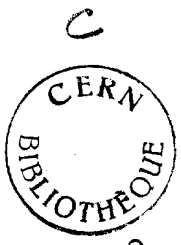

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PROPOSAL TO THE ISOLDE COMMITTEE

Laser Spectroscopy of Neutron Rich Bismuth Isotopes

CERN[1] – Mainz[2] – Manchester[3] – Stony Brook[4] Collaboration

J. Behr[4], J. Billowes[3], P. Campbell[3], T.G. Cooper[3], U. Georg[2], I.S. Grant[3], G. Gwinner[4], G. Huber[1], M. Keim[2], J. Kilgallon[3], A. Klein[2], R. Neugart[2], M. Neuroth[2], G.D. Sprouse[4], P.D. Wheeler[3], F. Xu[4] and the ISOLDE Collaboration[1].

Spokesman: J. Billowes

Contactman: G. Huber

Summary

The aim of the proposed experiment is to measure the optical isotope shifts and hyperfine structures of bismuth isotopes in the region $^{210-214}$Bi which lie above the N=126 shell closure. The change in nuclear mean square charge radii and static moments can be deduced. These will be the first isotones of lead to be measured immediately above the shell closure. This will provide new information on the systematics of the kink in the charge radii change with neutron number seen in the Pb isotopic chain, and will represent the first measurement of the odd proton $h_{9/2}$ moment in the region above the closed ^{208}Pb core.

Laser resonance fluorescence will be used on the isotopic bismuth samples as they are released into a gas cell trap. This is a method that has been applied very successfully at SUNY, Stony Brook to the neutron deficient bismuth isotopes and it makes efficient use of the small samples available. The bismuth samples of ^{212}Bi and ^{213}Bi will be prepared by catching intense beams of ^{220}Fr and ^{221}Fr on thin lead foils. The francium decays to the bismuth isotopes by sequential 2-α-emission. The bismuth will subsequently be released from a thermal oven in an off-line gas cell for a laser resonance fluorescence measurement. Smaller samples of ^{211,214}Bi can be made in the same way and ^{210}Bi can be collected directly with a bismuth beam.

1. Physics motivation

Changes in the nuclear mean square charge radii immediately above the N=126 neutron shell are known for the lead isotopes alone. Measurements of other isotones are generally hindered by the very short half-lives in this region. The available data for Z$\geq$ 82 in the region of the N=126 shell are shown in figure 1 where the isotope chains have been internally normalized to $\delta\langle r^2\rangle^{124,126} = -1$. Below the N=126 shell the Pb, Bi and Po isotopes are expected to to be almost spherical and, within the errors, their behaviour in nuclear size and the odd-even staggering is identical (intriguingly this is not the case for the Tl isotones which have a single proton hole in the Pb core). Rn and Fr start to deviate from these systematics below N=121 and this is where they are expected to develop modest oblate deformations[1].

The increase in charge radius as neutrons are added is more rapid above the shell closure than below and this produces the kink in the lead chain at N=126 and it is a familiar feature in isotope chains at all other neutron magic numbers. A good theoretical description of this behaviour has been elusive but a recent publication[2] has now shown the relativistic mean field theory can reproduce the trend very successfully. In the light of this, the apparent failure of the Skyrme mean field approach is not fully understood but it becomes important to understand why the differences arise since this has implications for predictions of nuclear properties further from the line of stability.

Comparisons between the lead and other isotopic chains are important in understanding the nature of the kink but, because of the short half-lives of most of the isotones in the region above N=126, measurements are presently only feasible on the bismuth chain. Furthermore, it will be interesting to determine whether the apparently exact agreement between Pb and Bi below the shell is repeated above the shell. Both the Pb and Bi isotopes are near-spherical throughout this region, whereas the Rn and Fr isotopes that have been measured (above N=132) are prolate deformed.

The proposed experiment will also represent the first measurement of the odd proton $h_{9/2}$ moments in the same region. This provides information on first order core polarization effects and hence the re-normalization of spin and orbital g factors.

