STRAY-LIGHT SUPPRESSION FOR THE MIRACLS PROOF-OF-PRINCIPLE EXPERIMENT*

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The Multi-Ion Reflection Apparatus for Collinear Laser Spectroscopy (MIRACLS), currently under development at ISOLDE/CERN, aims to combine the high resolution of fluorescence-based collinear laser spectroscopy (CLS) with a high sensitivity. This will be achieved by confining 30-keV ion bunches in a Multi-Reflection Time-of-Flight (MR-ToF) device which allows laser spectroscopic probing for several thousand times. An MR-ToF setup operating at ~ 1.5 keV beam energy has been adapted for a proof-of-principle experiment. Thus, efforts had to be undertaken to reduce the laser stray light as the leading source of background of this apparatus, not originally designed for CLS. These measures enabled CLS of $^{24,26}\mathrm{Mg}^+$ ions in single-path mode, *i.e.* without ion trapping, which is the reference point to gauge the gain in sensitivity of the MIRACLS technique.

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1. Introduction

Collinear laser spectroscopy (CLS) is a powerful tool to measure nuclear properties such as spins, electromagnetic moments and differences in mean-square charge radii of short-lived radionuclides via their hyperfine spectrum [1–4]. For these measurements, a narrow-band laser beam

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is (anti-)collinearly overlapped with a fast beam of radionuclides. When the Doppler-shifted frequency of the laser beam matches the selected electronic transition frequency, the laser-excited atom or ion emits fluorescence light which can be monitored by photon detectors in an optical detection region.

In CLS, beam energies of $\geq 30\,\mathrm{keV}$ are used to minimize the Doppler broadening, which provides high spectral resolution, approaching the natural linewidth of the optical transition [4]. In order to increase the signal-to-noise ratio, CLS is performed with bunched beams [5]. Nevertheless, its fluorescence-light detection limits the applicability to nuclides with yields of at least a few thousand ions/s, depending on the specific case and spectroscopic transitions. In fact, the "effective laser probing" and observation time for fluorescence lasts at most a few microseconds when the bunch of radionuclides passes the optical detection region. This is in contrast to the nuclides' half lives which range from milliseconds to seconds and longer at low-energy branches of radioactive ion beam (RIB) facilities.

Matching the observation time to the nuclides' lifetimes would extend the reach of CLS to the most exotic nuclides available at today's RIB facilities. To this end, the Multi-Ion Reflection Apparatus for CLS (MIRACLS) is currently under development at ISOLDE/CERN. By repeatedly reflecting the ion bunch between two electrostatic mirrors of a Multi-Reflection Time-of-Flight (MR-ToF) device, the laser beam probes the ions during each revolution. Compared to conventional CLS, the observation time is therefore multiplied by the number of revolutions as well.

To demonstrate the MIRACLS technique, a low-energy MR-ToF device [6] has been adapted for CLS [7–9]. In the following, we describe the measures taken to reduce the laser-induced stray light which dominates the background in the fluorescence signal. As a result, conventional CLS, *i.e.* without ion storage, has been performed with $^{24,26}\mathrm{Mg}^{+}$ ions.

2. The proof-of-principle experimental setup for MIRACLS

As a more detailed discussion can be found in Ref. [7], the description of the experimental setup (see Fig. 1) is limited to aspects relevant for the present work. A continuous beam of $^{24-26}\mathrm{Mg}^{+}$ ions is captured in a He-buffer-gas filled Paul trap which provides well-defined ion bunches of $\sim 464\,\mathrm{eV}$ beam energy. After passing an electrostatic quadrupole bender, the ions enter the MR-ToF region. In order to establish conventional CLS, the ions are not stored in the MR-ToF device for the present measurements. Thus, the MR-ToF mirror electrodes are all grounded. Its central drift tube is biased to $-1010\,\mathrm{V}$ for an ion beam energy of $\sim 1.474\,\mathrm{keV}$ which is comparable to previous MR-ToF operation at this setup [7–9].

