Physics Letters B 779 (2018) 324–330

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

The nuclear magnetic moment of ^{208}Bi and its relevance for a test of bound-state strong-field QED

S. Schmidt [a,*,1], J. Billowes [b], M.L. Bissell [b], K. Blaum [c], R.F. Garcia Ruiz [b], H. Heylen [c], S. Malbrunot-Ettenauer [d], G. Neyens [e], W. Nörtershäuser [a], G. Plunien [f], S. Sailer [c,g], V.M. Shabaev [h], L.V. Skripnikov [h,i], I.I. Tupitsyn [h,j], A.V. Volotka [h,k], X.F. Yang [e]

[a] Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany
[b] School of Physics and Astronomy, The University of Manchester, Manchester, M13 9PL, United Kingdom
[c] Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
[d] Experimental Physics Department, CERN, 1211 Geneva 23, Switzerland
[e] KU Leuven, Instituut voor Kern-en Stralingsfysica, 3001 Leuven, Belgium
[f] Institut für Theoretische Physik, TU Dresden, 01062 Dresden, Germany
[g] Technische Universität München, 80333 München, Germany
[h] Department of Physics, St. Petersburg State University, 199034 St. Petersburg, Russia
[i] National Research Centre "Kurchatov Institute", B.P. Konstantinov Petersburg Nuclear Physics Institute, Gatchina, Leningrad District 188300, Russia
[j] Center for Advanced Studies, Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia
[k] Helmholtz-Institut Jena, 07743 Jena, Germany

ARTICLE INFO

Article history:
Received 12 November 2017
Received in revised form 9 February 2018
Accepted 12 February 2018
Available online 14 February 2018
Editor: D.F. Geesaman

Keywords:
Nuclear magnetic moment
Bismuth
Hyperfine anomaly
Specific difference
Quantum electrodynamics
Laser spectroscopy

ABSTRACT

The hyperfine structure splitting in the $6p^3\,{}^4S_{3/2} \rightarrow 6p^2 7s\,{}^4P_{1/2}$ transition at 307 nm in atomic ^{208}Bi was measured with collinear laser spectroscopy at ISOLDE, CERN. The hyperfine A and B factors of both states were determined with an order of magnitude improved accuracy. Based on these measurements, theoretical input for the hyperfine structure anomaly, and results from hyperfine measurements on hydrogen-like and lithium-like ^{209}Bi$^{80+,82+}$, the nuclear magnetic moment of ^{208}Bi has been determined to $\mu(^{208}\mathrm{Bi}) = +4.570(10)\,\mu_N$. Using this value, the transition energy of the ground-state hyperfine splitting in hydrogen-like and lithium-like ^{208}Bi$^{80+,82+}$ and their specific difference of $-67.491(5)(148)$ meV are predicted. This provides a means for an experimental confirmation of the cancellation of nuclear structure effects in the specific difference in order to exclude such contributions as the cause of the *hyperfine puzzle*, the recently reported 7-σ discrepancy between experiment and bound-state strong-field QED calculations of the specific difference in the hyperfine structure splitting of ^{209}Bi$^{80+,82+}$.

1. Introduction

Since its development in 1947, the theory of (bound-state) quantum electrodynamics (BS-QED), a major keystone within the standard model of physics, has an impressive and long history of success [1–4] and has so far mastered all tests in light systems [5,6] with unprecedented accuracy. In contrast, first attempts to probe BS-QED in the regime of the heaviest elements, in particular by using heavy highly charged ions (HCIs), are much less accurate [7–9]. The best tests performed so far reached accuracies at the level of a few permille, even though the sensing power of the bound electron to QED effects is strongly enhanced – HCIs are like a magnifier for QED related contributions. Besides the measurements of the Lamb-shift [10–12] and the Landé g-factor [13–16] in HCIs, one promising quantity to access this non-perturbative regime of BS-QED is the ground-state hyperfine structure (hfs) splitting in hydrogen-like (H-like) ions, nowadays accessible by high-precision laser spectroscopy.