Relatively large samples of two isotopes of bismuth, ^{212}Bi and ^{213}Bi, can be prepared easily and quickly at ISOLDE. These are products in the decay chains of ^{220}Fr and ^{221}Fr. The laser spectroscopy of these isotopes in an off-line measurement will be sufficient to establish the change in gradient at the kink and an odd-even staggering parameter. The measurement of these two isotopes is straightforward and is the primary goal of the proposal. The expected positions of ^{212}Bi and ^{213}Bi in the charge radii systematics are shown in figure 1. We will attempt to extend the measurement to ^{214}Bi but it will depend critically on the α-decay branching ratio of ^{222}Fr which lies between 1% and 0.01%. Heavier francium isotopes do not α-decay. It should be possible to acquire a sufficiently large sample of ^{210}Bi using a bismuth beam with extended collection times (the half-life of ^{210}Bi is longer than the beam time requested) and, by moving the gas cell to an on-line position during the end of the experiment, we will have the ability to measure the 2.17 min ^{211}Bi isotope.

2. Experimental method

Off-line tests on the isotope separator at the Daresbury Nuclear Structure Facility have shown that the bismuth atomic system is poorly suited to the collinear-beams method of laser spectroscopy and, even at ISOLDE, the ion beam fluxes would be too low for any radioisotope measurement. However, it was discovered that the bismuth atom was ideally suited to the gas cell method[3] which can be used even when the sample comes from the daughter products of intensely produced elements such as francium. Here a cell filled with an inert buffer gas acts as an atom trap which greatly extends the atom-laser interaction time compared to collinear-beams or crossed-beams techniques. If an atom can be repeatedly cycled by resonance-excitation and spontaneous photon emission then a high fluorescence rate per atom can be achieved, providing sufficient signal to measure extremely small samples. The atomic levels of bismuth are shown in figure 3. The fluorescence is observed on the 472 nm line (a 6% branch from the excited state) as the laser is tuned across the 306.7 nm ($^4S_{3/2}$—$^4P_{1/2}$) transition, the UV light being produced by intra-cavity frequency doubling with a lithium iodate crystal. An important feature of the system is that the huge background of Rayleigh scattered UV light from the buffer gas can be filtered out. A very beneficial property of the system (that we do not yet understand) is that the metastable state populated by the 472 nm transition relaxes very quickly in the buffer gas. There is little evidence of optical pumping and all components of the hyperfine structure are present with the same relative intensities that one would expect from a vapour sample (with no repeated excitation).

The bismuth isotope shifts and hyperfine structures are large compared with the Doppler and pressure broadenings inherent in the technique and high precision is obtained on the nuclear parameters of size and static moments. Bismuth has a good vapour pressure at modest temperatures (400°C) and can be evaporated from a lead catcher foil directly into the laser interaction volume of the gas cell. The experiment at ISOLDE would proceed in the following way. Beams of francium from the separator would be caught on thin self-supporting foils of Pb. The decay schemes of ^{220,221}Fr are shown in figure 2. Within a few minutes most of the francium has decayed by sequential 2-α-emission to the ground states of ^{212}Bi ($T_{1/2}$ =1 hour) or ^{213}Bi (45.6 mins). Each implantation would take a maximum of one half-life. The catcher foil is contained within a tantalum tube mounted on a flange that becomes the oven of an off-line gas cell. The entire unit is removed from the ISOLDE beam line and inserted into the off-line gas cell, so the collected activity is not removed from its container. The cell is evacuated and filled with argon to 5 mBar. A 1 mW beam of narrow bandwidth UV laser light passes close to the end of the oven inside the cell. The oven is made of a tantalum tube and is heated to about 400°C by passing an electric current through it. As the oven is heated the laser frequency is repeatedly scanned across the 306.7 nm resonance region. A single bismuth atom would take typically 1 second to diffuse from the oven to the walls of the cell and could spend some milliseconds actually in the laser beam. The fluorescent light is collected through a lens and filter system and detected by a single-photon counting photomultiplier tube. The entire sample is evaporated from the oven in 5–10 minutes. This time is so short that

it is best to restrict the laser scan to cover only one set of the hyperfine components (as shown in figure 4) so for most of the time the laser is actually on resonance. The precisely know hyperfine structure of stable ^{209}Bi (which is inevitably present in the catcher foil) provides the perfect local frequency calibration. The ^{212}Bi and ^{213}Bi hyperfine components will probably be fully separated from the natural signal. The ISOLDE samples will actually have more radioactive ^{212}Bi or ^{213}Bi material than the stable ^{209}Bi. Even if components were to overlap with the stable hyperfine structure then deconvolution is possible since the lineshapes are understood and can be fitted very well. Minimum sample sizes of $\approx 10^9$ atoms could be obtained in about 1 second from the isotope separator for these isotopes. A number of samples must be successfully measured for each isotope to cover the whole hyperfine structure. The advantage of using the gas cell off-line is that samples can be collected while the laser spectroscopy is carried out on earlier samples. For the short-lived ^{211}Bi the gas cell will simply connect to the ISOLDE beam line flange to become an on-line cell, reducing the time between collection and evaporation.

