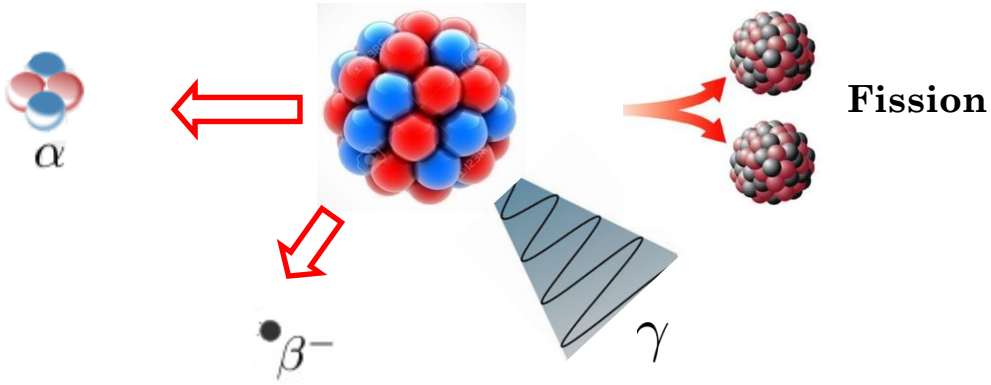
Precision Measurement of the Half-life of ^{110}Sn in Large and Small Lattice Environments

A.Ray, A. K. Sikdar, P. Das

Variable Energy Cyclotron Centre, 1/AF Bidhannagar, Kolkata 700064, India

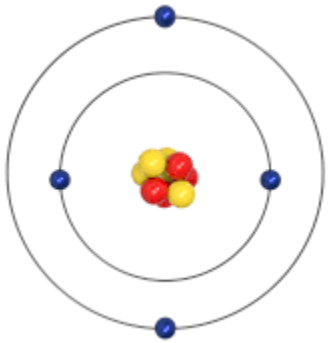
Local Contact: Karl Johnston
CERN, Geneva, Switzerland

Unstable nuclei



Radioactive decay generally known to be independent of temperature, pressure and chemical environment.

However, e^- capture nuclear decay is susceptible to environmental change.



^{7}Be lightest electron-capturing nucleus.

λ(electron capture decay rate)$\propto |\psi(0)|^2$

Valence 2s electrons of ^{7}Be gives 3.3% of total electron density at nucleus.

Electron capture decay rate

$$\lambda_{EC} = \frac{(E_\nu)^2}{\pi c^3 \hbar^4} g^2 |H_{fi}|^2 |\psi_e(0)|^2$$

E_ν kinetic energy of neutrino.

$$|\psi_e(0)|^2 = |\psi_{1s}(0)|^2 + |\psi_{2s}(0)|^2 + \ldots |\psi_V(0)|^2$$

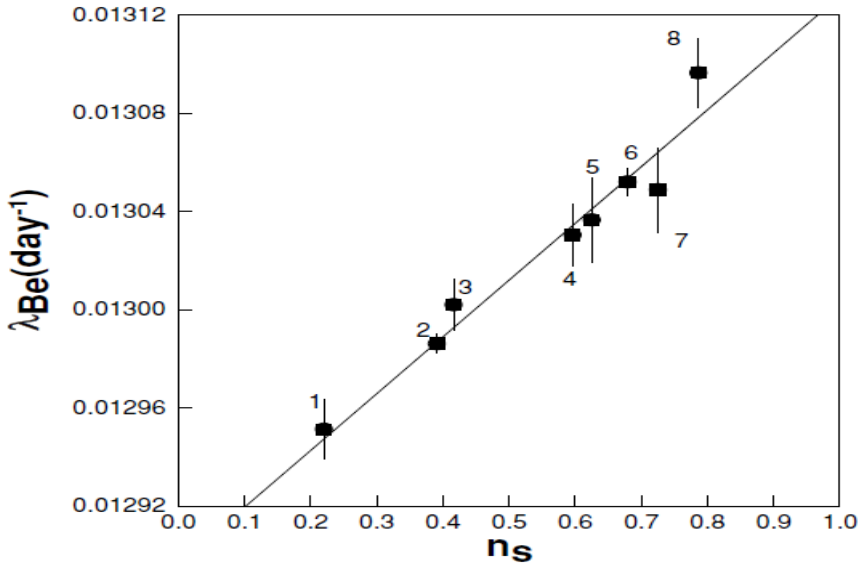
E. Segré and C. E. Weigand [Phys. Rev. **75**, 39 (1949)]