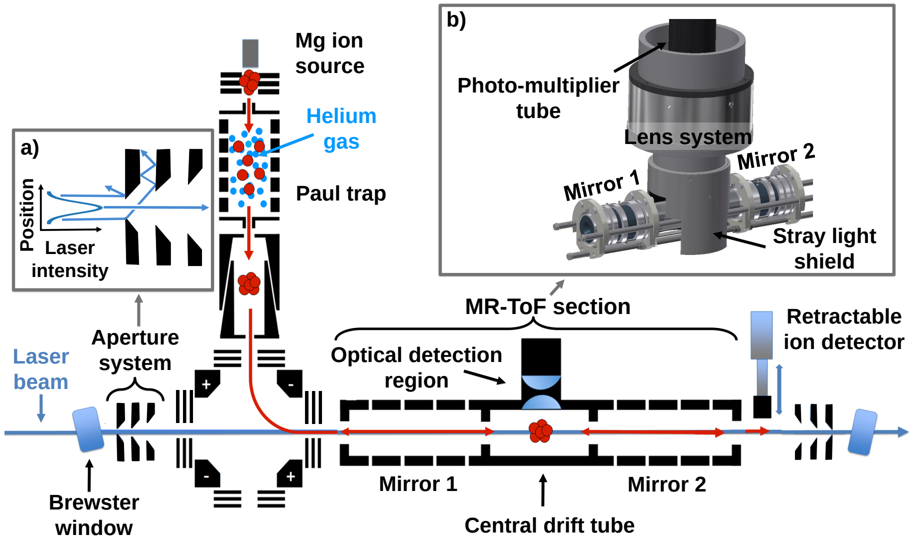

Fig. 1. Simplified schematics of the MIRACLS proof-of-principle experiment with close-up insets of the laser-entrance aperture system (a) and the stray light shield of the optical detection region (b). For details, see the text.

In the optical detection region located at the central drift tube, the fluorescent light is guided onto a photomultiplier tube by an optical lens system [10]. The photoexcitation of Mg^+ ions itself is achieved with a continuous-wave laser beam of $\sim 280\,\mathrm{nm}$ wavelength [7] which enters the setup through a Brewster-angled quartz window to minimise reflections. The laser and ion beams are collinearly overlapped along the MR-ToF axis. A retractable ion detector is located downstream of the MR-ToF device for beam diagnostics and allows the estimation of the number of ions in an ion bunch [11].

3. Stray-light suppression

In order to perform efficient CLS with a high signal-to-noise ratio, the background-photon rate in the optical detection region has to be minimised. The leading source of this photon background is laser stray light, for example, light scattered off components in the beam line, which finds its way into the photodetector. Therefore, the photon background is reduced by decreasing the scattered laser light reaching the detector. In the MIRACLS proof-of-principle setup, this is achieved by a lens system in front of the photomultiplier tube, similar to what is used at the COLLAPS beamline at ISOLDE [10], and by a stray light shield around the optical detection region. These are designed to block out photons which are geometrically not originating from the ions in the optical detection region, while not reducing the signal of fluorescence light. Additionally, to prevent the tails of the laser-beam profile from scattering on elements inside the MR-ToF device, aperture sets are installed next to the laser entrance and exit windows. Each set consists of three apertures with inner diameters of 6, 8 and 10 mm. It is designed in such a way that laser light scattering from the first aperture hits the next apertures rather than propagating into the optical detection region (see Fig. 1 (a)). Since the diameters are smaller than the smallest diameter of any MR-ToF element (12 mm), the scattered light inside of the MR-ToF device is significantly reduced. Finally, scattered light is further minimized by reducing the reflectance of surfaces which are potentially hit by photons of the laser beam. Typically, this is achieved by coating the inside of the setup with a highly light-absorbing black paint. However, MR-ToF operation requires excellent UHV conditions which is often in conflict with outgassing rates of conventional black-coloured paints. As a compromise, surfaces with photon-absorbing black colour (*Tetenal* camera varnish spray) are introduced in the MIRACLS' proof-of-principle setup exclusively at the most critical places, *i.e.* the apertures and the stray light shield.

No degradation of the vacuum quality, in the range of 10^{-7} mbar, is observed at the vacuum gauges with the black color applied on the aforementioned components. As outgassing from the blackened surfaces may locally lead to higher pressures, we investigate the photon-background rate as a function of vacuum quality. This is achieved by turning the turbo pumps of the setup off until a prevacuum pressure is reached. Note that for higher pressures ($> 10^{-2}$ mbar), once the refractive index changes, the laser beam does not remain aligned with the MR-ToF axis. For MR-ToF operation at the best achievable vacuum quality, the detected photon rate is unrelated to the exact pressure. Only at pressure readings above 10^{-5} mbar an increase in the photon rate is observed.