Throughout the experiment all the activity accumulates in one of the several ovens we will be using or is trapped on the walls of the gas cell which is sealed during the evaporation procedure. Before each sample is collected, a new lead catcher foil is inserted in the oven. This is destroyed by the evaporation.

3. Status of research

We have recently used the same gas cell method to measure isotope shifts and hyperfine structures of the neutron deficient ^{202,203,204}Bi at SUNY, Stony Brook[4]. The results are shown in figure 1. The samples were produced by the bombardment of gold foils with beams of 75–87 MeV ^{11}B. The bismuth was released from the gold by baking at 1000°C and allowing the vapour to condense inside a tantalum oven which was subsequently inserted in a gas cell. Sample sizes were typically 10^{9-10} atoms and examples of the spectra are shown in figure 4. The work is being extended to even lighter isotopes at Stony Brook. The ISOLDE facility offers tremendous advantages: (i) the samples will be mono-isotopic (ii) the samples will be at least two orders of magnitude larger than could be produced in a reaction with a tandem accelerator beam and, critically (iii) we will have access to the neutron-rich side of the line of stability. It is simply not possible to produce these isotopes with sufficient yield in any heavy-ion reaction on a tandem accelerator.

4. Technical, financial and manpower requests

None.

5. Apparatus to be used

The gas cell will be brought to ISOLDE and mounted off-line in a position convenient for laser beam delivery. We require a beam line on ISOLDE for repeated foil implantations

and removals. We will fit an isolation valve and end-flange on the beam line which will then accept either the oven and catcher foil unit or the gas cell itself for on-line running. The cw lasers of the collinear laser spectroscopy experiment IS 304 can be used in the frequency-doubled version. Therefore it would be convenient to put the apparatus close to the existing beam line. Additional equipment for calibrating laser scans can be placed in the laser room, and counting electronics and computers will also be taken mainly from IS 304.

6. Beam time request

We estimate that 12 shifts will be sufficient for the complete set of measurements. The beams of ^{220,221}Fr are so intense that we are limited by the speed of preparing the off-line cell and doing the laser spectroscopy. It may take several attempts to get the evaporation and laser conditions right simultaneously. At some point it might also be necessary to delay measurements for some hours to reduce the background due to radioactivity in the cell. Thus we estimate that ^{212,213}Bi measurements would be completed in 4–5 shifts which also includes the preparation work with the ISOLDE beam. We will be able to assess in one hour whether it is worthwhile to pursue a full ^{214}Bi measurement which may then take 2 shifts. The ^{210}Bi measurement is merely a problem of collection time. For an ISOLDE beam flux of 10^5 s^{-1} it would take 14 hours to produce a useful sample of 5×10^9 atoms but we may be able to collect this sample during the earlier laser spectroscopy work on ^{212,213}Bi since that will not require continuous production of samples. So we estimate 5 shifts for ^{210,211}Bi which includes the mounting of the gas cell on-line and re-arranging the apparatus and laser beam delivery.