Observed $\frac{\lambda_{BeO} - \lambda_{Be}}{\lambda_{Be}} = (-3 \pm 1.8) \times 10^{-4}$ (Ionization counter experiment)

Johlige et al. Phys. Rev. C**2**, 1616 (1970) measured decay rate changes from different ^{7}Be compounds by ionization counter technique and found maximum variations ~0.2%.

^{7}Be electron capture Decay in different chemical environment

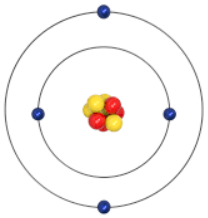
Electron affinity of surrounding medium affects decay rate of ^{7}Be
Host atoms of high electron affinity takes away valence 2s electrons of ^{7}Be.
Decay rate reduced.



Results could be understood by Density Functional calculations.

P. Das and A. Ray, Phys. Rev. C71, 025801 (2005).
T. Ohtsuki et al., Phys. Rev. Lett. 93, 112501 (2004).
E. B. Norman et al., Phys. Lett. B 519, 15 (2001).

Effect of compression on ^{7}Be decay rate

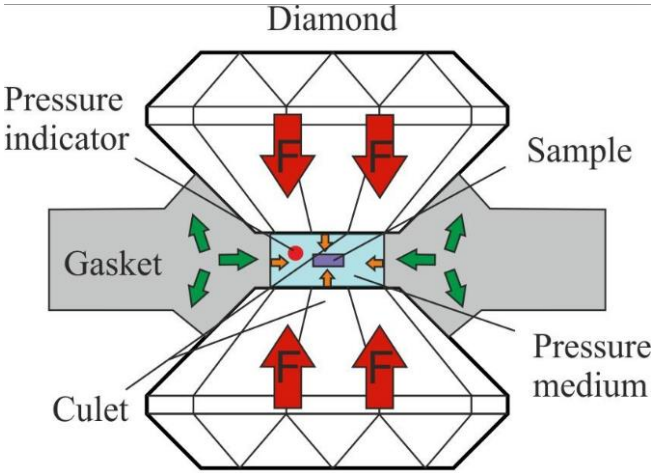


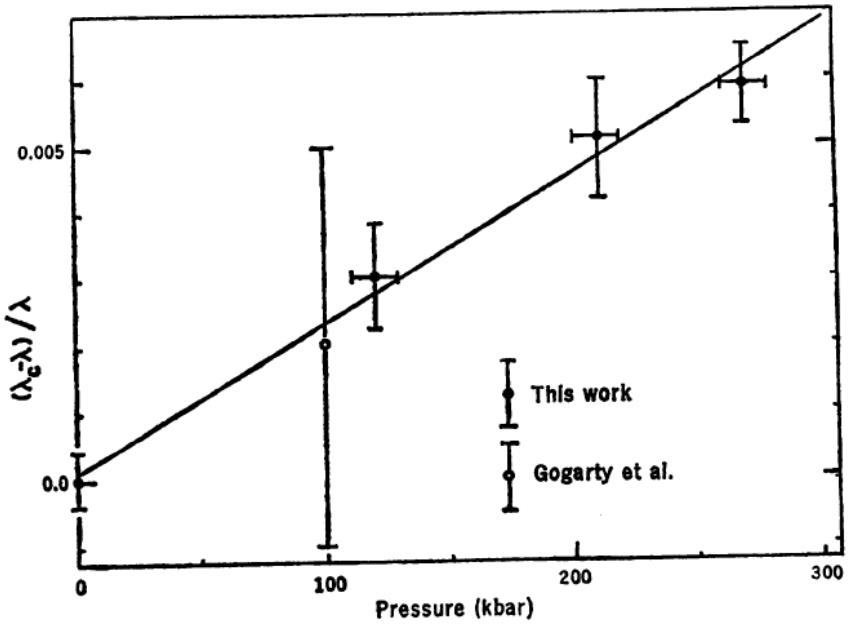
2s valence electrons pushed in towards nucleus.
Increases 2s electron density at nucleus.

