Electron Capture Nuclear Decay Rate under Compression

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Introduction

The electron capture nuclear decay rate is proportional to the electron density at the nucleus [1] and affected by the chemical environment, particularly in the case of electron capturing ^{7}Be. In the case of higher Z elements, such effect is expected to be negligible as the valence electrons contribute very insignificant percentage of electron density at the nucleus. The change of electron capture nuclear decay rate of ^{7}Be in different chemical environments has been observed experimentally and density functional calculations calculating the change of electron density at the nucleus generally give a reasonable explanation of the effect.

The electron capture nuclear decay rate should change under compression as the valence electron configuration would be modified under external pressure. Such studies are of current interest in many areas such as astrophysics, nuclear physics, atomic physics, condensed matter physics and geophysics. There are a few measurements of the change of electron capture nuclear decay rate of ^{7}Be under compression by applying external pressure to ^{7}BeO lattice [2] and $^{7}Be(OH)_2$ compounds. The change of decay rate of electron capturing ^{109}In and ^{110}Sn implanted in a small lattice such as Au and large lattice such as Pb was measured [3]. All these measurements show significantly higher percentage increase of the decay rate under compression compared to the expectations from standard density functional and Hartree-Fock calculations [4]. However, earlier calculations did not include the effect of finite nuclear size and quantum electrodynamics (QED). We have performed calculations including the effects of finite nuclear size and (QED). We shall discuss whether the experimental results could be a manifestation of quantum Zeno effect considering the disruption of the time evolution of the electron-capturing nuclear state due to the repeated measurements of the nuclear charge by the valence electrons.

Density Functional Calculations

Hensley et al. [2] measured the fractional change of decay rate of ^{7}Be by putting external pressure on ^{7}BeO crystal and obtained the relationship: $\frac{\Delta\lambda}{\lambda} = (2.2 \pm 0.1) \times 10^{-4} P$, where $\Delta\lambda/\lambda$ is the fractional change of decay rate λ and P is external pressure in GPa unit. Using WIEN2k density functional code [5] and experimentally obtained lattice parameters of BeO lattice, we have calculated the change of electron density at beryllium nucleus as a function of the lattice parameter of BeO crystal and obtained the relationship $\frac{\Delta\rho(0)}{\rho(0)} = 0.01 \left| \left(\frac{\Delta V}{V}\right)_{BeO\_lattice} \right|$, where $[\Delta\rho(0)/\rho(0)]$ and $(\Delta V/V)$ are the fractional changes of electron density at the nucleus and volume of BeO lattice respectively. Then, using the known relationship between $(\Delta V/V)$ and applied pressure [6], we get $\Delta\lambda/\lambda=0.41\times10^{-4}$P, where P is in GPa unit. So the density functional calculations predict about a factor of 5 smaller increase of $\Delta\lambda/\lambda$ compared to the experimental results. Bibikov et al. [4] performed Hartree-Fock calculations and obtained that the calculated rate of increase of $\Delta\lambda/\lambda$ is a factor of 2.5 times smaller than the experimental value. No pressure induced phase transformation of lattice structure is expected even at the maximum applied pressure of 27GPa. Moreover, a pressure induced phase transformation of BeO lattice from wurtzite to rock-salt structure would reduce [7] the rate of increase of decay rate with pressure, contrary to the experimental result. The electron capturing nuclear decay rates of ^{109}In and ^{110}Sn implanted in small Au lattice (lattice parameter = 4Å) increase [3] by (1±0.2)% and (0.5±0.25)% respectively compared to the corresponding decay rates when implanted in large Pb lattice (lattice parameter =5Å). Our density functional calculations predict an increase of only about 0.04% in those cases. So clearly the density functional and Hartree-Fock

calculations underpredict the increase of $\Delta\lambda/\lambda$ with pressure by a large factor compared to the available data. However, all these calculations were performed assuming a point nucleus and neglecting QED effects.

Effect of Finite Nuclear Size and QED

We have performed density functional calculations including the effect of finite nuclear size and vacuum polarization potential (QED effect). As expected, the results for beryllium remained essentially unchanged. The beryllium nucleus is very small and the electrons are relatively far away from the nucleus because of its lower nuclear charge and thus finite nuclear size effect could be ignored. QED effects are also negligible for such small nuclear charge. Vacuum polarization effect has been found to be negligible even for indium and tin and the self-interaction effect of electrons even much smaller. However, the effect of finite nuclear size is relatively significant for indium and tin. It was found that the calculated percentage increase of decay rate of indium implanted in small Au lattice versus large Pb lattice could increase by a factor of 4 when the point indium nucleus is replaced by a finite spherical nucleus of expected radius. So, considering the effect of finite nuclear size, the electron capture decay rate of indium in Au could be 4×0.04%=0.16% higher compared to the decay rate of indium in Pb. However, this number is still significantly smaller compared to the observed increase of (1±0.2)%.

Quantum Zeno Effect

Let us examine how the atom could be considered as a detector [8] to record the β-decay electron capture process. As an atomic nucleus captures an electron and transforms to a nucleus of lower atomic number, the inner electronic orbitals are only slightly modified. However, the valence orbitals are dramatically altered and define the chemistry of the new element. So the valence electrons could be considered as a pointer state that records the electron capture β-decay process. Considering repeated measurements of the nuclear charge by the orbiting valence electron inhibiting the time evolution of the decaying nuclear state, Fonda et al. [9] predicted fractional decrease of nuclear decay rate compared to theoretical decay rate as $\frac{\Delta\lambda}{\lambda} = \frac{N_R d}{v}$, where N_R is the number of times per second the nuclear charge is measured, d is taken as the atomic radius and v the speed of emitted or captured particle. The energy difference between 2s electrons as Be is transformed to Li in BeO lattice is=2.61 eV and a minimum time of 2.4×10^{-16} s is required to differentiate between them. So $N_R=4\times10^{15}$. In a BeO lattice under 27GPa pressure, the corresponding energy difference is =2.3 eV and longer time is required to determine whether Be has been transformed to Li. This means smaller number of interruptions per sec (N_R) to determine the nuclear charge and faster decay rate in compressed ^{7}BeO. The fractional increase of decay rate in compressed ^{7}BeO lattice (under 27 GPa) compared to normal ^{7}BeO lattice is given by $\frac{\Delta N_R d}{v}$ =0.005 (taking v as the speed of Be 1s electron), in agreement with the experimental result. Similar analysis gives approximate agreement with the experimental result for the electron capture decays of In and Sn under compression.

Conclusion

The observed percentage increase of electron capture nuclear decay rate under compression is significantly higher than the calculated values, even after the inclusion of finite nuclear size and QED effect. The results could be quantitatively explained by Quantum Zeno effect, as discussed.

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