References

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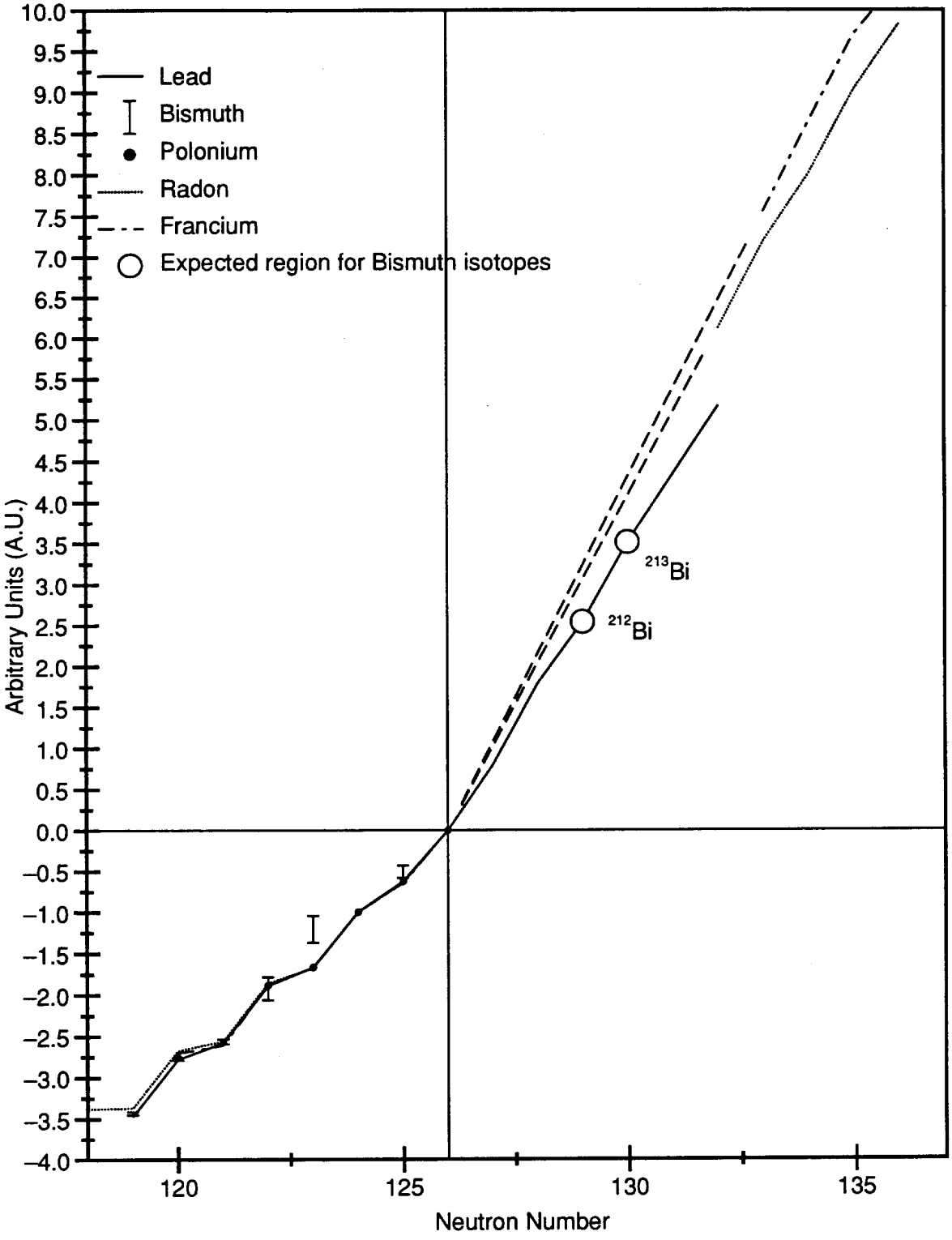
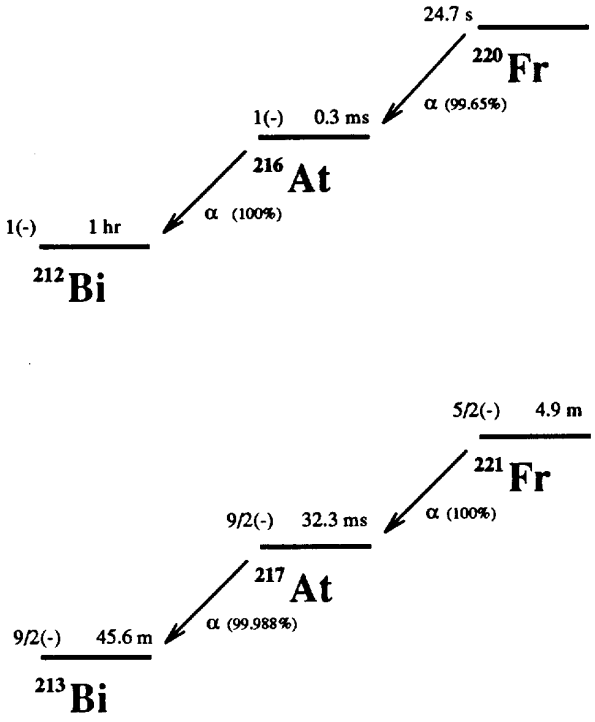


Figure 1: Relative Isotope Shift ($IS^{124,126} = -1$ a.u.)



Decay schemes from Francium to Bismuth isotopes.

