Change of $^7$Be decay rate under compression

A. K. Sikdar$^1$, A. Ray$^1$, P. Das$^1$, S. Pathak$^1$ and J. Datta$^2$

$^1$Variable Energy Cyclotron Center, 1/AF, Bidhannagar, Kolkata 700064, India
$^2$Analytical Chemistry Division, BARC, Variable Energy Cyclotron Center, 1/AF, Bidhannagar, Kolkata 700064, India

E-mail: ray@vecc.gov.in; amlanray2016@gmail.com

Abstract. We have studied the change of decay rate of $^7$Be implanted in the small Pd lattice versus large Pb lattice. Since the electron affinities of Pd and Pb are very low and similar, any observed increase of the decay rate of $^7$Be could be attributed to the compressional effect in the smaller confinement of Pd lattice. It has been found that the decay rate of $^7$Be is faster in Pd lattice compared to that in Pb lattice by $(0.82 \pm 0.16)\%$. Similar results were observed by applying high external pressure on $^7$BeO lattice. Density functional calculations underpredict the increase of $^7$Be decay rate under compression by a large factor. It is important to understand this result because of its significance in calculating $^7$Be decay rate in the solar core and corresponding $^8$B neutrino flux.

1. Introduction

The decay rate of electron-capturing $^7$Be is known to be susceptible to external environment and its decay rate has been studied by implanting $^7$Be in different media [1-4]. 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 [2,5]. The effect of free conduction electrons (Debye screening) of metal on the electron density at the nucleus was studied and found to be negligible [6].

There are very few studies [7,8] on the effect of compression on the decay rate of $^7$Be. However, such studies are important and have astrophysical significance regarding the calculation of $^7$Be decay rate in the solar core [9,10]. The effect of compression on the decay rate of $^7$Be was experimentally measured earlier by applying high pressure up to 27GPa on crystalline $^7$BeO using a diamond anvil cell [7]. Another way to compress a radioactive atom is by implanting it in the interstitial voids of a small lattice where the smaller confining space would compress the radioactive ion. We implanted $^7$Be in Pd [face-centered cubic lattice; lattice constant =3.89Å] and Pb [face-centered cubic lattice; lattice constant =4.95Å] lattices. Since the electron affinities of Pb (electron affinity = 0.37 eV) and Pd (electron affinity = 0.56 eV) are low and similar, any observed increase of decay rate of $^7$Be in Pd could be attributed to the effect of compression on decay rate.

2. Experimental Procedure

A 7 MeV, 500 nA proton beam from Variable Energy Cyclotron Center, Kolkata, India was used to bombard a 400 μg/cm$^2$ LiF target evaporated on a 1.5 μm thick aluminum foil. $^7$Be ions with (1-3) MeV kinetic energy were produced by $^7$Li($^1$H,e)$^7$Be reaction and implanted 1 μm – 3.3 μm inside a 25 μm thick Pb or Pd catcher foil placed behind the LiF target. The 7 MeV proton beam went through the...
catcher foil and was stopped in a water-cooled aluminum plate placed behind the catcher foil. The implantation run in each catcher foil was for (10-12) hours. We waited for about 5 months for the decay of all short-lived radioactive elements produced by the bombardment of the proton beam. Then we alternately placed $^7$Be implanted Pb or Pd foil in front of a high efficiency HPGe detector and counted them along with a $^{60}$Co source that emits 1173.2 keV and 1332.5 keV $\gamma$-ray photons. The counting was done in a low background counting room. $^7$Be decays to the first excited state of $^7$Li by electron capture with about 10% probability and a 477.6 keV $\gamma$-ray is emitted. We counted for 24 hours, then saved the singles $\gamma$-ray spectrum and restarted counting. A precision pulser was counted by a scaler and used as a clock. The pulser was calibrated by a quartz clock.

