Search for possible effects of temperature and electron environment on the α-decay lifetime

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Abstract

We report on recent experimental and theoretical findings on possible effects of temperature, metal electron environment and pressure on the α-decay constant. Contrary to recent claims, a possible screening effect of free electrons in a metal lattice at low temperature has to be ruled out on the basis of the experiment, while we find that effects induced by means of state-of-the-art compression techniques, although much smaller than previously speculated, might however be measurable. Considerable effects are expected in ultra-high-density stellar environments.

Introduction

Whether and to which extent the α-decay width might be modified upon the electron environment of the decaying nuclide has been the subject of numerous theoretical and experimental investigations (see, e.g., refs. [1-5]), boomed over the last years. It has in fact been put forward that this effect could have implications in the stellar nucleosynthesis of heavy elements [6], and applications to nuclear waste management [7,8] as well as to the determination of the screening enhancement factor in nuclear reactions [9,10].

In particular, recent works [4,11] have predicted or claimed to have measured significant lifetime variations for α emitters when embedded in a metal lattice and cooled down to low temperature, as a consequence of free-electron screening of the nuclear Coulomb potential. These claims have triggered a real scientific *querelle*, on the ground of both theory and experiments [12, and references therein].

Here we summarise methods and findings of the last experiment which has contributed to this debate. The experiment, designed to tackle ambiguities and shortcomings of previous studies [4,13,14] as best as possible, has provided no evidence of lifetime variation for ^{210}Po implanted in a copper matrix between 4.2 K and room temperature. Previously, a reduction of (6.3±1.4)% had instead been measured at 12 K [4].

We also report on further theoretical findings on the possible influence of very high pressure on the α-decay lifetime.

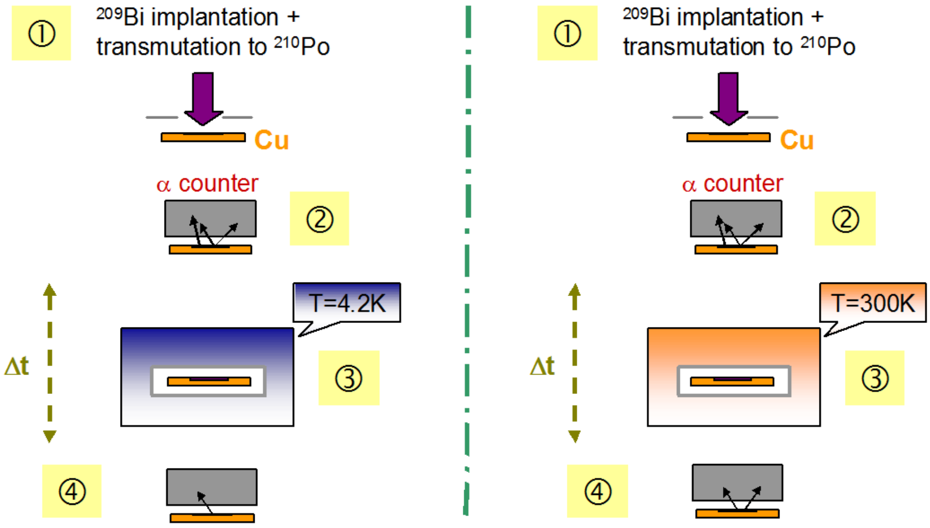

Fig. 1. Layout of the ^{210}Po experiment.

Effect of temperature and metal lattice

The layout of the experiment is sketched in Fig. 1. Four Cu disks (99.9871% wt., ø = 10 mm, 0.5 mm in thickness) were implanted at the Tandem Van-de-Graaff accelerator of the Max-Planck-Institut für Kernphysik, Heidelberg, Germany. A polyenergetic ^{209}Bi ion beam was used (15–60 MeV; ion charge states between +1 and +9), which spanned implantation doses of the order of 10^{15}–10^{16} ions (depending on the sample) over the range 1–4 μm beneath the disk surface, resulting in a Bi/Cu concentration lower than 1% at., as calculated by means of the code SRIM-2010 [15].

