Dense Hydrogen and Quantum Sensing under Extreme Pressure

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Abstract

Dense hydrogen has long been regarded as one of the most fascinating systems in condensed matter and high-pressure physics because of its predicted metallic, superconducting, superfluid, and other exotic quantum states. Owing to its light mass, strong nuclear quantum effects, and pronounced isotopic dependence, hydrogens exhibit an exceptionally rich phase diagram and novel properties that remains far from fully understood.

Using high-pressure and low-temperature Raman spectroscopy together with optical transmission measurements, we have systematically investigated the phase behavior of H_2, D_2, and HD mixtures up to 350 GPa over the temperature range of 10–300 K. We report the first observation of the **ΔJ = 0** rotational excitation in dense hydrogen, providing new insight into molecular rotational dynamics under extreme compression [1]. Our studies also reveal an unusual isotope-doping effect in H_2–HD–D_2 molecular alloys below 200 GPa, originating from the nuclear quantum effects and exchange symmetry[5-7]. At higher pressures, the HD mixture exhibits the same phase-transition sequence (**III**–IV–V) as pure hydrogen, while its pressure-dependent band gap remains comparable to those of H_2 and D_2, indicating that isotopic alloying has little influence on the metallization pressure[3]. These results provide new insights into the quantum behavior of dense hydrogen approaching the metallic regime.

The definitive confirmation of superconductivity at very high compressions in diamond anvil cell ultimately requires local magnetic measurements, which remains a major experimental challenge. To address this challenge, we have developed quantum sensing techniques based on nitrogen-vacancy centers in diamond and silicon-vacancy/divacancy defects in 4H-SiC for in situ magnetometry in diamond anvil cells. These quantum sensors enable highly sensitive local magnetic detection in microscopic samples under multi-gigapascal pressures and have been applied to pressure-induced magnetic phase transitions in $Nd_2Fe_{14}B$ [8], the pressure-dependent superconducting phase diagram of $YBa_2Cu_3O_{6.6}$[4], and the direct observation of the Meissner effect in $La_3Ni_2O_{7-\delta}$ by combining local magnetometry with four-probe electrical transport [2]. Spatial mapping of the Meissner response further visualizes superconducting inhomogeneity and provides complementary magnetic and electrical evidence for superconductivity.

Together, these advances establish quantum sensing as a powerful platform for exploring magnetism and superconductivity under extreme conditions and open new opportunities for future studies of dense hydrogen and hydride superconductors at ultrahigh pressures.

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