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ABSOLUTE NUCLEAR CHARGE RADIUS MEASUREMENTS WITH EUV SPECTROSCOPY AT TITAN EBIT *

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Abstract

Nuclear charge radii, a quantity crucial in many nuclear physics studies, can be extracted from Li-like electronic transitions, even in heavy ions, when combined with atomic theory [1,2]. This has progressed to permit such calculations from transitions in Na-like ions [3,4]. Charge breeding to Na-like charge state eases experimental requirements. To this end, at TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) facility, we are developing a high-efficiency, flat-field grazing incidence extreme-ultraviolet (EUV) spectrometer, for the measurement of absolute nuclear charge radii of short-lived nuclides. It will be installed to the Electron Beam Ion Trap (EBIT), which is capable of electron beam energies up to 66 keV. The spectrometer is designed to optimize transmission efficiency in the EUV regime. The ray-tracing simulations done in Shadow3 [5] will be presented. The first measurement candidates are ^{211}Fr and a suitable spin-0 isotope of Ra. These two elements are relevant for atomic parity violation (APV) experiments and searches for time-reversal violating permanent electric dipole moments (EDM).

INTRODUCTION

The nuclear charge radius is a fundamental property of the nucleus, and it plays a key role in understanding nuclear and atomic phenomena. Accurate measurement of nuclear charge radii is vital to understand nucleon-nucleon interactions, the appearance of non-traditional magic numbers, the onset of deformation, and the structure of exotic halo nuclei [6,7]. Precision atomic tests of fundamental symmetries, such as atomic parity violation (APV) or searches for permanent electric dipole moments (EDM) as a signature of time reversal violation, require knowledge of nuclear charge distributions to extract the weak interaction physics from the measurement.

Some standard methods available to measure the absolute charge radius include elastic electron scattering [8] and muonic atom spectroscopy [9]. However, these techniques require macroscopic samples, exceeding by orders of magnitude the amount of short-lived radioactive isotopes that can be accumulated at radioactive beam facilities.

The critical ingredients to measure the absolute nuclear charge radius of short-lived heavy isotopes are access to intense radioactive ion beams (RIB), charge breeding to Na-like or higher charge states, optical access to the stored highly charged ions, and finally a spectrometer matched to the EUV light. All of these ingredients are united at TITAN [10], making it presently the only facility in the world capable of such measurements. Our first candidates are ^{211}Fr and a suitable spin-0 isotope of Ra. These two elements are of interest for APV experiments and the searches for EDM. We plan to probe the light emitted from the $3s\ ^2S_{1/2} - 3p\ ^2P_{1/2}$ ($D1$) transition of Na-like Fr and Ra isotopes to measure the energy emitted from this electronic transition. This specific transition is chosen as it offers the strongest optical signal, which is in the EUV regime, hence the necessity for a spectrometer that is highly sensitive to the EUV light. We will also probe the same transition from several isotopes of elements with well-known charge radii charge bred to the same charge state, which are used as references. We will then compare the energy shift with the expected theoretical energy difference, and obtain the charge radius of the isotope being measured by adjusting it in the theoretical calculation to match the measured transition energy shift.

In this proceeding, we describe the status and outlook of this nascent program.

EUV SPECTROSCOPY WITH TITAN EBIT

The TITAN EBIT [11] permits electron beams with currents up to 5 A and energies up to 66 keV. The Helmholtz style magnet allows optical access through seven radial ports. On one of these ports an EUV spectrometer will be installed. We have designed our spectroscopy setup, as illustrated in Figure 1. It will contain three major components: the EUV focusing optics, the EUV monochromator, and the charge coupled device (CCD) camera, where two key optical elements in the EUV monochromator will be an entrance slit and a grating substrate.

