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EDITORIAL

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2020—Transformative science in the pressure dimension

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Materials transform abruptly under compression, with their properties varying as strong functions of pressure. Advances in high-pressure and probe technology have enabled experimental characterizations up to several hundred gigapascal (GPa). Studies in the physical sciences are now expanding to include a vast previously uncharted pressure region in which transformative ideas and discoveries are becoming commonplace. *Matter and Radiation under Extremes (MRE)* is taking advantage of this opportunity to provide a forum for publishing the finest peer-reviewed research in high-pressure science and technology on the basis of its interdisciplinary interest, importance, timeliness, and surprising conclusions. This *MRE HP Special Volume* gathers together a set of contemporary perspectives, highlights, reviews, and research articles in multiple disciplines of high-pressure physics, chemistry, materials, and geoscience that illustrate both current and forthcoming trends in this exciting research area.

The year 2020 has turned out to be a bountiful one for high-pressure physics, culminating in milestone achievements in a couple of century-old quests: room-temperature superconductivity and metallic hydrogen. These two phenomena are closely related to each other: the new families of superconductors with the highest critical temperature T_c can also be viewed as hydrogen alloys with minor impurities of key secondary elements. Theorists at Jilin University have searched the periodic table for the most appropriate secondary elements and have predicted the specific structures and T_c of the resulting materials at high pressures, leading the way for experimentalists to successfully discover some highest-T_c superconductors based on hydrogen-dominant compounds alloyed with sulfur and rare-earth elements. In this *HP Special Collection*, Lv *et al.*[1] contribute an insightful perspective on the guiding criteria for optimizing superconductivity: a large hydrogen-derived electronic density of states at the Fermi level and large modifications of the electronic structure in response to vibrations of the hydrogen atoms. To satisfy both criteria and stabilize the hydrogen-dominant compounds requires pressures of several hundred GPa, with hydrogen approaching its atomic metallic state. Struzhkin *et al.*[2] contribute a comprehensive review on high-pressure experimental determinations of electrical conductivity, magnetic susceptivity, crystal structure, and chemical composition for hydrides with T_c near room temperature. Chen[3] presents an expanded view of all high-T_c superconductors based on the general theme of phonon mode softening. This approach leads to the suggestion that ferroelectrics and other materials in the vicinity of structural instability might exhibit high-T_c superconductivity at pressures low enough for possible practical applications.

Successful scientific investigations at high pressure rely on the availability of appropriate technology. The symbiotic development of diamond anvil cells (DACs) to create ultrahigh P–T environments and synchrotron X-ray techniques to probe materials *in situ* has enabled the exploration of many areas of high-pressure science. Beyond the current static compression frontier, pure hydrogen has been predicted to transform to a metal that has been postulated to be a wonder material as a high-T_c superconductor, a two-component (electron and proton) superfluid, a new state of matter, the most energetic material, the most efficient fusion fuel, and the main constituent of giant planets and other celestial bodies. Attempts to reach the necessary pressures and to demonstrate metallization have become a century-old quest by physicists and astrophysicists, and have provided a unique driving force for advancing the high-pressure experimental frontier. Gregoryanz *et al.*[4] present a critical account of the various claims of discovery of metallic hydrogen that need to be substantiated and reproduced. The true significance of "metallic hydrogen" relies upon its postulated exotic behaviors, and these can only be confirmed by further advances in our current experimental capabilities. Ji *et al.*[5] describe the technical advances that have been made in overcoming the seemingly insurmountable challenge of X-ray diffraction measurement of the extremely weak hydrogen signal when attempting to determine the crystal structures of hydrogen phases III and IV up to 254 GPa. Hirao *et al.*[6] present an overview of the high-pressure facility at the BL10XU beamline of the SPring-8 synchrotron facility, which integrates membrane-controlled

pressurization of a DAC with *in situ* X-ray diffraction, X-ray Mössbauer spectroscopy, Raman spectroscopy, and electrical resistance measurement probes, thus providing comprehensive information on pressure-induced changes during experiments. Successful high-pressure experiments depend critically on all components of the pressure assembly. Walker and Li[7] describe the development of superior castable solid pressure media for multianvil devices that substantially improve the operation of such high-pressure devices with large sample volumes.

External pressure directly compresses chemical bonding and affects the structure of condensed matter, thus having a great impact on chemistry and its applications to materials sciences. Yoo[8] presents a systematic review of pressure-induced changes and their energetic and electronic consequences for simple molecular systems of light elements such as H, C, O, and N, which, in effect, are opening a novel frontier of high-pressure organic chemistry with new rules determined by the pressurized bonding. The development of novel materials based on the covalently bonded diamond form of C is a classical example of a successful application of high-pressure research. Xu and Tian[9] discuss improvements in hardness and toughness beyond those of single-crystal diamond achieved by additional considerations of nanoscaling, dimensionality, and nanotwinning. Yang *et al.*[10] describe a study of the yield strength of tungsten based on diffraction peak width. Their results show that the strength of 10 nm nanograins is 3.5 times that of 1 μm–3 μm grains, and the Hall–Petch relation is thus satisfied. The Hall–Petch relation holds under high pressure, as strength increases with increasing pressure. Chen[11] discusses the powerful rDAC technique for conducting radial X-ray diffraction under high pressure and thereby yielding quantitative information on the Hall–Petch relation by probing nanoscale effects on dislocation, grain rotation, and ductility. Such information provides guidance for developing methods to enhance the strength of nanomaterials and for high-pressure fabrications. Halide perovskites represent an emerging class of photovoltaic and optoelectronic materials whose properties are strongly dependent upon composition, dimensionality, and morphology. Pressure provides an additional important parameter by which to tune and optimize perovskite functionality, as reviewed by Li *et al.*[12]

Recent progress in high-pressure geoscience is particularly exciting. For the first time, major cataclysmic events in the atmosphere, hydrosphere, biosphere, and lithosphere during Earth's long history can be unified under a single theory based on pressure-induced chemistry in the bottom half of the lower mantle. Mao and Mao[13] summarize the essential research directions needed to complete this grand picture.

In the future, after this debut 2020 issue, we aim to make the *MRE HP Special Volume* a yearly event to cover key progress in diverse areas of this multidisciplinary field.

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