The remaining amount of stray light at the optical detection region is quantified by sending a laser beam of ~ 0.6 mW and ~ 280 nm in wavelength through the apparatus. Under these conditions, a photon rate of typically 40–100 kHz depending, among others, on the laser-beam size is observed at the photo-multiplier tube (*ET Enterprises 9829QSA*). When the laser is blocked, this count-rate drops to a few kHz which is the detector's dark count-rate. Although the achieved photon rate is still more than an order of magnitude worse compared to the (almost) identical lens system at COLLAPS, it is sufficiently low to perform single-pass laser spectroscopy.

To demonstrate CLS at this setup, the laser wavelength is scanned without storing the ions in the MR-ToF device. The resulting resonance spectra of the D2 line of $^{24,26}Mg^{+}$ ions are shown in Fig. 2 (a) and Fig. 2 (c). The ratio in the integrated signal intensities corresponds to the natural abundances of the magnesium isotopes. In the present study, a single-ion bunch consists of a few thousand $^{24}Mg^+$ ions per measurement cycle. Assuming that the width of the resonance is entirely due to Doppler broadening, the observed FWHM of 230(10) MHz corresponds at this beam energy to an energy spread of $\approx 1.7(1)$ eV. The photon intensity on resonance as a function of time is illustrated in Fig. 2 (b). Note the peak width of $\sim 0.5\,\mu$s which allows narrow gating in time of flight. Compared to typically a few microseconds as seen, for example, at the COLLAPS beam line at ISOLDE, this partially compensates for the higher stray-light photon rate in this work.

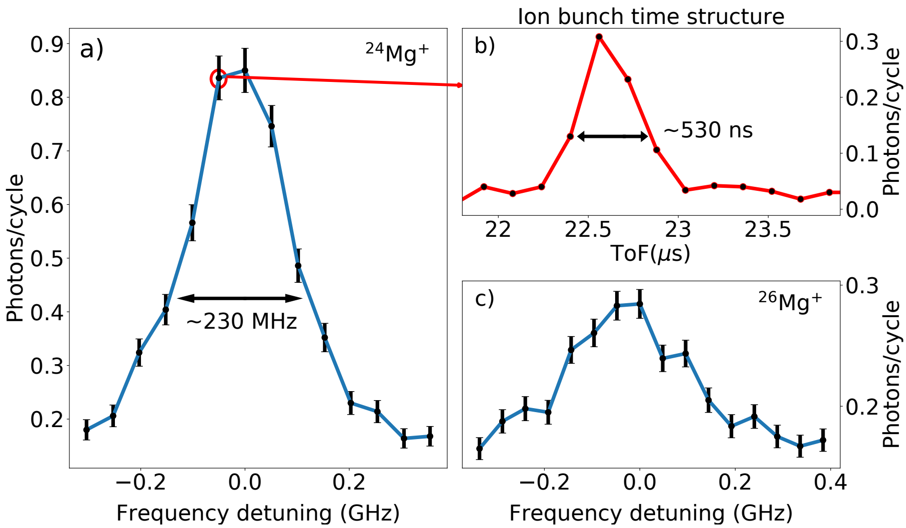

Fig. 2. (a) D2-line resonance of $^{24}Mg^+$ ions averaged over 500 measurement cycles per frequency step. (b) Fluorescence signal over time of flight (ToF) for the resonance frequency of $^{24}Mg^+$ ions. (c) Resonance of $^{26}Mg^+$ ions averaged over 2 000 measurement cycles.

4. Conclusion and outlook

MIRACLS is a novel technique under development at ISOLDE/CERN which aims to combine the high resolution of conventional fluorescence-based collinear laser spectroscopy (CLS) with a high sensitivity by repeatedly probing the same ion bunch. Within a low-energy Multi-Reflection Time-of-Flight (MR-ToF) setup, conventional CLS has been performed on stable Mg^+ ions. This is achieved thanks to the implementation of aperture sets and a stray light shield around the optical detection region, all coated with highly absorbing black paint, resulting in a sufficiently low background of laser stray light for the purpose of the proof-of-principle experiment. Moreover, the advantages of short temporal ion bunches for background suppression have been illustrated. Both, this and the reduction of the longitudinal emittance in CLS, *i.e.* a simultaneous decrease of the energy spread, will be addressed at MIRACLS by a cryogenic Paul trap for optimal beam preparation in the future 30-keV setup. In the future, an adjustable aperture at the entrance of the MR-ToF device may further reduce the laser stray light and will facilitate better alignment of laser and ion beams. Finally, development is ongoing towards versatile UHV compatible and highly UV absorbing coatings for more advanced stray-light suppression.

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