3. Data analysis and experimental results
In Fig. 1, we show typical $\gamma$-ray spectra of $^7$Be implanted Pb and Pd catcher foils. We see 477.6 keV $\gamma$-ray line along with $\gamma$-ray lines from $^{60}$Co source in both the spectra. Long-lived $^{105}$Ag ions were produced by the reaction $^{105}$Pd($^1$H,n)$^{105}$Ag. The strong $\gamma$-ray lines at 280.4 keV, 344.5 keV, 442.3 keV and many other weaker $\gamma$-ray lines produced by electron capture and $\beta$ decay of long-lived $^{105}$Ag to the excited states of $^{105}$Pd are seen in the $\gamma$-ray spectrum of Pd catcher foil. We also see all the expected natural background lines.

![Image of gamma-ray spectra](image)

Fig. 1. Typical $\gamma$-ray spectra of $^7$Be implanted in Pd and Pb catcher foils.

In Fig. 2(a,b), we show the plots of the ratios of peak areas of 477.6 keV $\gamma$-ray line from $^7$Li to the sum of peak areas of 1173.2 keV and 1332.5 keV $\gamma$-ray lines from $^{60}$Co with time for $^7$Be implanted in Pd and Pb lattices. The uncertainties shown on the data points in Fig. 2 (a,b) reflect our uncertainties in
the determination of peak areas obtained by subtracting out a linear background drawn under the peak by joining two points on the opposite sides of the peak. The corresponding exponential fits for the data points have been superimposed. The reduced $\chi^2$ values for Pd and Pb data sets are 1.1 and 0.9 respectively. The corresponding residual plots obtained by subtracting out the calculated fitted points from the actual data points are shown in Fig. 2(c,d). We show frequency plots for the two fits in Fig. 2(e,f). The residual values are plotted along X-axis. The frequency is the number of data points (with the statistical uncertainties) in a specific bin around that residual value and plotted along Y-axis. Reasonable Gaussian fits with reduced $\chi^2$ values = 1.11 and 1.08 for Pd and Pb data sets respectively have been obtained. These results show that the fluctuations around zero shown in the residual plot [Fig. 2(c,d)] are statistically random and do not show any indication of systematic errors. From the exponential fits of the data points, we obtain that the decay rate of $^7$Be in Pd is faster compared to the decay rate of $^7$Be in Pb by $((\Delta \lambda / \lambda) = (0.82 \pm 0.16)\%$. Using the result of Hensley et al. [7], we estimate that the additional compression that would cause the observed increase of $^7$Be decay rate in Pd compared to that in Pb is equivalent to applying about 40 GPa pressure on $^7$BeO lattice.

Fig. 2. Exponential plots of time versus the ratio of the peak areas of 478 keV $\gamma$-ray from $^7$Li to the sum of the peak areas of 1173 keV and 1332 keV $\gamma$-rays from $^{60}$Co for $^7$Be in Pd and Pb (a,b). Residual plots of the data points for $^7$Be in Pd and Pb (c,d). Frequency plots of the residual data points with Gaussian fits for $^7$Be in Pd and Pb (e,f).
4. Discussions
We have performed density functional WIEN2k code calculations [11] and found that the code predicted a factor of about 4-5 times smaller increase of decay rate compared to the experimental results for both the application of external pressure on $^7$BeO lattice [7] as well as for the implantation of $^7$Be in Pd and Pb lattices. So, the density functional calculations underpredict the increase of $^7$Be decay rate under compression by a large factor.

In summary, we have measured $(0.82\pm0.16)\%$ increase of decay rate of $^7$Be in Pd lattice compared to that of $^7$Be in Pb lattice. Density functional code WIEN2k underpredicts this result by a large factor. It is important to understand the increase of $^7$Be decay rate at pressures achievable in laboratory experiments to obtain more confidence in the calculation of $^7$Be decay rate in the solar core that is not directly accessible by experiment. A. Ray acknowledges financial assistance provided by Science and Engineering Research Board, Government of India, grant no: EMR/2016/001914.

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