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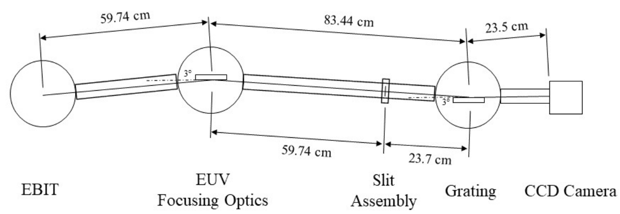

Figure 1: A sketch of the EUV spectroscopy setup that will be installed to the TITAN EBIT. Light collected from the EBIT will be focused and reflected by the focusing optics on the entrance slit, then diffracted by the grating substrate. The diffraction pattern will be collected by the CCD camera and analyzed.

The focusing optics will be a gold-plated, 15 cm long by 3.5 cm wide spherical mirror with a radius of curvature of 1141.471 cm. The center of the mirror will be placed 59.74 cm from the center of the EBIT chamber, at a grazing incidence angle of 3°. The mirror will collect light from the electronic transition in EBIT and concentrate it onto the bilateral entrance slit, with a continuously adjustable width from 0.001 to 3 mm [12]. There will be a 1:1 ratio between the source-to-mirror and the mirror-to-image distances. After passing through the entrance slit, the focused light will be diffracted by the spherical grating. The 50 mm by 30 mm flat-field grating with variable groove spacing will have a radius of curvature of 564.9 mm and nominal groove density of 1200 g/mm, which is ideal for the spectral range of 5 to 20 nm (62-248 eV) [13]. It will be located 23.7 cm from the entrance slit, at a grazing incidence angle of 3°. The diffraction pattern will be collected by the CCD camera, which will be placed in the focal plane of the grating, 23.5 cm away from the grating center [14].

We have commissioned the focusing optics and the monochromator from McPherson Inc. [12] for capabilities similar to the NIST EBIT's [14]. It will have a flat-field grazing incidence. The aspheric wavefront of the spherical substrate grating will allow corrections of aberration, thus providing high-resolution spectra. The device will be optimized for the range of 5-20 nm (62-248 eV) [15]. We have an existing CCD camera (iKon-L SO 936 series by Andor Technology), which offers a 2048 by 2048 array of active pixels, 13.5 by 13.5 μm in size, delivering a 27.6 by 27.6 mm active image area [16].

RAY-TRACING SIMULATIONS

The EUV spectrometer was simulated with SHADOW3, a widely used open-source ray-tracing program [5], through its recommended graphical environment, OrAnge SYnchrotron Suite (OASYS). Three optical elements (OE) were modelled: 1) geometrical source, 2) spherical mirror, and 3) spherical grating.

OE 1: Geometrical Source

We estimated a cylindrical ion cloud inside TITAN EBIT based on Herrmann theory [17, 18]. Since SHADOW3 only allows a one- or two-dimensional geometrical source, a cross section of the cylinder, a 0.01 cm by 7.0 cm rectangle, was used as the simulated source, with 25000 rays generated randomly through the Monte Carlo method. We chose a set of discrete photon energies, at 248 eV, 124 eV, 83 eV, and 62 eV (5 nm, 10 nm, 15 nm, and 20 nm). These energy values are chosen to correspond to the grating substrate in the monochromator, optimized for the 5 to 20 nm wavelength range as mentioned before, to examine the spatial separation of the diffraction pattern for photons with wavelengths in the EUV region of interest.

OE 2: Spherical Mirror

The gold plating of the spherical mirror was simulated through a pre-processor linked to an optical library that processes the reflectivity and transmission of the mirror [5], with the element of gold ($Z = 79$) and its density (19.32 g/cm^3) inputted as reflectivity parameters. This preliminary program generates the complex dielectric constant based on the user-defined mirror material from the atomic scattering factor library. The file is read and used by SHADOW to compute the local reflectivity based on Fresnel equations and phase shifts [19].

SHADOW allows users to define a continuation plane, where an image can be generated. This image then becomes the source for the next optical element, and is traced through to the final image position [19]. Such a continuation plane was created at the location of the entrance slit as shown in Figure 1. This serves as a virtual stopping point to examine the focused image at the slit, before passing the optical information to the spherical grating. The image generated at the continuation plane is shown in Figure 2. This focused image of the rectangular geometrical source serves as a validation that the optical parameters of the spherical mirror, including its position and its radius of curvature, are appropriately chosen.

