# Towards Optical Control over the Lowest Nuclear Excited State in $^{229}$Th ◇

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The MLL IonCatcher buffer gas cell facility forms the key component of our experimental efforts to study the isomeric ground state transition of the lowest nuclear excited state in $^{229m}$Th at 7.6(5) eV as described in the 2007 annual report [1]. There the goal is to exploit the unique properties of this lowest excited nuclear state with its unprecedented narrow relative linewidth of about $10^{-21}$ for metrology as well as for fundamental physics studies (such as a potential time dependence of fundamental constants like the fine structure constant $\alpha$). Using the gas cell as an 'isomer generator' from the $\alpha$ decay of $^{233}$U, the production of the $^{229}$Th isomers can be decoupled from the fluorescence decay of the isomeric first excited state in $^{229m}$Th, thus avoiding any background contaminations from atomic or conversion processes.

In 2008 the experimental setup at the MLL-IonCatcher facility [2] has been improved. Detection of the UV fluorescence light (about 163(11) nm) from the isomeric decay of $^{229m}$Th, collected on a needle tip behind the buffer gas cell subsequent to $\alpha$ decay of $^{233}$U, is envisaged via an MCP and a phosphorous screen, observed by a highly sensitive CCD camera. In order to enable the operation of the MCP under optimum vacuum conditions even in view of the ambient gas load introduced by the buffer gas cell (operated at a helium pressure of 50 mbar), the isomer collection chamber and the UV detection section have been decoupled. A $MgF_2$ viewport flange (DN38CF), which allows for the transmission of deep-UV radiation, has been introduced between the two sections, thus enabling to achieve a vacuum pressure of $2{\cdot}10^{-8}$ mbar at the MCP. A deuterium lamp has been introduced into the collection chamber to characterize the detection properties of the MCP/CCD assembly via the prominent $D_2$ light around 160 nm, sent via a 50$\mu$m pinhole onto the MCP. Optimzation of the optical imaging is in progress.

In parallel the optical setup to enable sympathetic laser cooling of $^{229}Th^{3+}$ with laser-cooled $^{24}Mg^{+}$ ions in a linear Paul trap has been addressed. Once the energy of the isomeric ground state decay has been determined to a precision of about $10^{-4}$ - $10^{-5}$ optical control of this transition will be addressed. Laser cooling in a linear Paul trap is envisaged, exploiting the favourable atomic level scheme of $^{229}Th^{3+}$, which is displayed in Fig. 1. The level scheme of the lowest electronic levels corresponds to a Rn core plus a single valence electron. A closed 3-level $\lambda$ system and a closed 2-level system (both indicated in the figure) are available for laser cooling and fluorescence detection.

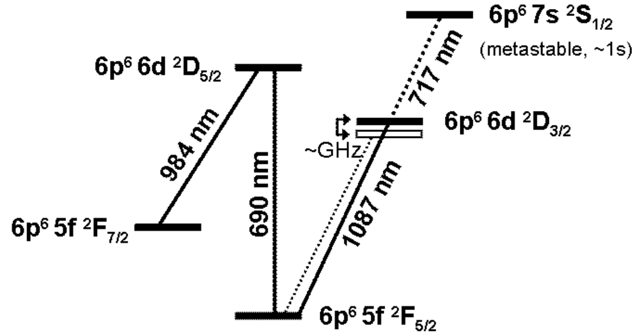


Fig. 1: Atomic level scheme of $^{229}Th^{3+}$ allowing for laser cooling.

From a closed optical transition a constant resonance fluorescence scattering will result, while after a nuclear excitation to the isomeric state the transition will be out of resonance, leading to a drop in the fluorescence intensity as an indicator for the isomer excitation process. This is schematically indicated in Fig. 2 and based on a detection scheme already proposed by Peik and Tamm [3] using a closed 2-level system in the electron shell. A nuclear transition to the excited state will result in a change of the nuclear moments and the spin, hence also of the hyperfine splitting. Using a double resonance method (similar to 'electron shelving'), $\omega_1$ will be out of resonance (in the order of GHz), thus leading to a drop in the resonance fluorescence.

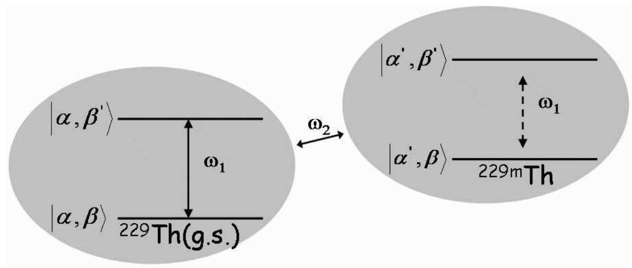


Fig. 2: Detection scheme for the excitation of the isomeric excited state in $^{229}$Th. $\alpha$ and $\beta$ denote the nuclear and electronic quantum numbers, respectively [3].

In order to prepare for the sympathetic laser cooling of $^{229m}$Th in a strongly coupled $^{24}Mg^{+}$ plasma, the construction of the necessary laser system has been started. A novel, compact and stable high power all solid state laser system has been acquired, emitting 1.4 W continuous wave at a wavelength of 559 nm or 380 mW near 280 nm, which is the required wavelength for laser cooling of $^{24}Mg^{+}$. The laser system consists of a 2 W Yb fiber laser with a line width of less than 200 kHz at 1118 nm followed by two home-built subsequent second harmonic generation (SHG) external ring cavities using LBO and BBO crystals, respec-

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tively. The system is designed to act as a detection and cooling laser for trapped $Mg^+$ ions driving the transitions from the ground state $3S_{1/2}$ to the $3P_{1/2}$ or $3P_{3/2}$ levels at approximately 280 nm. Fig. 3 illustrates the setup of the frequency quadrupling system to generate the required wavelength of 280 nm from the initial 1118 nm wavelength.

