

Spectroscopy of a single Al⁺ ion via coupling to Be⁺

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We perform precision spectroscopy on ²⁷Al⁺ with the aid of a ⁹Be⁺ ion. Using sympathetic cooling and quantum state transfer, we efficiently interrogate the ¹S₀ → ³P₁ and ¹S₀ → ³P₀ transitions.

Single ion optical clocks have the potential to achieve very high accuracies [1]. In the past, the choice of atomic species was limited to those ions which have suitable transitions for laser cooling, state preparation, and detection, as well as a stable clock transition. Recently however, a two-ion optical clock was proposed [2] in which the cooling and read-out functions are fulfilled by an auxiliary ion. We have implemented this technique, using a Be⁺ ion to help interrogate the ³P₀ and ³P₁ transitions of Al⁺.

The ¹S₀ → ³P₀ transition in ²⁷Al⁺ (λ ≈ 267 nm) is attractive for optical clocks, because of its long lifetime (≈ 30 s), low sensitivity to magnetic fields, as well as the absence of an electric quadrupole shift. However, the only transition that would scatter enough photons for direct laser-cooling and state detection is the ¹S₀ → ¹P₁ transition at 167 nm, which is beyond the limits of readily accessible laser technology.

Instead we simultaneously load single Be⁺ and Al⁺ ions in a linear Paul trap. The two ions form a stable crystal whose motional modes are cooled to near the ground state by Doppler cooling the Be⁺ ion. After Doppler cooling, we interrogate the spectroscopy transition in Al⁺ with a stable laser (δν < 3 Hz), which leaves the Al⁺ ion in a superposition of ground and excited states. Next we cool one motional mode of the two-ion crystal to the ground state ($\bar{n} < 0.02$) with Raman sideband cooling pulses [3], which prepares the two-ion crystal for quantum state transfer.

As explained more thoroughly in [2], we are able to faithfully transfer the quantum state from one ion to the other through their shared motional (vibrational) state. Since the motional frequencies (several MHz) are well resolved for both the Al⁺ and Be⁺ ions, we can cleanly drive transitions |g, 0⟩ → |e, 1⟩ and |g, 1⟩ → |e, 0⟩ where g and e are the internal ground and excited states, and 0 or 1 is the motional quantum number. We transfer the internal state of the Al⁺ to the Be⁺ by applying a |g, 0⟩ → |e, 1⟩ pulse on the Al⁺, followed by a |g, 1⟩ → |e, 0⟩ pulse on the Be⁺ ion. This pulse combination transfers the Al⁺ excited state amplitude to the Be⁺ excited hyperfine state amplitude, which can be efficiently detected.

We have used this technique to perform precision spectroscopy on transitions connecting the ¹S₀ ground state to the three hyperfine levels (F=3/2, 5/2, 7/2) of the ³P₁ state of ²⁷Al⁺. Quantum state transfer steps similar to those above also allowed us to deterministically prepare the Al⁺ ion in each of its ground Zeeman states ¹S₀ (F=5/2, m_F=-5/2...+5/2) and perform spectroscopy on all of these internal states.

We have also performed spectroscopy on the ¹S₀ → ³P₀ clock transition. A narrow laser was locked to the mean frequency of the transition pair ¹S₀ (m_F = ±5/2) → ³P₀ (m_F = ±5/2). Its frequency was measured using a femtosecond comb laser [4] referenced to the NIST-F1 Cs fountain [5] through a hydrogen maser.

This technique allows precise measurements on ions that are otherwise inaccessible for lack of suitable cooling or detection transitions. Another promising clock ion, based on the ¹S₀ → ³P₀ transition in ¹⁰B⁺ (also at 267 nm), could be evaluated with only minor changes in the apparatus.

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