PRECISION HALF-LIFE MEASUREMENT OF ^{7}Be IMPLANTED IN DIFFERENT MATERIALS*

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The decay rates of ^{7}Be implanted into gold, platinum, graphite, kapton and Al_2O_3 have been measured with an accuracy better than 0.1%. The results obtained are compared with the existing experimental data and confronted with theoretical predictions.

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1. Introduction

The electron capture decay probability depends on the electron density in the nuclear volume. Therefore, environmental factors that can alter the electron density at the nucleus, such as pressure, temperature, chemical form, magnetic fields, *etc.*, may affect the electron capture decay rates. Since the overlap of the electronic wave functions with the nucleus decreases for outer electron shells, only for low-Z elements the valence electrons have a measurable contribution to the electron density at the nucleus. This effect was discussed already in the late 1940s by Segrè and Wiegand [1].

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Since ^{7}Be is the lightest nucleus decaying by electron capture, it is the most suitable case to investigate the variations of its decay rate in different environments. These studies are relevant not only for nuclear physics but also for nuclear astrophysics, since the half-lives of such nuclei as, *e.g.*, ^{7}Be will depend on the surrounding plasma density in the stellar environment, thus influencing the calculations of the ^{8}B solar neutrino flux [2].

^{7}Be decays with an average half-life of 53.22(6) days [3]. About 89.5% of its electron capture decay proceeds to the ground state of the daughter ^{7}Li, while the remaining 10.5% to the first excite state at 478 keV. Most measurements aiming at determining the half-life of ^{7}Be look at the intensity of the 478 keV gamma transition in ^{7}Li.

The first observations of the environmental variations of the ^{7}Be half-life were reported already in the 1940s and 1950s [1, 3]. Recently, it was remeasured several times with high accuracy (0.5% or better). Small changes of 0.1–0.2% depending on the beryllium compound were observed [4]. However, relatively large differences in the decay rates of up to 1% were reported for ^{7}Be nuclei implanted in different media [2, 5, 6, 7, 8].

As suggested by Das and Ray [2], these variations of the ^{7}Be half-life can be qualitatively understood in terms of electron affinities of beryllium and neighboring atoms. A beryllium atom forming a compound or implanted in a high electron affinity medium generally loses a larger fraction of its $2s$ electrons compared to a beryllium atom interacting with an element of low electron affinity. The loss of $2s$ electrons of ^{7}Be should also depend on the average distance between the beryllium and the neighboring host atoms, hence the dimension and structure of the host lattice have to be taken into account. Another effect is the screening of the Coulomb potential by the quasi-free electrons in metallic samples, which was investigated by Wang *et al.* [9].

In the present work we report on high-precision measurements of the half-life of ^{7}Be implanted into Al_2O_3, gold, graphite, kapton and platinum. The results obtained are compared with the existing experimental data and confronted with theoretical predictions.

2. Experiment

The nuclei of ^{7}Be were produced at ISOLDE, CERN, and implanted into the sample materials to be later analyzed in an off-line measurement. A standard ISOLDE UC_x/graphite target was bombarded with 1.4 GeV protons: the ^{7}Be atoms were produced by spallation and fragmentation reactions and diffused to the ionizer tube, where they were resonantly laser-ionized by two ultraviolet transitions (234.9 nm and 297.3 nm) leading to an auto-ionizing state. The target and the attached tungsten ionizer were kept at a temper-

ature of about 2000°C. The ions were extracted and accelerated to 50 keV, mass separated with the ISOLDE general purpose separator (GPS) and implanted into the samples through collimators of $5 \times 5\,\mathrm{mm}^2$ (square) and 2 mm diameter (round), respectively. The implantation depth ranged between 60 nm for Pt and 320 nm for kapton [10]. The mass-separated beam consisted of $^7\mathrm{Be}^+$ and a similar amount of surface-ionized $^7\mathrm{Li}^+$ that was co-implanted into the samples, but at greater depth because of its lower Z. The implantations were performed at room temperature and lasted 4 to 20 minutes at ion currents of 0.5 to 1 nA leading to ^{7}Be activities of few ten kBq. No further treatment was applied to the samples studied in this work.

The samples were then transported to the University of Warsaw, Poland, and to the University of Aarus, Denmark for off-line measurement. We report here only on the measurement performed at the University of Warsaw.

In order to determine the half-life of ^{7}Be, the intensity of the 478 keV gamma transition in ^{7}Li was measured as a function of time. The gamma-ray detection set-up consisted of a high-purity single crystal germanium detector (15% relative efficiency) with a holder attached to it to host the samples at about 25 mm from the end-cap of the detector. The holder was designed in such a way that the position of the sample was reproducible with an accuracy of 0.1 mm. The detector was placed inside a 10 cm thick lead shield for background suppression. Each measurement lasted 8 hours. The fixed measurement-time allowed to use relative activity for the half-life determination, hence reducing the systematic uncertainty on the data points and on the half-life fit.