1s electrons see less nuclear charge due to more screening by 2s electrons.
1s electron density at nucleus decreases.

Net result: Total electron density at nucleus generally increases under compression

Compression of ^{7}Be atom by applying external pressure on ^{7}BeO lattice





W. K. Hensley *et al.*, Science 181, 1164 (1973)

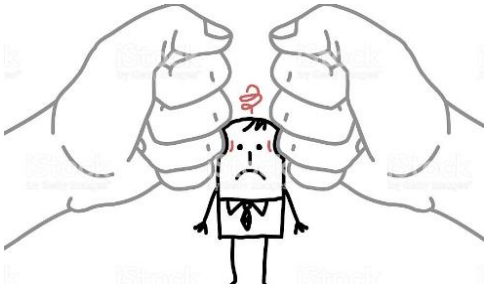
$$\frac{\Delta\lambda}{\lambda} = (2.2 \pm 0.1) \times 10^{-4} P \ ,$$

where P is the applied pressure in GPa.

Density functional calculations underpredict experimental result by a factor of 5.

Compression of ^{7}Be atom by confining in a small lattice

^{7}Be ion compressed when implanted in a small lattice such as Palladium (Pd).
Lattice constant = 3.9Å
Compared to
when implanted in a large lattice such as lead (Pb).
Lattice constant = 5Å
Both Pd and Pb have low and similar electron affinity.
Observed increase of decay rate of ^{7}Be in Pd could be attributed to compression.



Measured increase of decay rate of ^{7}Be in Pd w.r.t Pb is $\Delta\lambda/\lambda=(0.82\pm0.16)\%$
[A. Ray *et al*., Phys. Rev C **101**, 035801 (2020)]
WIEN2K predicts ~0.2% increase of decay rate of ^{7}Be in Pd.
Large discrepancy between measurements and DFT calculations

Effect of Compression on ^{7}Be Decay rate: Not Understood

Does the large discrepancy with DFT calculations exist in general?

Electron capture nuclear decay rate plays an important role in the creation of heavy elements during the merger of neutron stars and core collapse of supernova.
Significant heat produced by the electron capture of ^{40}K at the earth's core.
DFT calculations generally used to model these decays.

