^6 g$ at high temperature for a long time would be indispensable. For such studies, the authors developed an ultracentrifuge that generates strong acceleration fields up to or over $10^6 g$ at several hundred °C for several days [8]. Figure 2 shows a schematic layout of this apparatus [8]. The system consists of a turbine motor with oil floating bearing and a specimen rotor. The turbine motor is driven by hot compressed air. The specimen rotor of 46 mm in outer diameter is made of a titanium alloy. The specimen can be heated up to higher than 300°C. The maximum measured rotation rate was 224,000 rpm, and the maximum acceleration 20 mm from the axis was $1.12 \times 10^6 g$.

3. SEDIMENTATION OF ATOMS IN BI–SB SYSTEM ALLOY

We first examined a completely miscible alloy, Bi–Sb (30 : 70 in mol%) [9], under a mega-gravity field. Figure 3 shows an EPMA color-mapping