EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time of Flight Committee for IS538

Precision measurement of the half-life of ^{109}In in large and small lattice environments

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Abstract

The high precision measurements to determine the change of the half-life of electron-capturing heavy nuclei such as ^{109}In under compression have remained relevant and important. Such studies are of general interest having implications in many areas ranging from astrophysics to geophysics. At present, very little data is available on the change of electron capture decay rate under compression and the available data seems to indicate that the observed increase of the electron capture decay rate under compression is much greater than the predictions of the best available density functional calculations. One way to significantly compress ^{109}In ion is by implanting the ions in a small lattice such as palladium (Pd) and compare with the decay rate when ^{109}In is implanted in a large lead (Pb) lattice. High energy (100-150 MeV) pure ^{109}In beam available from HIE-ISOLDE provides a unique opportunity for clean implantation to perform such measurements.

Requested shifts: 4 shifts (each shift is 8 hours long)
Beamline: [HIE-ISOLDE 2nd beam line (for setups other than MINIBALL)]

1 Motivation:

The study of the change of electron capture nuclear decay rate in different environments has fundamental significance and applications in many areas such as nuclear physics, condensed matter physics, astrophysics, geophysics etc. The electron capture nuclear decay rate is proportional to the electron density at the nucleus [$|\psi(0)|^2$], where $\psi(0)$ is the electronic wave function at the nucleus. Since the atomic valence electron configuration could be modified by the surrounding environment and that would slightly affect the electron density at the atomic nucleus [$\psi(0)$], the electron capture nuclear decay rate is susceptible to the surrounding environment. ^{7}Be is the lightest nucleus that decays by electron capture and its decay rate is expected to be most susceptible to the surrounding environment because its electronic configuration is $1s^2 2s^2$ and the valence 2s electrons contribute ≈3.3% to the total electron capture decay rate. The decay rate of ^{7}Be in different media has been extensively studied [1-7]. It was found that the electron affinity of the surrounding medium could affect the decay rate of ^{7}Be by measurable amount and density functional calculations provided reasonable agreement with the experimental results for such cases [4, 8]. The effect of conduction electrons of metal(Debye screening) was studied and found to be negligible [9].

On the other hand, the change of electron capture nuclear decay rate under compression is not at all well studied, although this has various astrophysical and geophysical significances. During the core collapse of the massive stars, the electron capture rate by the nuclei is expected to increase initially and the process plays an important role in the creation of heavy elements [10]. The electron capture nuclear decay is also important in heating up the earth's core where the pressure is very high (3.3 Mbar – 3.6 Mbar). A large amount of heat (about 8 TW power) could be produced [11] by the electron capture of ^{40}K in the core alone and this heat production is important in determining the thermal and tectonic evolution of the earth. So it is important to understand the change of electron capture nuclear decay rate under compression. However there is very little data available so far. W. K. Hensley et al. [12] studied the change of electron capture decay rate of ^{7}BeO under compression and found that the decay rate increases by about 0.6% at a pressure of 270 kbar. Liu and Huh [13] applied high pressure on amorphous $^7Be(OH)_2$ gel and obtained similar results. On the other hand, density functional and Hartree-Fock calculations [14-17] predicted ~(0.1-0.2)% increase of the electron density at the ^{7}Be nucleus due to the application of 270 kbar of pressure on ^{7}BeO lattice. In the cases of the compression of the larger many-electron radioactive (electron capturing) atoms such as ^{40}K, ^{109}In, ^{110}Sn etc., the increase of the electron density at the nucleus is generally expected to be very small, because the overlap of the orbital valence electrons (such as 4s, 5s etc.) at the nucleus is exceedingly small. K. K. M. Lee and G. Steinle-Neumann performed [14] WIEN2k density functional calculations [15] to calculate the increase of electron density at ^{40}K nucleus due to the compression of $^{40}K_2O$ and found that the electron density at the ^{40}K nucleus should increase by < 0.01% even at a pressure of 500 kbar. On the other hand, there is only one set of available experimental data for ^{109}In and ^{110}Sn showing a relatively large increase of the electron capture nuclear decay rate under compression. It was found [18] that the orbital electron capture rates of ^{109}In and ^{110}Sn increased substantially by (1.00$\pm$0.17)% and (0.48$\pm$0.25)% respectively when implanted in the smaller Au lattice compared to implantation in a larger Pb lattice. The electron affinity of Au (electron affinity=2.2 eV) is much larger than that of Pb (electron affinity=0.35 eV) [19]. However, the electron affinity of the surrounding medium could only affect the valence (5s) electronic orbital of ^{109}In and ^{110}Sn implanted in Pb and Au. Since the valence electronic orbitals of ^{109}In or ^{110}Sn give negligible contribution to the total electron density at the nucleus, the effect of electron affinity of the surrounding medium would be negligible on the decay rate. So the observed relatively large increase of decay rate could be attributed to the compressional effect in the smaller Au lattice. However, our density functional calculations using WIEN2k code [15] indicate only about 0.1% increase of decay rate of ^{109}In in Au compared to that in Pb, even after considering finite nuclear size and quantum electrodynamics effects. So the reported large increase of decay rate has remained unexplained so far.