Figure 2:

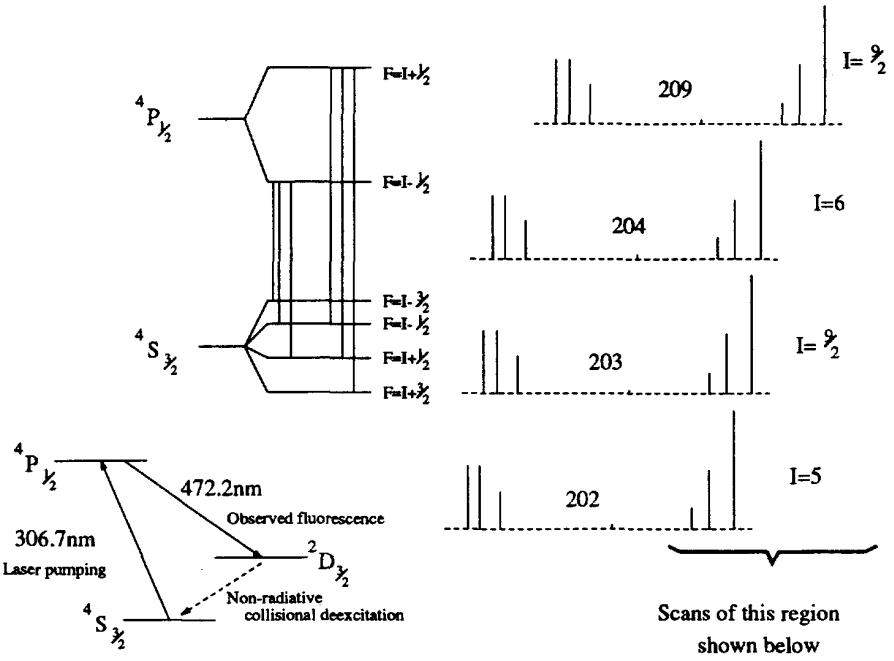


Figure 3: Atomic level scheme and hyperfine structure of 306.7 nm line.

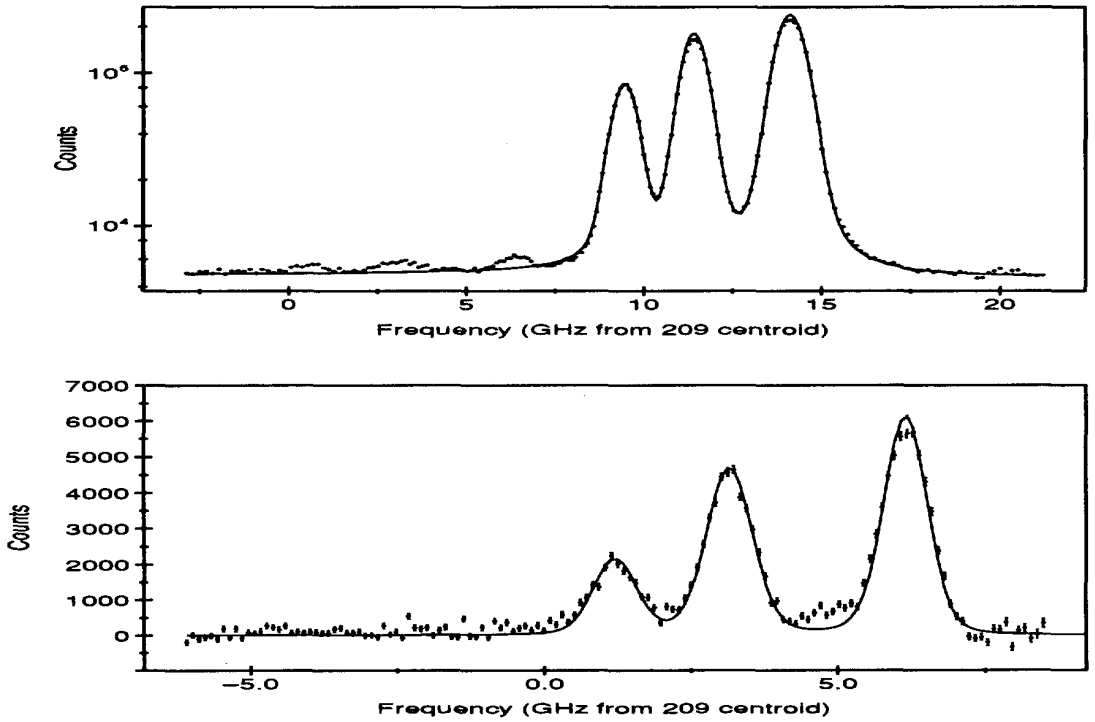


Figure 4: Fits for ^{209}Bi (upper plot) and the residual ^{203}Bi (lower)