OE 3: Spherical Grating

The spherical grating receives and processes information from the previous continuation plane. We simulate an imaging plane past the grating, at the location of the CCD camera in Figure 1, to visualize the diffraction pattern shown in Figure 3. We observe four spectral lines with distinct spatial separation, with larger spatial deviation corresponding to lower photon energy or longer wavelength.

This simulation modelled the optical path of the EUV light collected from the EBIT and processed by the spectrometer, and confirmed that the design of the optical elements in the spectroscopy setup is suitable.

STATUS AND OUTLOOK

The TITAN EBIT has been successfully operated for charge breeding of radioactive ion beams and in-trap spec-

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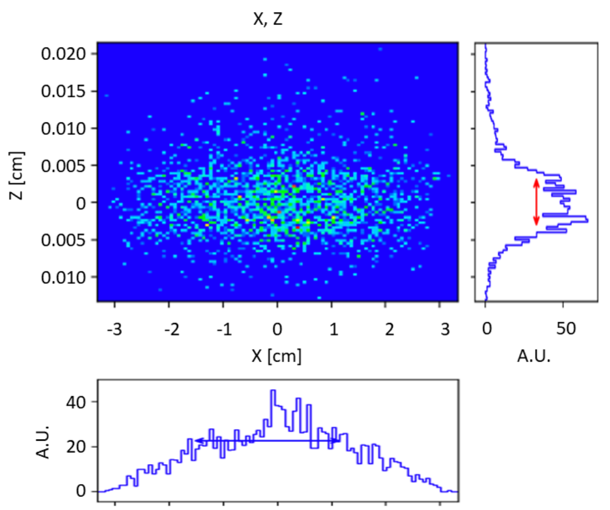

Figure 2: The focused image of the geometrical source at the entrance slit, simulated in SHADOW3.

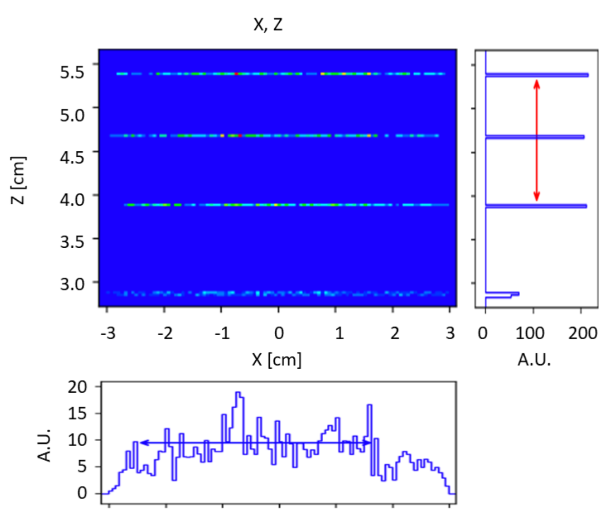

Figure 3: Spectral lines collected in SHADOW3 at the position of the CCD camera, spatially separated by the diffraction grating. From bottom to top, each line corresponds to photon energies of 248 eV (5 nm), 124 eV (10 nm), 83 eV (15 nm), and 62 eV (20 nm).

troscopy for more than a decade. These efforts have hitherto been focused either to support Penning trap mass spectrometry or focused on more traditional nuclear-physics studies. The addition of a newly commissioned EUV spectrometer from McPherson will expand TITAN's capabilities to include absolute and relative determination of nuclear charge radii. SHADOW3 simulations were performed to determine the optical properties required of the spectrometer system. Aside the spectrometer, the TITAN facility is otherwise experiment ready. With off-line tests of the spectrometer planned in fall 2022 and installation in spring 2023, the spectrometer should be ready for on-line experiments by summer 2023. The first measurements will validate the method using a suitable ion of a stable, heavy element with a well-determined nuclear charge radius. Subsequently, we plan to measure Ra and Fr relative to this anchor.

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