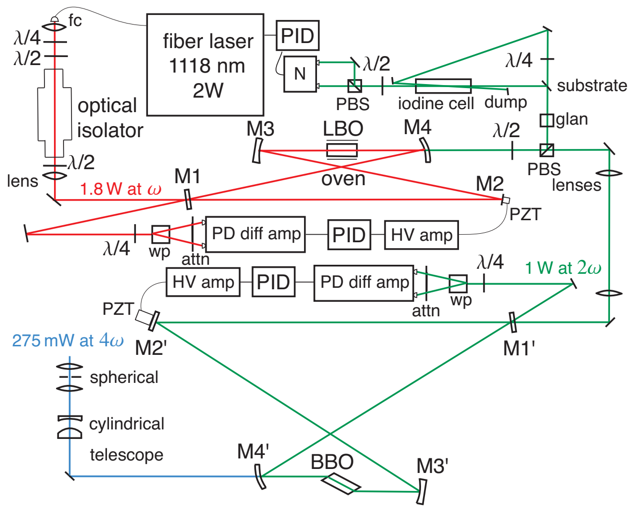


Fig. 3: Optical setup of the laser system with the frequency quadrupling setup.

The light coming from the fiber laser is collimated by the fiber collimator (fc) and passes the optical isolator after polarization adjustment by a quarter and a half wave plate ($\lambda/4$ and $\lambda/2$). After passing another half wave plate the beam is modematched (lens) into the LBO cavity consisting of mirrors M1, M2, M3, and M4. The light reflected at M1 passes a quarter wave plate and a Wollaston prism (wp) is attenuated (attn) and falls on a photo diode (PD) differential amplifier. That signal goes to a PID servo and after amplification (HV amp) is fed to the piezo (PZT) where the mirror M2 is mounted on. The second harmonic beam generated in the LBO crystal leaves the cavity via the output coupler M4 and 10 mW are separated from the beam for the iodine lock using a half wave plate and a polarizing beam splitter (PBS). With this beam we implement polarization spectroscopy using a glan laser polarizer (glan) and a New Focus Nirvana photo detector (N). The larger part traversing the PBS is modematched in the BBO cavity consisting of mirrors M1', M2', M3', M4' using two modematching lenses. The generation of the error signal is identical to the first cavity. The ultraviolet beam generated in the BBO crystal leaves the cavity via M4' and is projected into a Gaussian TEM00 mode and collimated with the help of a cylindrical and a spherical telescope. The whole setup fits on a breadbord measuring $90 \times 30\,\mathrm{cm}^2$ and is moveable.

Fig. 4 shows the hardware setup of an identical laser system at the MPQ/Garching, serving as prototype for the setup of our system, which is presently under construction. It is foreseen to start with characterizing studies of the cooling behaviour of the strongly coupled $^{24}Mg^+$ plasma in the existing PALLAS Paul ring trap prior to the construction of a dedicated linear Paul trap for the $^{229m}Th^{3+}$ laser cooling.

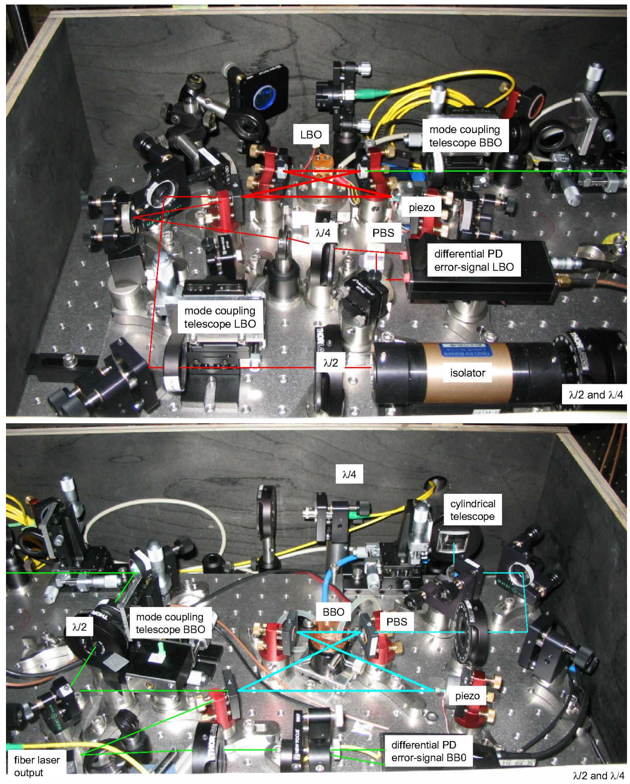


Fig. 4: Laser setup with frequency quadrupling system able to generate up to 350 mW of laser power at the wavelength of 280 nm suitable for $^{24}Mg^+$ laser cooling. The light path depicted in Fig. 3 has been overlaid to the actual optical assembly.

## References


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[2] J. Neumayr *et al.* Rev. Sci. Instr. **77** (2006) 065109
[3] E. Peik and Chr. Tamm Eur. Phys. Lett. **61** (2003) 181