For all samples except platinum, the initial total counting rate of the detector was about 70 counts/s, whereas for the latter sample it was about two times higher. The total counting rate of background was about 2 counts/s.

The dead time of the system was controlled by introducing ∼1 Hz signal from a precise pulse generator into the test input of the germanium detector. The number of generated pulses was measured by a counter. By comparing the number of events registered in the pulser peak in the energy spectrum and in the counter, the effective dead time of the system was determined to be 52 μs/event.

3. Results

For each of the samples analyzed, the intensity of the 478 keV peak, corrected for background and for dead time was plotted as a function of time and fitted with a single exponential function using the maximum likelihood method. In figure 1 the activity of ^{7}Be implanted into kapton is plotted as a function of time. The respective fit with an exponential decay curve is shown as well as the residual of the fit itself.

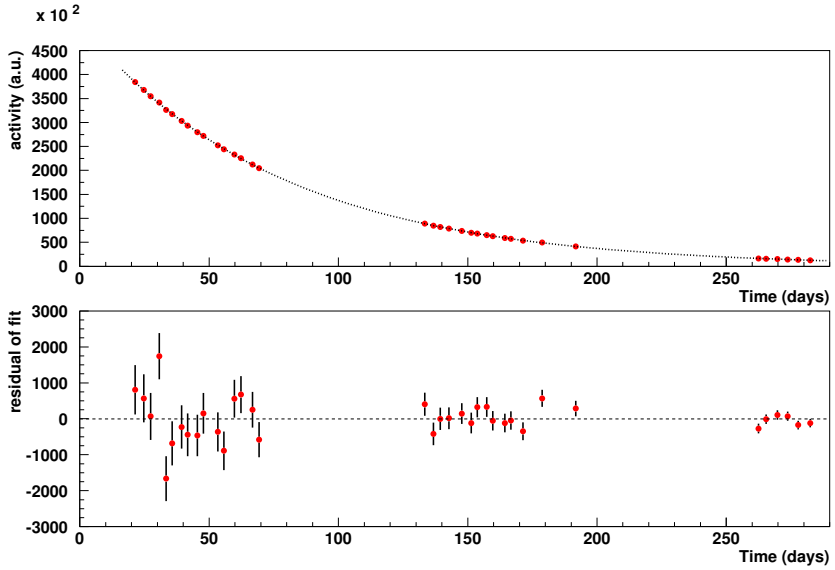

Fig. 1. Upper panel: decay curve of the 478 keV transition; error bars are smaller than the symbol. The dashed line displays the curve corresponding to the exponential decay fit. Lower panel: residual of the fit calculated as difference of the experimental value of the activity (in a.u.) and the expected value from the fit.

In Table I and figure 2 the ^{7}Be decay half-lives for all the measured samples are shown in comparison to literature values. The ^{7}Be half-lives for gold, graphite and platinum matrices determined in this work are in good agreement with the values reported in literature [11,8,13,14]. Our result for

TABLE I

Half-life of ^{7}Be implanted into the different host materials, decay constant, half-life from literature and from model predictions [2] (see the text for details).

Material	Half-life [days] this work	λ [days^{-1}] this work	Half-life [days] literature	Half-life [days] theory
Graphite	53.05(4)	0.013066(12)	53.11(2)[a]	53.10
Au	53.27(3)	0.013012(11)	53.31(4)[a]	53.34
Pt	53.20(2)	0.013029(5)	53.26(7)[b]	52.93
Al_2O_3	53.29(4)	0.013007(11)	53.18(4)[c] 52.89(6)[d]	53.00
Kapton	53.30(4)	0.013006(11)	—	—

[a]Ref. [11]. [b]Ref. [13] scaled for λ_{Al} from [14]. [c]Ref. [8]. [d]Ref. [6] scaled for $T_{1/2}$ for gold host material from this work.

the Al_2O_3 sample is consistent with the value reported by Nir-El *et al.* [8] but it disagrees with the half-life extracted from the ^{7}Be decay rate measured by Ray *et al.* [6]. The cause of this discrepancy is difficult to identify; a possible explanation is the difference in the radiation damage on host lattice sites — while the ^{7}Be samples studied by Ray *et al.* [6] were produced in the ^{7}Li (p, n) reaction with ^{7}Be recoil energy of ~ 3 MeV, samples studied by Nir-El *et al.* [8] and in this work were produced by implantation of 50 keV, mass separated ^{7}Be+^{7}Li beam.

