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Enhancement of β^+-Decay Rate of ^{22}Na in Metal Pd at Low Temperature *

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Temperature dependence of nuclear decays in metallic environments is a controversial issue. We measured the temperature dependence of the β^+-decay half-life of ^{22}Na implanted into the metal host of palladium. It is found that the β^+-decay half-life of ^{22}Na in the metal Pd cooled to $T = 15$ K is shorter by 0.46(14)% than that at room temperature. The result is consistent in sign with, but clearly smaller than, the estimated one by the Debye model.

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Investigations of the influence of host materials on nuclear fusion reactions and nuclear decays have attracted an increasing interest in recent years, which can provide valuable information on nuclear physics, nuclear astrophysics and condensed matter physics. It has been found that the cross sections of $\mathrm{D}(d,p)\mathrm{T}$[1−6] and some other reactions[2,7−9] at energies far below the Coulomb barrier were remarkably enhanced if the reactions occurred in the metallic hosts. These experimental results could be explained by the classical plasma model of Debye in which the screening of the quasi-free metallic electrons surrounding the interacting nuclei significantly reduces their effective Coulomb barriers, leading to an enhancement of the reaction rates. Meanwhile, a series of experiments[10−14] have been conducted to study a possible change of the electron capture rate of ^{7}Be in various metals and insulators at room temperature. The results exhibited a somewhat confusing divergence. The updated precise ones, however, showed no change of the half-life of ^{7}Be in different metals,[13,14] but the half life of ^{7}Be in metals was slightly (0.22%) longer than that in insulators.[14] A dependence of the α-decay rates on the host materials has also been investigated at room temperature by directly measuring the half-life of ^{221}Fr implanted in Au, W, Si and polyethylene at 60 keV.[15] It has been observed that the half-lives in the metals Au/W are slightly shorter by 0.30(17)%/0.42(21)%, respectively, compared to that in the insulator Si.

Most recently, a considerable effort has been devoted to finding the temperature dependence of radioactive decays in metals. It has been reported that at the temperature of metal hosts $T = 12$ K the electron-capture half-lives of ^{7}Be in the metals Pd/In are longer by 0.9(2)%/ 0.7(2)%,[16] the β^--decay half-life of ^{198}Au in the metal Au longer by 4.0(7)%[17] and the β^+-decay half-life of ^{22}Na in the metal Pd shorter by 1.2(2)%,[18] respectively, than those at room temperature. In the other experiment for the β^+-decay of ^{22}Na in the metal Al at $T = 90$ K, a shorter half-life by 0.70(45)% has been seen.[19] The experimental results for α-decays were of discrepancy. One has found that the α-decay half-life of ^{210}Po in the metal Cu cooled to $T = 12$ K is shorter by 6.30(45)%[20] than that at room temperature. Contrarily, compared with the room-temperature value in the literature, no change in the α-decay half-life of ^{253}Es has been observed within about 2%,[21] where the ^{253}Es ions of 160 keV were implanted in the metal Fe foil cooled to $T \leqslant 4$ K. In addition, one has not found an appreciable change of the α-decay half-lives from the low temperature nuclear orientation experiments,[22] where the α-emitters of 60 keV were implanted in the metal Fe foil cooled to $T \leqslant 1$ K. The disagreement concerning α-decays is a challenging question, which needs to be further investigated experimentally.

^{22}Na is an important unstable nuclide involved in the explosive hydrogen burning process in stars, and is also the commonly used β^+-source in positron-annihilation spectroscopy. The β^+-decay of ^{22}Na to the 1274.5 keV state in ^{22}Ne (see the inset in Fig. 2) may be an ideal case to reveal the temperature dependence of nuclear β^+-decays in metallic environments. The results of two experiments mentioned above[18,19] are of inconvenience to compare each other because they were conducted at different temperatures and with different metals.

In this Letter, we report an independent measurement on the ^{22}Na β^+-decay in the metal Pd cooled to

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$T = 15\,\mathrm{K}$. The experiment was carried out using the secondary beam facility of the HI-13 tandem accelerator at China Institute of Atomic Energy, Beijing. A 80-MeV ^{19}F beam from the accelerator impinged on a 4.8-cm-long ^{4}He gas cell at pressure 1.6 atm to produce the ^{22}Na ions via the ^{4}He(^{19}F,^{22}Na)n reaction. The front and rear windows of the gas cell were Havar foils, each with a thickness of $1.9\,\mathrm{mg/cm^2}$. The ^{22}Na recoils with energies ranging from 21 to 48 MeV were emitted into a cone with the maximum angle $\theta_L = 5.2°$ due to the inverse kinematics. They were directly implanted into a 50-μm-thick natural Pd foil of 10 mm in diameter. Calculations with the SRIM code indicate that the implantation depths of ^{22}Na ions range from 3.9 up to 7.9 μm, while the concurrently implanted ^{19}F ions stop at a different depth of about 12 μm. The ^{22}Na@Pd sample was then annealed for one hour in vacuum at 600°C to eliminate the damage of Pd lattice induced by the rolling and ion implantation processes. With a 100-pnA ^{19}F beam, the implanted ^{22}Na ions amounted to 2×10^{11} in 130 min, which led to a ^{22}Na activity of about 1700 Bq.