The implanted disks were irradiated at the High Flux Reactor (HFR) in Petten, The Netherlands, to transmute ^{209}Bi to ^{210}Po. The disks were placed in a specially manufactured holder made of titanium, which was then double-encapsulated in Ti irradiation capsules. To reach the activation required, the disks were irradiated for 29 days. After extraction from the irradiation capsule, the samples were cleaned in an ultrasonic bath.

The activity of the four disks was measured immediately before and after a storage period of ~200 days, i.e., one ^{210}Po lifetime. Two disks were stored in liquid helium (T = 4.2 K), while the other two were kept at room temperature (T = 293 K).

The α-activity measurements were carried out on an Ortec SpectrumMaster 920-8 equipped with an Ortec EG&G Soloist chamber and an ion-implanted Si detector (Ametek) with a surface of 900 mm^2. The chamber was equipped with a special sample holder to ensure precise and reproducible positioning of the disks. Energy and efficiency calibration of the detector were accomplished by using a certified α source (AMR 43, manufactured by Amersham). The background of the chamber was measured both before and after the measurement of a sample. The counting time of the samples was adjusted to achieve a total of 10^6 counts and thus a statistical error of 0.1%. Activity values were corrected (to the beginning of the individual measurement) for the counting time.

A typical α spectrum is shown in Fig. 2. The gross of the α intensity comes from the broad peak located at a lower energy compared to the ^{210}Po characteristic peak. The broad peak results from α particles emitted by deeply implanted ^{210}Po that suffer a certain energy loss while travelling to the sample surface.

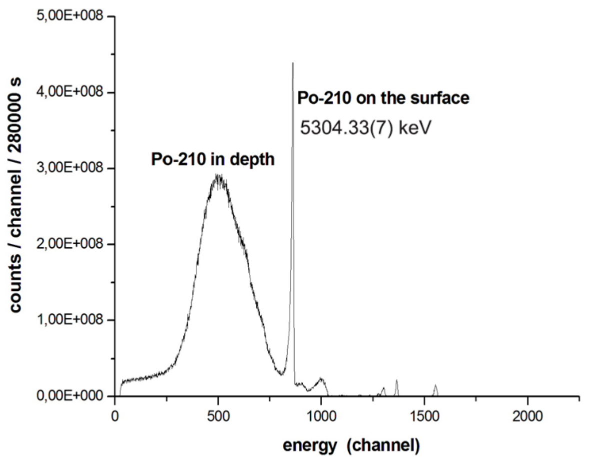

Fig. 2. A typical α spectrum from the ^{210}Po-implanted Cu disks.

This proves that the gross of ^{209}Bi was indeed deeply implanted into the Cu bulk and hence properly surrounded by metal atoms.

The four ^{210}Po half-life values calculated from the activity measurements range from 139.21 ± 2.90 d to 143.29 ± 2.98 d. These values are all longer than the value of 138.3763(17) d [16] here assumed as a reference, and compatible with it within 2σ. More importantly, within the measurement uncertainty, there is no evidence for a difference in half-life between the samples stored at 4.2 K and those stored at 293 K.

Effect of pressure

By using a free-electron approach based on Debye screening and pressure ionization model, Eliezer et al. [17] have recently reported that the lifetime of certain α emitters (e.g., ^{144}Nd and ^{154}Yb) might be reduced by about 15% at low temperature and pressures as high as those achievable in existing diamond anvil cells (DAC), ~ 4 Mbar.

In view of verifying these latter claims, we have derived a simple –though more rigorous and general– model for the calculation of the α lifetime in electron environments of increasing density. The model couples the customary Gamow theory of α decay in WKB approximation to the generalized Thomas-Fermi (TF) theory of the atom [18], at $T=0$. Details are given elsewhere [19]; here we summarise the main findings.

