

The 3^1S_0 – 3^3P_0 transition in the aluminum isotope ion $^{26}\text{Al}^+$: A potentially superior passive laser frequency standard and spectrum analyzer

(individual ion/trapped in vacuum/zero electronic angular momenta/no frequency shifts)

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ABSTRACT The aluminum 26 isotope ion is proposed here as a possible candidate for a superior atomic clock. For this even isotope, the extraordinarily long lifetime of the 3^3P_0 state offers a potential clock transition (3^1S_0 – 3^3P_0) linewidth of 300 μHz . The $m_F = 0 \rightarrow 0$ transition has only a quadratic Zeeman shift $\approx 4 \times 10^{-18}$ at 0.1 Gauss magnetic field, compared to $\approx 10^{-8}$ for the hydrogen maser. Electronic quadrupole moments vanish for both J and J' states and with them shifts due to electric field gradients. All shifts have been estimated and are orders of magnitude less than for Hg^+ and Ba^+ , which are being studied as atomic clock elements.

A mono-ion oscillator using the group IIIA ions was proposed as early as 1973 for use in a frequency standard or atomic clock (1). The use of an even, radioactive, isotope of thallium has been discussed in detail (2). Al^+ has a long-lived metastable 3^3P_0 state. Based on previous studies on Al^+ (3), the corresponding clock transition (3^1S_0 – 3^3P_0) linewidth is estimated as 300 μHz , or 3×10^{-19} of its optical transition frequency. This makes $^{26}\text{Al}^+$ a candidate for a potentially superior atomic clock. For comparison, the clock transitions for Ba^+ and Hg^+ , which have been used in the past mainly for technical convenience, are 5 mHz and 1.5 Hz wide, respectively.

To achieve the narrowest line that nature has to offer, an even isotope has to be used. The aluminum isotope ^{26}Al has a very long lifetime of 7×10^5 years against radioactive decay, a spin of 5, and an estimated magnetic moment of 2.8 nuclear magnetons (4). The spectrum of the $^{26}\text{Al}^+$ clock transition at 267.4 nm has a $m_F = 0 \rightarrow m_{F'} = 0$ component that shows only a quadratic Zeeman shift of $\delta_z/\nu \approx 4 \times 10^{-18}$ in a 0.1 Gauss field. This practically eliminates the need for magnetic field shielding. In the same field due to the hfs, on the other hand, the shift of the $0 \rightarrow 0$ clock transition is $\approx 2 \times 10^{-15}$ in $^{199}\text{Hg}^+$, $\approx 10^{-12}$ in $^{137}\text{Ba}^+$, and $\approx 2 \times 10^{-8}$ in the hydrogen maser. Likewise, because the electronic angular momenta for both ground and excited states vanish, the transition shows no electric quadrupole shift due to interaction with electric field gradients in an ion trap. These advantages of group IIIA ions for use in a mono-ion optical frequency standard or atomic clock have been recognized before. They were precisely the reasons for choosing the group IIIA ions in early proposals.

For $^{26}\text{Al}^+$, both the monitoring and clock transition wavelengths are at about 267 nm, close to the monitoring frequency used for Mg^+ . Thus the laser technology has been worked out to some extent. One drawback of Al^+ is its relatively low (3^1P_1 – 1^1S_0) transition rate of $3 \times 10^3 \text{ s}^{-1}$ used for cooling/monitoring. An ion trap system at liquid helium temperature with pre-LCR circuit cooling may solve the initial ion cooling difficulty. Also, a highly efficient light

collection system is called for. The pure ^{26}Al isotope is costly and chemically unstable. An alternative would be preparing an isotope-rich foil as an ion source through the nuclear reaction $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$ (5) at some nuclear accelerator facility as used in other radioactive isotope ion trapping experiments (6).

A spectroscopic study of the aluminum 26 isotope could proceed the same way as proposed for $^{204}\text{Tl}^+$ (2). Briefly, the 267.0-nm monitoring laser is tuned to the $F = 5$ to $F' = 6$ hfs component and is made circularly polarized so as to optically pump the ion into the opaque $m_F = 5$ level of the ground state. Quantization along the laser beam direction is assumed, and the effect of a small magnetic field applied perpendicular to the beam may be neglected for the pumping process. With the 267.0-nm laser turned off, a weak 267.4-nm flywheel laser linearly polarized parallel to the small dc magnetic field is applied to the ion. By tuning the laser frequency to the $m_F = 0 \rightarrow m_{F'} = 0$ component along the magnetic field, the forbidden optical transition will be excited one out of every four attempts.

Though currently no suitable laser flywheel oscillator is available for use in an active laser frequency standard, no serious obstacles appear to obstruct the realization with available means of an ultra-high-resolution optical spectrum analyzer or passive frequency standard based on the $^{26}\text{Al}^+$ ion.

For cooling and monitoring purposes, it may be advantageous to use the fully allowed (1^1S – 1^1P) transition at $\lambda_1 = 167.1 \text{ nm}$ instead of the weak intercombination line at 267 nm. Estimates suggest that dye laser power at $3\lambda_1 = 501.3 \text{ nm}$ circulating in a cavity might excite (1^1S – 1^1P) transition at rates as high as 10^6 s^{-1} when tightly focused on the stationary ion. One might think of mounting a UV filter-channeltron combination very close and without any collection optics beside the trapped ion and thereby collect a much larger fraction of the fluorescence photons than in the past experiments. Background might be very low because the filter does not pass the 501-nm light and the channeltron does not respond to it. This scheme might even be made to work for B^+ with the further advantage that the even nuclear spin ^{10}B isotope is stable and abundant.

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