Previous direct tests of BS-QED via the transition energy of various ground-state hfs splittings in H-like ions [17–19] could not be exploited due to the large uncertainty in the theoretical predictions, mainly arising from the magnetic moment distribution over the finite nuclear size, the Bohr-Weisskopf effect [20]. It was sug-

* Corresponding author.
E-mail address: stefanschmidt@uni-mainz.de (S. Schmidt).
[1] Present address: Institut für Physik & Exzellenzcluster PRISMA, Johannes Gutenberg-Universität Mainz, 55122 Mainz, Germany.

https://doi.org/10.1016/j.physletb.2018.02.024

gested that the combination of the hfs splittings $\Delta E^{(1s)}$ of H-like and $\Delta E^{(2s)}$ of Li-like systems in the so-called specific difference $\Delta' E = \Delta E^{(2s)} - \xi \Delta E^{(1s)}$ would yield a conclusive test of BS-QED in strong magnetic fields [21]. This is because if the parameter ξ is suitably chosen, nuclear effects will cancel in $\Delta' E$. A first measurement of the specific difference in ^{209}Bi was reported in [22], but did not provide sufficient experimental accuracy to become sensitive to the remaining QED contributions [22,23]. With recent experimental improvements [24], the specific difference was determined with more than an order of magnitude improved accuracy [25]. However, a large discrepancy between the specific difference extracted from the hfs splitting in H-like and Li-like ^{209}Bi and theoretical expectation was reported, establishing the *hyperfine puzzle* of BS-QED. This result challenges BS-QED, but might also be explained by a value for the nuclear moment of ^{209}Bi which deviates from literature, as it enters linearly into the theoretical value for the specific difference. As discussed in Ref. [24], there are three possible reasons for the *hyperfine puzzle*: (i) The magnetic moment of ^{209}Bi is different from the literature value, (ii) the elimination of nuclear structure contributions in the specific difference $\Delta' E$ does not work as expected or (iii) QED fails. Please note that it is not excluded that the discrepancy is caused by more than one of these reasons. Therefore, all points should be addressed in future experiments.

Explanation (i) has been checked by improved high precision calculations of the shielding and chemical shift corrections for available and new NMR data. Results have been published in [26] and do indeed agree with the storage ring results within uncertainties. However, the extraction of the nuclear moment depends again on advanced theoretical calculations of the shielding constant which is, from a fundamental point of view, not completely satisfying taking into account remaining uncertainties of molecular calculations. Therefore, a strong need remains to measure magnetic moments of such nuclei on a bare or hydrogen-like system, where shielding effects are absent or under very good control.

In order to check (ii) we suggest to measure the specific difference of ^{208}Bi and provide here the crucial information for this experiment. From a nuclear physics point of view, the nuclear magnetic moment distribution in ^{208}Bi must be considerably different from that of ^{209}Bi. The latter has a single proton in the $h_{9/2}$ shell outside of the ^{208}Pb core, while in the former there is an additional contribution from a $p_{1/2}$ neutron hole in the ^{208}Pb core. This, and their large magnetic moments make these isotopes an ideal pair to check the independence of $\Delta' E$ from the nuclear moment contribution. To predict the specific difference of ^{208}Bi, which is required for this test, the magnetic moment of this isotope must be determined with better accuracy. The most accurate values for the magnetic moments of short-lived isotopes are obtained from hyperfine structure measurements but require a well-known magnetic moment of a stable isotope. In addition, one has to include predictions for the hyperfine structure anomaly in a given atomic state. In order to disentangle (i) from (ii), we assume that the observed discrepancy in $\Delta' E$ is solely due to a wrong magnetic moment. In this case, we can use the measured specific difference and extract the magnetic moment of ^{209}Bi required to bring experiment into agreement with theory. Based on this assumption, we calculate the hyperfine structure splittings and the specific difference for H-like and Li-like ^{208}Bi with respect to the new value. If our predictions will be in accordance with the measurements, explanation (ii) can be ruled out within the accuracy of the results.