We have estimated the lifetime variation for three selected nuclides, i.e., ^{144}Nd, ^{154}Yb and ^{210}Po, when dispersed in a compressed Pb matrix. Denoting by $\eta \equiv \rho/\rho_0$ the compression ratio between the matter density ρ at a certain pressure and a reference density ρ_0 (here, ρ_0 is the Pb density at STP, i.e., 11.35 g/cm^3), and by τ_b the (mean) lifetime for the decay of the bare nucleus, the fractional lifetime variation $\delta\tau/\tau_b \equiv \tau/\tau_b - 1$ induced by the electron environment has been plotted as a function of η in Fig. 3, for each selected nuclide. Error bands (dashed lines) express the uncertainty in the calculation; continuous curves correspond to the mean value between the upper and lower band.

We find that $\delta\tau/\tau_b$ is always negative (meaning a reduction of the lifetime), and may be compatible with positive values only at low compression, within the uncertainty. Average curves exhibit a common, definite and monotonic trend with increasing η. The findings of Eliezer et al. [17] for ^{144}Nd and ^{154}Yb in the region $1 \le \eta \le 10$ are disproved in extent. Lifetime variation proceeds slowly in this region, at an extent that might however be measurable by using state-of-the-art static compression techniques [17]; on the other hand, absolute measurements of bare lifetimes (which would allow the experimental determination of $\delta\tau/\tau_b$ at $\eta=1$) are currently being attempted on radioactive ion beams [20]. Above $\eta=10$, the trend of $-\delta\tau/\tau_b$ accelerates, collectively as $\sim \eta^{0.62}$, resulting in lifetime reduction by factors between 2 and 10 –depending on the nuclide– at $\eta \approx 10^4$, a density regime beyond which relativistic effects need to be included in the TF treatment of electrons.

Contrary to the mechanism outlined by Zinner [3], which results in the increase of

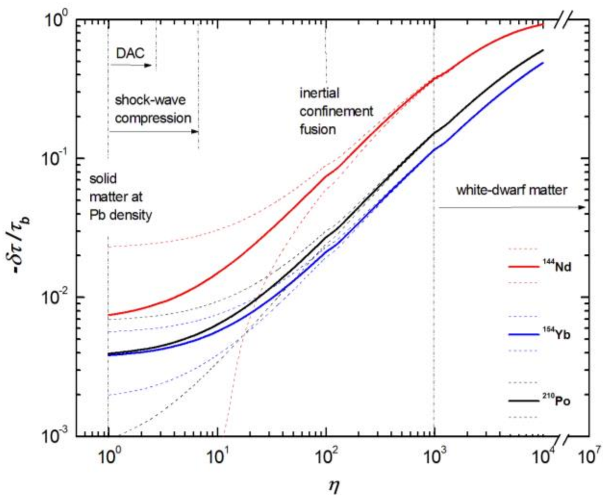

Fig. 3. Lifetime variation relative to the bare nucleus, as a function of compression, for selected nuclides. Relevant physical environments and compression techniques are also indicated as terms of reference for η.

lifetime with electron density and in the suppression of the decay (i.e. infinite lifetime) when extrapolated to the limit of ultra-high-density stellar environments, our calculations point toward a dramatically increased instability of α emitters in those environments, in line with previous findings by Liolios [6].

Conclusions

On the basis of theory and experiment, we find that temperature and metal-lattice free electrons do not play any (appreciable) effect on the α-decay lifetime in matter at ordinary density. Nevertheless, considerable effects are expected in ultra-high-density stellar environments (with possible implications for heavy-elements nucleosynthesis and cosmochronology). Although small, effects induced by means of state-of-the-art compression techniques might however be measurable. In this connection, from the experiment on ^{210}Po we learn that measurements based on reactor-irradiated samples are lengthy and cumbersome; when applicable, sample implantation by radioactive ion beams should be preferred.

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