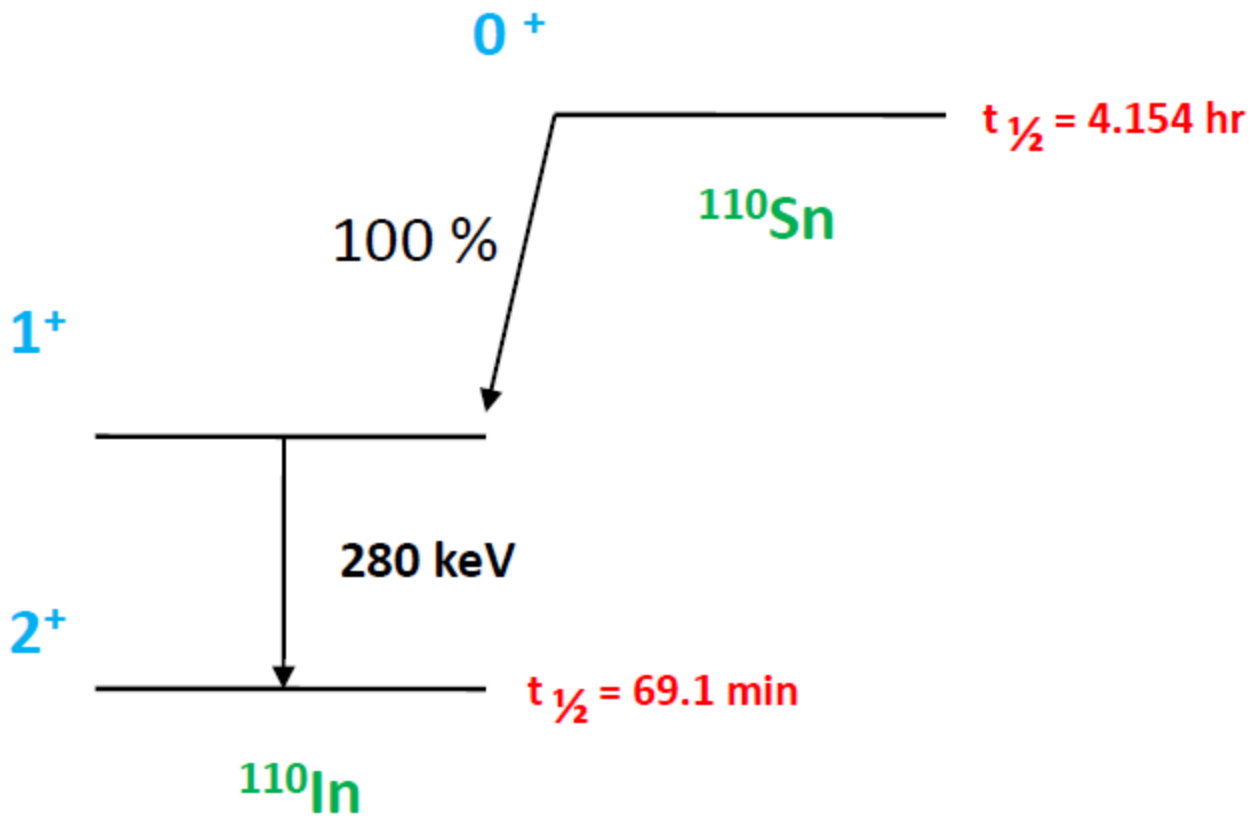
Is observed electron capture nuclear decay rate under compression (achievable in Laboratory) for heavy elements ≫DFT prediction

Propose to study the effect of compression on the decay rate of ^{110}Sn.

Measure decay rate of ^{110}Sn implanted in large Pb lattice (lattice constant=4.95Å) versus small Pd lattice (lattice constant=3.89Å).
DFT codes predict (<0.1%) increase of decay rate.

Earlier Measurement (^{20}Ne+^{93}Nb reaction) found
Decay rate of ^{110}Sn in Au (lattice constant=4.08Å) faster than in Pb (lattice constant=4.95Å) by (0.48±0.25)%. **(Null result within two standard deviations)**
[A. Ray *et al*., Phys. Lett. B **679**, 106 (2009)]

Decay Scheme of ^{110}Sn



Reasons for performing ^{110}Sn experiment at CERN HIE-ISOLDE with much higher precision

In the earlier experiment [^{20}Ne+^{93}Nb reaction at E(^{20}Ne)=80 MeV],
ALL radioactive products implanted in Pb and Au catcher foils.
Area of 280 keV γ-ray emitted by ^{110}In following electron capture by ^{110}Sn monitored with time along with the areas of γ-ray peaks from ^{60}Co.
(Null result within two standard deviations).

Uncertainties in 280 keV γ-ray peak area determination

Ratio of peak to valley for 280 keV γ-ray line was on the order of 10 in earlier expt.
Uncertainties in drawing background line.
Leads to ≈0.2% uncertainty in half-life determination.

For higher precision experiment, plan to use

Intense (> 10^5 ions/s) energetic (2.2 MeV/A) ^{110}Sn beam from HIE-ISOLDE.
No nuclear reaction. Most intense γ-ray peak expected at 280 keV.
Peak to valley ratio for 280 keV γ-ray line expected to be ~500.
Half-life determination with ≈0.05% uncertainty possible.