Figure 1 shows the experimental setup, which mainly consisted of a cooling system of He closed cycle refrigerator with a cold finger and a HPGe detector of 20% relative efficiency. The ^{22}Na@Pd sample was attached to the cold finger along with a ^{137}Cs γ-ray source (661.7 keV, $T_{1/2} = 30.07$ y) as well as a Si diode to measure the temperature. Deposited on a plastic film, the ^{137}Cs source was used to monitor the change of effective solid angle of the detector, caused by the expansion and shrink of the Cu finger as the temperature changes. The chamber covering the cold finger was evacuated with a turbopump, reaching a pressure of about 7×10^{-8} mbar when the cooling system was turned on. The distance from the front-face of HPGe crystal to the ^{22}Na@Pd sample was 4.8 cm. The detector and chamber were shielded by the thick Pb bricks to reduce the background.

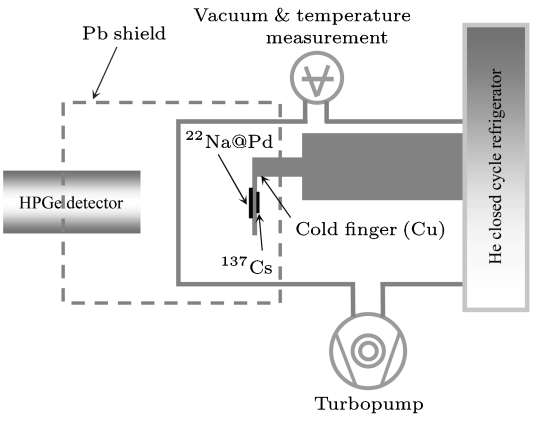

Fig. 1. Sketch of the experimental setup.

The experimental procedure included two steps: (i) starting at room temperature ($T = 298\,\mathrm{K}$) the relative activities of the 1274.5 keV γ-rays $A^{1274.5\,\mathrm{keV}}_{298\,\mathrm{K}}(t)$ and of the 661.7 keV γ-rays $A^{661.7\,\mathrm{keV}}_{298\,\mathrm{K}}(t)$ were measured hour by hour over a running period of 20 h; (ii) the cooling system was then turned on. At the time the fixed temperature $T = 15\,\mathrm{K}$ was reached in 3 h, the relative activities $A^{1274.5\,\mathrm{keV}}_{15\,\mathrm{K}}(t)$ and $A^{661.7\,\mathrm{keV}}_{15\,\mathrm{K}}(t)$ were measured again in the same way. The cooling system was then turned off, and the room temperature was regained in 12 h. In the present work, the above procedure has been performed three times, separately.

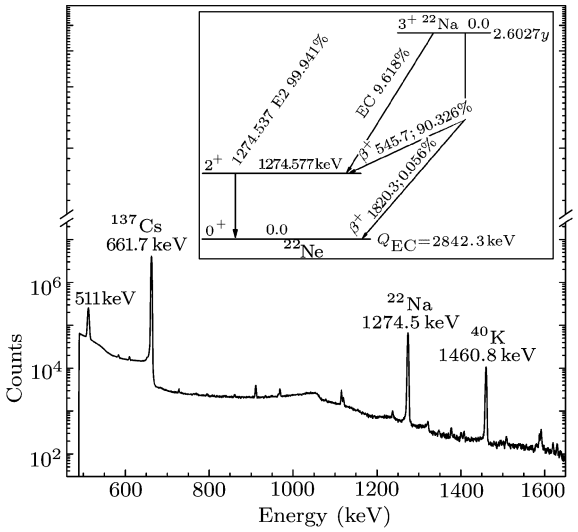

Fig. 2. Typical γ-ray spectrum observed in 20 h at $T = 15\,\mathrm{K}$.