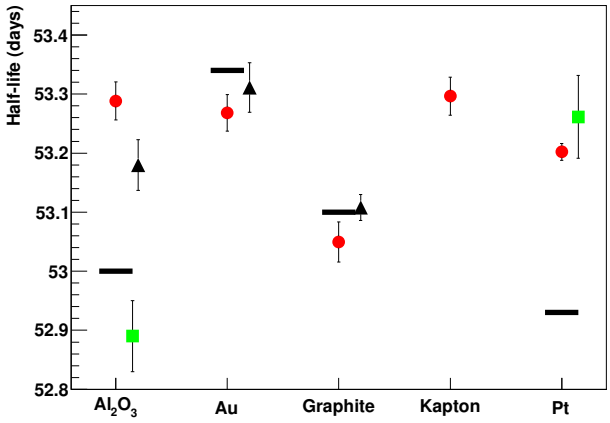

Fig. 2. Half-life of ^{7}Be implanted in different materials (solid/red circles) in comparison with literature absolute values (solid/black triangles) [11, 8], where available. The grey/green squares represent the half-lives extracted from relative data reported for Al_2O_3 [6] and platinum [13, 14]. The black thick solid lines display the predictions for the half-lives calculated within the TB-LMTO model [2]. See Table I and the text for details.

From the data presented in Fig. 2 it is evident that the half-lives of ^{7}Be implanted in Al_2O_3, gold, kapton and platinum are compatible with each other within 2σ, while the value for the graphite matrix is significantly lower.

In the last column of Table I the predictions of ^{7}Be half-lives based on the established linear dependence of the decay constant on the average number of ^{7}Be $2s$ electrons in the corresponding medium calculated within the TB-LMTO model [2] are given, when available. As can be noticed, the model seems to predict reasonably well the ^{7}Be decay half-lives for graphite and gold host materials whereas significant deviations of the half-lives predicted and measured in this work, 7σ and 13σ, are observed for Al_2O_3 and platinum hosts, respectively.

The predicted too short half-life of ^{7}Be implanted in platinum can be explained by a quasi-free electron screening correction which diminishes the effective decay Q_{EC}-value and slows down the decay rate. This effect was not

considered in the TM-LMTO calculations but it seems to be important for some metallic hosts including platinum, where it achieves the particularly high value of 2.7 keV [9]. The screening correction is expected to be negligible for insulators, hence it cannot explain the difference between the measured and predicted half-life for ^{7}Be implanted in Al_2O_3.

Further measurements should be carried out in order to fully understand the influence of the lattice structure, valence $2s$ electrons transfer and the role of quasi free electrons on the half-life of ^{7}Be. The effects of the lattice structure can be investigated by studying different samples with proper control of purity and radiation damage. A sensitive way to check the TB-LMTO calculations of the number of valence $2s$ electrons of ^{7}Be in different media is to look at the L/K electron capture ratio. So far it was done only for the HgTe sample in the work of [12]. The screening effect of the quasi-free electrons in metallic hosts can be investigated by systematic studies of ^{7}Be decay rate as a function of temperature in different samples. Direct measurements of the decay rate of ^{7}Be ions in selected charge states, relevant for calculation ^{7}Be decay rate in stellar environments, could be conducted in storage ring experiments, although the relatively high half-life would make such measurements extremely challenging.

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REFERENCES

[1] E. Segrè, C.E. Wiegand, *Phys. Rev.* **75**, 39 (1949).
[2] P. Das, A. Ray, *Phys. Rev.* **C71**, 025801 (2005).
[3] `www.nndc.bnl.gov/nudat2`
[4] M.M. Bé *et al.*, Table of Radionuclides (Comments on Evaluation), Monographie BIPM-5 (2004) Bureau International des Poids et des Mesures.
[5] D. Souza *et al.*, *Bull. Am. Phys. Soc.* **42**, 1679 (1997).
[6] A. Ray *et al.*, *Phys. Lett.* **B455**, 69 (1999).
[7] S.H. Zhou *et al.*, *Chin. Phys. Lett.* **22**, 565 (2005).
[8] Y. Nir-El *et al.*, *Phys. Rev.* **C75**, 012801(R) (2007).
[9] B. Wang *et al.*, *Eur. Phys. J.* **A28**, 375 (2006).
[10] `www.srim.org`
[11] E.B. Norman *et al.*, *Phys. Lett.* **B519**, 15 (2001).
[12] P.A. Voytas *et al.*, *Phys. Rev. Lett.* **88**, 012301 (2002).
[13] C.-B. Li *et al.*, *Chin. Phys. Lett.* **27**, 012301 (2010).
[14] F. Lagoutine *et al.*, *Int. J. Appl. Rad. Isotop.* **26**, 131 (1975).