THE SHEXI CONCEPT: SUPERHEAVY ELEMENT X-RAY IDENTIFICATION*

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Recent SuperHeavy Element (SHE) discoveries involve only a few events. The assignment of their mass and charge relies on calculations of the excitation function for the reaction and the measurement of their alpha decay, with cross-bombardments as a consistency check. However, a systematic and undetected charged particle evaporation channel would change the assignment. So, while the elements with atomic numbers $Z = 113$, 115, 117, and 118 complete the seventh row of the periodic table of the chemical elements, there is no direct proof of their atomic number, Z. X-rays are a fingerprint of the atomic number of a nucleus since the X-ray energy is proportional to the atomic charge Z. Our objective is to improve the detection efficiency by a factor of ten at L X-ray energies and the intrinsic resolution by a factor of twenty compared to the current performance of SIRIUS. The proposed detection system will be capable of unambiguously identifying the atomic number of the newly discovered superheavy elements through L X-ray measurements.

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1. Introduction

X-rays are emitted when outer-shell electrons fill a vacancy in the inner shell of an atom. These atomic levels are quantised; therefore, the energy of these X-rays is "characteristic" of each element. In the SHE region of the nuclear chart, X-rays are emitted mainly following Electron Capture (EC) and electromagnetic (EM) decay. During electron capture, an inner-shell atomic electron interacts with a proton, creating a neutron and a neutrino, leaving a hole in the atomic shell structure. Outer atomic electrons fill this hole and produce K (predominantly) or L X-rays characteristic of the daughter nucleus. This process is expected to become the dominant decay approaching

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the superheavy island of enhanced stability [1] (predicted between $N = 180$–184 and $Z = 114$–124). While K X-rays are preferentially emitted in the EC process, it is not necessarily the case for the EM decay between excited states within the nucleus (E2 and E3 transitions, for example). Additionally, the spacing between excited states is often below the K binding energy in these SHEs. Consequently, L X-ray emission is the predominant fluorescence. The last element to be identified through α–X-ray coincidences was ^{260}Db ($Z = 105$) [2] (L X-rays from the decay of excited states in ^{256}Lr). The decay-chain of ^{288}Mc [3], populated via the ^{48}Ca+^{243}Am fusion–evaporation reaction, is shown in Fig. 1. The alpha decay of ^{280}Rg ($Z = 111$) populates excited states in ^{276}Mt ($Z = 109$), which subsequently decay to the ground-state band via E1 transitions [4, 5]. The K-conversion coefficient for these first-step transitions is < 0.14. That is, less than 1 in 7 transitions result in the emission of a K X-ray. Furthermore, the K X-ray emission is distributed over several lines, with the most intense accounting for $\sim 40\%$. Given that current approaches have a 30–40% photo-peak efficiency in detecting these K X-rays, it is unsurprising that they were not observed in either [4] or [5]. However, the L-conversion coefficient for the 43 keV M1 transitions is 244, so the L X-ray emission is considerable (in this case, over 2000 times more likely than the aforementioned K X-ray emission). Current set-ups are either almost blind to these L X-rays or have limited detection efficiency for photons above 200 keV [6]. The exception might be the COMPEX [7] detection system. However, efficiencies are only ever quoted relative to TASISpec, making it difficult to have a clear picture. The main problem with systems based on germanium detectors is the requirement that they

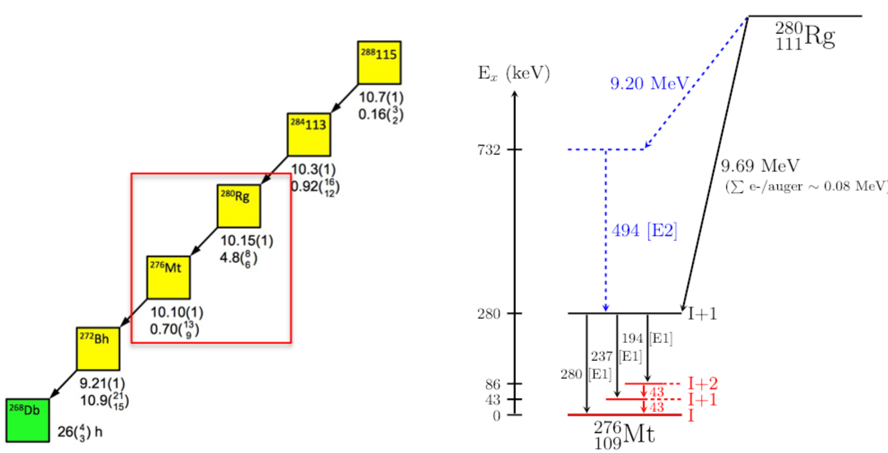

Fig. 1. The alpha-decay chain of ^{288}Mc. ^{280}Rg $\rightarrow$ ^{276}Mt is highlighted, and a decay scheme is proposed based on [4, 5].