Earlier experiment [18] was done by implanting ^{109}In and ^{110}Sn ions along with all other radioactive ions produced in the heavy ion reaction ^{20}Ne+^{93}Nb at E(^{20}Ne)= 80 MeV. Moreover, the very different electron affinities of Au and Pb might create some complications. The availability of energetic (>100 MeV) pure ^{109}In beam from HIE-ISOLDE, CERN would enable us to perform a much cleaner measurement of this important effect by measuring the change of decay rate of ^{109}In implanted in small Pd lattice (lattice constant= 3.89Å) versus large Pb lattice (lattice constant= 4.95Å) [19]. Since both Pb (electron affinity=0.35 eV) and Pd (electron affinity=0.54 eV) [19] have similarly small electron affinities, any observed increase of decay rate in Pd lattice could be unambiguously attributed to the higher compressional effect in Pd lattice.

2. Description of the experiment:

We propose to use a pure ^{109}In beam (having intensity $\sim 10^5$ ions/sec; energy= 100-150 MeV from HIE-ISOLDE and implant the ions in a Pd and Pb foil one by one. High energy (100-150 MeV) ^{109}In beam would penetrate >5μm inside Pd or Pb and hence surface effects cannot be responsible for any observed change of decay rate. The surface of Pb foil would be chemically treated to remove any lead-oxide layer on it and then immediately put in high vacuum. The implantation on each target would be for about 7 hours (half-life of ^{109}In being ~4.2 hours). There would be no nuclear reaction between ^{109}In and the nuclei of the catcher foil, because the relevant Coulomb barrier is much higher than the incident energy. After implanting ^{109}In ions in a Pd or Pb foil for 7 hours, the implanted foil along with a standard ^{60}Co γ-ray source would be counted by placing it in front of high efficiency HPGe detectors or CLOVER detectors or in MINIBALL array of ISOLDE. The counting would be done in a low background room. The singles count rate of each HPGe detector would be kept below 10,000 counts per sec to enable good energy resolution (FWHM$\approx$ 2 keV at 660 KeV energy). The time keeping would be done by using a precision pulser. The composite γ-ray spectrum from the decay of ^{109}In source (that emits 203 keV γ-ray photons due to the electron capture of ^{109}In nuclei) and ^{60}Co source (that emits 1173 keV and 1332.5 keV γ-ray photons) would be recorded in a data acquisition system. The ratio of the peak area of 203 keV γ-ray line from the decay of ^{109}In and the sum of the peak areas of ^{60}Co γ-ray lines would be monitored with time to cancel out the dead time effect of the data acquisition system. Simultaneously, a precision pulser would be counted by a scaler. Standard electronics and data acquisition system would be used. The γ–ray spectrum and the counts of the high precision pulser would be acquired for successive intervals of 15 minutes duration and then written on a computer disk. This would be followed by an automatic reset of the scalers, the erasure of the spectra from the spectrum buffer and the start of data collection for the next 15 minute interval. In this way the counting would continue for 7 hours at a stretch and then intermittently for another 20 hours. The livetime of the counting system would increase with time as the ^{109}In source (half-life ~4.2 hours) would cool down. However the ratio of the peak areas of 203 keV γ-line produced due to the electron capture of ^{109}In nucleus and the sum of the peak areas of 1173 keV and 1332.5 keV γ-lines from ^{60}Co would be independent of the live time of the counting system and this ratio would be monitored with time. There should be no radioactive contaminant in ^{109}In beam and the γ-ray peaks of 203 keV (from ^{109}In), 1173 keV and 1332.5 keV (from ^{60}Co) should be free from any background peak. The intensity of any accompanying stable beam with the radioactive ^{109}In beam should be $\leq 10^3$ ions/sec so that the lattice damage done by any such beam at the depth where ^{109}In would be implanted should be negligible (< 0.001 vacancies /ion/angstrom).