Implantation in bulk region required

50-60 keV ^{110}Sn ions from CERN ISOLDE implanted at depths of (10±6) nm.
Surface effects.

Proposed Experiment

^{110}Sn ions (lifetime ≈4.2 hours) with intensity >10^5 ions/s and energy = 2.2 MeV/A would be implanted in Pd and Pb catcher foils (25 μm thick) one by one.
Implantation at a depth of 10-15 μm.
No surface effect.
Electron affinity of Pd is = 0.56 eV and Pb is = 0.37 eV.
Energy of ^{110}Sn beam below Coulomb barrier for nuclear reactions with Pb or Pd.

Implantation on each catcher foil for 8 hours.
Implanted Pb and Pd foil along with a ^{60}Co γ-ray source to be placed one by one before a 80% efficiency HPGe detector in a low background room.

Count for 15 minutes, then save spectrum, reset and start for next 15 minutes.
Continue in this automated way for 10 hours at a stretch, then intermittently up to 24 hours or longer.

Complete measurements for Pb and Pd foils. Repeat measurements once.
Time keeping by a calibrated pulser.
Monitor ratio of 280 keV γ-ray line to 1332.5 keV γ-ray line from ^{60}Co with time to cancel out dead time and pile-up effects.
Measure Relative change of decay rate of ^{110}Sn in Pb and Pd foils.

Requirement of Beam Purity

^{110}Sn beam would contain ^{110}In impurity.
^{110}In→ ^{110}Cd emits 657.8 keV γ-ray. Compton edge at 280 keV.
Contamination could be reduced by electronic gating.

Want radioactive contaminant ^{110}In to be ≤0.1% of ^{110}Sn beam intensity.

Stable beam contaminants could produce additional lattice damage.
Might produce nuclear reaction.

Heavier (stable) contaminants could be more acceptable.

Prefer **^{110}Sn (27^{+})** beam with Xe, Ce, La stable contaminants.

Want heavy stable contaminants ≤1% of ^{110}Sn beam intensity.

Rate Estimate

1) Assuming Intensity of ^{110}Sn beam from HIE-ISOLDE=10^5 ions/s,
Number of implanted ^{110}Sn ions on catcher foil (Pb or Pd) in 8 hours =2.8×10^9

Total number of 280 keV γ-ray photons emitted in 15 minutes $\approx10^8$

Total number of counts in photo-peak at 280 keV in a 80% HPGe detector
in 15 minutes $\approx5\times10^6$ at the beginning of the counting.

γ-ray photo-peak counts (1332.5 keV) from ^{60}Co source in 15 minutes $\approx10^6$
Background counts near 1332.5 keV much smaller than those near 280 keV.

2) Intensity of ^{110}Sn beam preferably be increased to $\sim10^6$ ions/s for better peak to background ratio ($\sim$1:500) for 280 keV γ-ray photo-peak.

Ratio of 280 keV peak area to 1332.5 keV peak area would be independent of dead time and pileup effects.

3) If ^{110}Sn beam intensity ($\sim10^7$ ions/s) with the required purity is available, each implantation run would be for 2 hours.
background ratio ($\sim$1:500) for 280 keV γ-ray photo-peak could be achieved.

Requested Shifts

1) Assuming ^{110}Sn beam current ∼10^6 ions/s

^{110}Sn beam current ∼10^6 ions/s

So required time for implantations is = 8×4=32 hours.

Allowing for 2 hours time to change targets each time after an implantation run

Total required time = 2×4=8 hours.

Total beam time =(32+8) hours = 40 hours=5 shifts.

2) Assuming ^{110}Sn beam current ∼10^7 ions/s

Required time for 1st set of implantations is = 2×2=4 hours.

Target changing time = 2×2=4 hours.

1st set completed in (4+4) hours=8 hours.

Gap of 24 hours to complete counting.

Repeat set measurements

Time required =8 hours.

Total time = 16 hours and a gap of 24 hours between two sets of implantations.

Total time = 40 hours.

4-5 hours time required for initial setup.


thanks