are encapsulated. Therefore, photons must still traverse an aluminium absorber/scatterer, even if placed inside the vacuum chamber. We believe we can solve this problem by exploiting recent technological advances in X-ray fluorescence and silicon detector fabrication.

2. The SHEXI detection system

The "CUBE" ASIC from XGLab [8], Milano, Italy, was developed for high-resolution X-ray spectroscopy. XGLab has several charge-sensitive preamplifiers implemented in 0.35 μm CMOS technology. These can be matched to detector capacitances and operational energy ranges for the detector's junction and ohmic sides. Specifically, the PRE_39 has been designed for detector capacitances of 3–10 pF. It has a full-scale energy range of 3.5 MeV and an intrinsic resolution of 0.17 keV with a 1 μs shaping time. Figure 2 shows calculations of the energy resolution of the PRE_39 with a ten pF load as a function of peaking time for various leakage currents. As an indication, the $L_{\alpha 1}$ X-ray in element 108 is 19.4 keV, while that for element 109 is 19.8 keV. For the $L_{\beta 1}$, the energies are 27.1 and 27.8 keV, respectively [9]. The 0.4 keV FWHM resolution goal should be reached with a sufficiently cooled system.

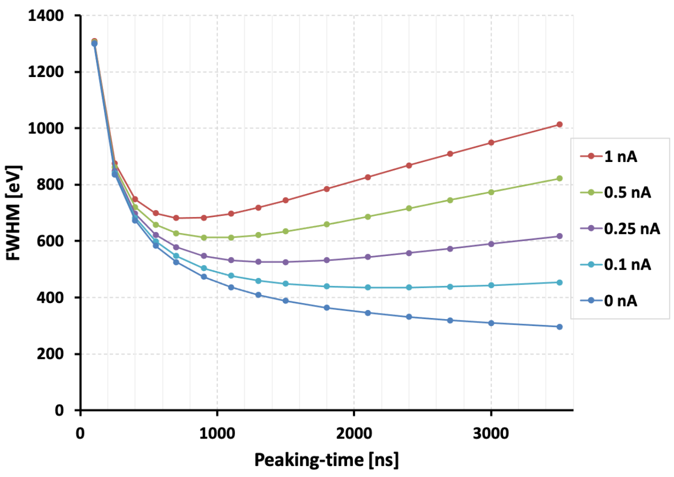

Fig. 2. Simulated FWHM [eV] as a function of peaking time [ns] for various leakage currents [nA].

Large-area (100×100 mm^2) Double-sided Silicon Strip Detectors (DSSD) with individual strip capacitances of < 10 pF, required for high-resolution spectroscopy using an ASIC from XGLab, already exist. They have been manufactured as prototypes for various satellite-based Compton telescope proposals by the Laboratoire Astroparticule et Cosmologie [10] and used at ACCULINNA-2 [11]. At room temperature, the leakage current of these high-resistivity (20 kΩ.cm) 1.5 mm thick "TTT6" detectors is $\sim$12 nA/strip at a depletion voltage of $\sim$ 300 V. In collaboration with Micron Semiconductor Ltd, we have modified this detector design to improve the fabrication yield. Therefore, Micron has agreed to produce a detector using rare ultra-high-resistivity silicon (30–50 kΩ.cm), which will reduce the depletion voltage and minimise the detector leakage current. It should also be noted that the leakage current halves for every 7°C of cooling.

The scheme illustrated in Fig. 3 (a) indicates that the new SHEXI detection system keeps the basic silicon box geometry of SIRIUS [12] with the 1.5 mm thick silicon detectors 2–5, allowing for an unattenuated detection of the low-energy L X-rays. Detector #6 is the current 300 μm thick 128×128 DSSD used as the implantation detector. Therefore, L X-rays will have to traverse detector #6 before being registered in #1, which sits directly downstream. By comparing the spectra observed in the tunnel detectors with that observed in the upstream detector, we will be able to distinguish between low-energy photons and conversion electrons. As with SIRIUS, the K X-rays and gamma-rays will be detected in the Ge detectors outside the chamber. Because the ASICs have an extremely high gain, $\sim$ 1 mV/keV, their energy range is only about 3.5 MeV. We intend to use the standard charge-sensitive preamplifiers on the other side of the SHEXI DSSDs to register escape alphas and fission fragments in the tunnel detectors.

