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**Al**$^+$ optical clocks for fundamental physics, geodesy, and quantum metrology$^1$

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Laser-cooled trapped atoms have long been recognized as potentially very accurate frequency standards for clocks. Ultimate accuracies of $10^{-18}$ to $10^{-19}$ appear possible, limited by the time-dilation of trapped ions that move at laser-cooled velocities. The Al$^+$ ion is an attractive candidate for high accuracy, owing to its narrow electronic transition in the optical regime and low sensitivity to ambient field perturbations. Precision spectroscopy on Al$^+$ is enabled by quantum information techniques. With Al$^+$ “quantum-logic” clocks, the current accuracy of $8.6 \times 10^{-18}$ has enabled a geo-potential-difference measurement that detected a height change of $37 \pm 17$ cm due to the gravitational red-shift. We have also observed quantum coherence between two Al$^+$ ions with a record Q-factor of $3.4 \times 10^{16}$, and compared the Al$^+$ resonance frequency to that of a single Hg$^+$ ion to place limits on the temporal variation of the fine-structure constant. This work is done in collaboration with D. B. Hume, M. J. Thorpe, D. J. Wineland, and T. Rosenband.

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