The measurements would be done by placing ^{109}In implanted Pd and Pb foils in front of high efficiency γ-ray detectors one by one after the respective implantation run. Then the entire experiment would be repeated once starting with the implantation on Pd and Pb foil.

3. **Experimental equipment**:

   We propose to use HIE-ISOLDE 2nd beam line (other than MINIBALL line) for implantation runs. The counting would be done later using high efficiency HPGe or CLOVER detectors or MINIBALL array in a low background counting room. A standard ^{60}Co source (20-50 μC strength) is required. A precision pulser would be used for time keeping. Standard electronic and a data acquisition system will be required.

Summary of requested shifts:

The aim of the work is to achieve high-precision measurements of the half-life of ^{109}In implanted in large and small lattice spaces. It would provide information about the effect of compression on electron capture nuclear decay rate. The uncertainty in the measurement of the half-life would be kept within 0.15% to look for any change of decay rate under compression.

We request 4 shifts for this experiment. Each shift would be 8 hours long.

^{109}In can be obtained from HIE-ISOLDE with an intensity of 10^5 ions/sec and energy =100-150 MeV. The number of ^{109}In ions implanted after 7 hour run $\approx 2.5 \times 10^9$ ions. We need 1-1.5 hours to take out the implanted foil, put in another foil and start the next implantation run. The total number of 203 keV photons emitted initially from the source in 15 minutes $\approx 10^8$. The total number of counts in the photo-peak of high efficiency HPGe detector in 15 minutes $\approx 5\times10^6$ counts at the beginning of the counting. The singles count rate in each γ-ray detector would be kept below 10000 counts per sec to enable good energy resolution of HPGe detectors. The dead-time would be manageable as we shall take singles spectra. The effect of dead time of the data acquisition system would be cancelled by monitoring the ratio of the peak areas of 203 keV γ-ray line and ^{60}Co γ-ray lines with time.

The measurements would be done for 2 targets (Pd and Pb) and then repeated.

We shall need 4-5 hours of initial setup time.

We shall need 4 shifts for our implantation run.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
HIE-ISOLDE 2nd beam line other than MINIBALL line) for implantation experiment. A low background room for counting will be required. High efficiency HPGe or CLOVER detectors or MINIBALL array along with standard electronics and data acquisition system will be required.	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards			
	[Part 1 of the experiment/equipment]	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	Standard ISOLDE vacuum		
Vacuum			
Temperature	Room temperature		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	None		
Electrical and electromagnetic			
Electricity	Standard requirement		

Static electricity	No		
Magnetic field	None		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	Pb, Pd		
Beam particle type (e, p, ions, etc)	^{109}In		
Beam intensity	~10^{5} particles/sec		
Beam energy	100-150 MeV		
Cooling liquids	None		
Gases	None		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope	^{60}Co sealed source		
• Activity	(20-50)µC		
Use of activated material:			
• Description	☐ ^{109}In implanted Pb and Pd foils		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope	^{109}In		
• Activity	<100µC		
Non-ionizing radiation			
Laser	No		
UV light	No		
Microwaves (300MHz-30 GHz)	No		
Radiofrequency (1-300MHz)	No		
Chemical			
Toxic	Pb foils		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	No		
Irritant	No		
Flammable	No		
Oxidizing	No		
Explosiveness	No		
Asphyxiant	No		
Dangerous for the environment	No		
Mechanical			
Physical impact or mechanical energy (moving parts)	No		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	None		
Noise	**No**		
Frequency	[frequency],[Hz]		
Intensity			
Physical			

Confined spaces	No		
High workplaces	No		
Access to high workplaces	No		
Obstructions in passageways	No		
Manual handling	[location]		
Poor ergonomics	[location]		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*

1 kW