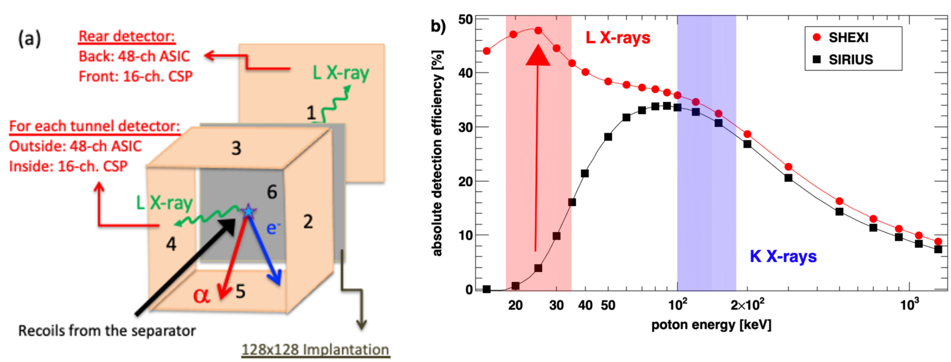

Fig. 3. (Colour on-line) (a) A schematic presentation of the upgraded SIRIUS silicon detector array for the X-ray identification of superheavy elements. (b) Geant4 simulated absolute photon detection efficiency for a complete array using five of the proposed X-ray detectors compared to SIRIUS. A gain of an order of magnitude in the region of the L X-rays is possible.

A Geant4 simulation of the absolute photopeak detection efficiency for the complete SHEXI detection system, including five EXOGAM clovers, is shown in Fig. 3 (b). The red/grey band indicates the factor of 10 enhancement expected for the detection of SHE L X-rays SHEXI will provide compared to SIRIUS.

3. Expectected SHEXI results

In the following section, two experiments were simulated to show the improvements we would expect with SHEXI.

3.1. $^{243}Am(^{48}Ca,3n)^{288}Mc \xrightarrow{\alpha} {}^{284}Nh \xrightarrow{\alpha} {}^{280}Rg \xrightarrow{\alpha} {}^{276}Mt^{*}$

Figure 4 (a) and (b) shows a comparison between simulated experiments to observe the characteristic X-rays of the element Meitnerium performed on SIRIUS and the proposed full upgrade SHEXI. Both experiments assume a beam intensity of 3 pμA of ^{48}Ca provided by the NEWGAIN facility [13] impinging on a 250 μg/cm^2 thick ^{243}Am target and a production cross-section of $\sim$ 17 pb [14]. Even after a 6-month long experiment, the K X-rays are barely visible above the background, in stark contrast to L X-rays that could be measured during a 6-week run using SHEXI. Such a measurement will allow the unequivocal Z identification of the new, isolated, Superheavy Elements, paving the way for future discoveries with the full SHEXI array.

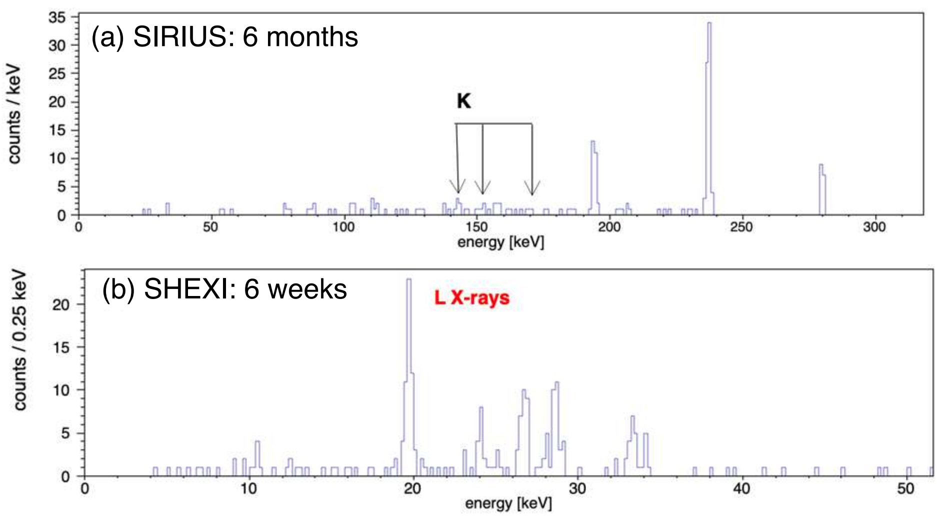

Fig. 4. A comparison of simulated photon detection in ^{276}Mt for experiments at the NEWGAIN facility using (a) 6 months of beam time and SIRIUS and (b) a 6-week long on SHEXI.