Here, we have measured the hfs splitting of the $^4S_{3/2}$ and $^4P_{1/2}$ states in atomic ^{208}Bi by means of collinear laser spectroscopy performed at the ISOLDE facility at the European Center for Nuclear Research (CERN). In the analysis we also include hyperfine structure anomaly calculations to extract the most precise value of the nuclear magnetic moment of the bismuth isotope ^{208}Bi. Based on the improved value, a reliable prediction of the ground-state hfs splitting in H-like and Li-like ^{208}Bi and their specific difference is made. If those values will be confirmed in upcoming laser-spectroscopy experiments on ^{208}Bi$^{80+,82+}$, the proposed cancelation of the nuclear magnetic moment distribution in the specific difference can be firmly established.

2. Experimental setup

The measurements on the long-lived bismuth isotope ^{208}Bi (half-life of 3.7×10^5 y) with respect to a reference isotope (^{209}Bi) were performed at the radioactive ion beam facility ISOLDE, located at CERN. A schematic of the on-line isotope separator and the collinear laser spectroscopy experiment (COLLAPS) [27–29] is shown in Fig. 1. In brief, the bismuth isotopes are produced in the target section by impinging high-energy proton pulses at 1.4 GeV on a uranium carbide target. The target material itself is heated to about 2200 °C to promote the diffusion process of the chemical compounds in the target material as well as the effusion through the transfer line towards the ionization region. Element selective ionization is performed on the neutral atoms using a (multi-step) resonance ionization scheme [30], followed by mass-selection with the High-Resolution Mass Separator (HRS).

Before the injection of the almost mono-isotopic ion beam into the collinear beamline apparatus, the ions are stopped inside a gas-filled radiofrequency quadrupole (RFQ) trap for ion bunching, cooling and accumulation. The voltage applied to the RFQ defines the starting potential of the ion bunch for collinear laser spectroscopy. It is set to about 30 kV in order to accomplish the mandatory velocity compression [27], which sets the basis for high-resolution experiments of this kind.

After releasing the bismuth ions from the RFQ, they enter the COLLAPS beamline, where they are collinearly superimposed with a continuous wave laser beam at 307 nm provided by a frequency-doubled Matisse dye-laser, stabilized to a high-finesse wavemeter (WS-10) [31]. The beamline consists of a 10° electrical bender, ion optical components to guide the beam (these components are not shown in Fig. 1), a sodium vapor charge-exchange cell (CEC) and an optical detection region (ODR), mounted perpendicular relative to the propagation direction of the ion beam. The post-acceleration voltage (positive or negative) applied to the CEC allows for fast and precise Doppler-tuning of the ion bunch. After neutralization in the CEC, the hfs of the bismuth atoms (see level scheme in Fig. 1 for details) can be probed. Light scattered by the atoms is focused by a two lens system on a photomultiplier tube. For background suppression, the photomultiplier tubes were gated for 15 µs with respect to the time-of-flight window of the ion bunches.

3. Experimental results

The hfs splitting of the two bismuth isotopes ^{209}Bi and ^{208}Bi were alternately measured within a six-hour measurement campaign. In total seven spectra were recorded, four in the case of ^{208}Bi and three for ^{209}Bi. Each spectrum was taken with an accumulation time between thirty and sixty minutes. The obtained hfs spectra (see Fig. 2 for ^{208}Bi) were fitted using a sixfold line-profile of individual amplitudes and with their positions correlated through the hfs which depends on the magnetic and quadrupole hyperfine parameters [32]. Best agreement was found using a Lorentzian- or a Voigt-profile with a dominating Lorentzian part. Thus, the former one was used in the following analysis. The residuals (not displayed) show no indication for *satellite peaks* [33].

During the measurement campaign, the starting potential, the ion optical settings as well as the laser frequency were kept con-