3.2. $^{208}Pb(^{48}Ca, 1n)^{255}No \xrightarrow{\alpha} {}^{251}Fm^*$

In figure 5, measurements that revealed the octupole-phonon character of a state in ^{251}Fm [15] using GABRIELA [16, 17] are compared with a Geant4 simulation of the same measurement expected with SHEXI. It shows the considerable gain in resolving power expected: the L3, M, and N conversion lines will be distinguishable. Such a resolving power is crucial to untangle complex decay cascades involving many converted transitions, such as those from high-K isomers. It also adds the ability to determine transition multipolarities from sub-shell conversion coefficient ratios. We therefore expect SHEXI to significantly advance our understanding of nuclear structure in the fermium ($Z = 100$) to darmstadtium ($Z = 110$) region.

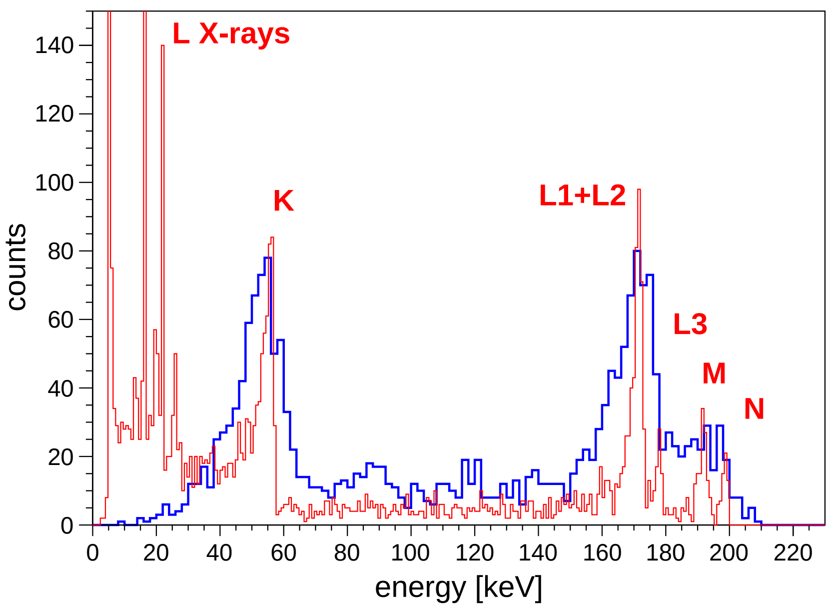

Fig. 5. (Colour on-line) A comparison between the spectra observed in the tunnel detectors of GABRIELA following the decay of an isomeric state in ^{251}Fm [15] (blue/black: counts/2 keV) with Geant4 simulations of the same decay observed with SHEXI (red/grey: counts/0.5 keV). The Geant4 simulations are roughly normalised to the peak height of the K conversion line.

4. Conclusion

We propose a new detection system that is sensitive to the L X-rays of superheavy elements by exploiting recent technological advances in silicon detector fabrication and ASICs from X-ray fluorescence spectroscopy. Our objective is to improve the detection efficiency of SIRIUS by a factor of ten at L X-ray energies of interest and the intrinsic resolution by a factor of 15–20. This new detection system will be capable of unambiguously identifying the atomic number of the newly discovered superheavy elements through L X-ray measurements. In addition to this first-ever Z identification of these SHE, the SHEXI detection system will also offer new, unique possibilities in internal conversion electron spectroscopy. In these highly-charged and massive systems, internal conversion is a process that often dominates electromagnetic decay. SHEXI's enhanced resolution and unmatched lower thresholds will significantly increase resolving power, shedding light on the nature of the electromagnetic radiation, therefore allowing for a better understanding of the all-important quantal structure of these nuclei at the limits of the nuclear chart. It will help us answer fundamental questions of nuclear stability and nuclear structure at the limits of charge and mass.

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