Figure 2 exhibits the γ-ray spectrum acquired at $T = 15\,\mathrm{K}$ over a running time of 20 h. In the data processing, the backgrounds under the peaks of 661.7 keV and 1274.5 keV were subtracted first. The normal decays of ^{22}Na and ^{137}Cs were then corrected hour by hour, respectively. The dead time of the measurement system was 0.8%, which remained to be unchanged at $T = 298\,\mathrm{K}$ and $T = 15\,\mathrm{K}$, and thus did not bring an error to the relative measurement. The relative total activities in 20 h $A^{1274.5\,\mathrm{keV}}_{298\,\mathrm{K}}$, $A^{661.7\,\mathrm{keV}}_{298\,\mathrm{K}}$, $A^{1274.5\,\mathrm{keV}}_{15\,\mathrm{K}}$, $A^{661.7\,\mathrm{keV}}_{15\,\mathrm{K}}$ were obtained by adding up the corresponding activities per hour.

Strictly speaking, the change of effective solid angle of the HPGe detector caused by the expansion and shrink of the Cu finger is dependent on the γ-ray energy. We have carried out a global simulation of the detection efficiency versus the distance from source to detector with the GEANT3 code. In the simulation the areas of ^{137}Cs and ^{22}Na sources, their distances from the front-surface of the HPGe crystal, the materials in their passages and the detector structure were entirely taken into account, respectively. The simulation result indicates that the difference between the

changes of effective solid angles for the ^{137}Cs and ^{22}Na sources is much smaller than the statistical error in the present experiment. Thus, the ^{137}Cs γ-ray source can serve as a standard for normalization.

Normalized to the ^{137}Cs γ-ray source, the relative change of the half-life of ^{22}Na β^+-decay between $T = 15\,\mathrm{K}$ and $T = 298\,\mathrm{K}$ is given by

$$\frac{\Delta T_{1/2}}{T_{1/2}} = -\frac{\Delta A}{A} = -\Big(\frac{A^{1274.5\,\mathrm{keV}}_{15\,\mathrm{K}}}{A^{661.7\,\mathrm{keV}}_{15\,\mathrm{K}}} - \frac{A^{1274.5\,\mathrm{keV}}_{298\,\mathrm{K}}}{A^{661.7\,\mathrm{keV}}_{298\,\mathrm{K}}}\Big) \cdot \Big(\frac{A^{1274.5\,\mathrm{keV}}_{298\,\mathrm{K}}}{A^{661.7\,\mathrm{keV}}_{298\,\mathrm{K}}}\Big)^{-1}. \quad (1)$$

The changes in three separate measurements are shown in Fig. 3, respectively. The final result was then derived to be $-(0.46 \pm 0.14)\%$ by taking their average, which is listed in Table 1 together with those reported in Refs. [18,19] for comparison.

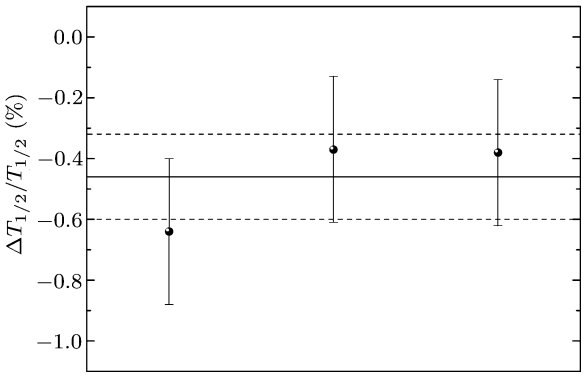

Fig. 3. Variations for the half-life of ^{22}Na β^+-decay observed in three separate measurements. The solid- and dashed lines denote their average and the $\pm 1\sigma$ error band, respectively.

Table 1. Comparison of the present work with the experiments in Refs. [18,19].

	Sample	Production of ^{22}Na	Temperature (K)	$\Delta T_{1/2}/T_{1/2}$ (%)
Present work	^{22}Na@Pd	^{4}He(^{19}F,^{22}Na)n at $E(^{19}\mathrm{F}) = 80\,\mathrm{MeV}$	$T = 15$	$-(0.46 \pm 0.14)$
Ref. [18]	^{22}Na@Pd	^{19}F(α,^{22}Na)n at $E_\alpha = 10\,\mathrm{MeV}$	$T = 12$	$-(1.2 \pm 0.2)$
Ref. [19]	^{22}Na@Al	^{27}Al(p,^{22}Na)^{6}Li at $E_p = 70\,\mathrm{MeV}$	$T = 90$	$-(0.70 \pm 0.45)$

In summary, the half-life of ^{22}Na β^+-decay occurring in the metal Pd cooled to $T = 15\,\mathrm{K}$ was measured to be shorter by 0.46(14)% than that at $T = 298\,\mathrm{K}$. The result is clearly smaller than the estimated one (6%)[18] by the Debye model. We are planning to carry out a new experiment in which the ^{22}Na ions will be produced via the ^{19}F(α,^{22}Na)n reaction using a 30 MeV ^{4}He beam to bombard a LiF target and implanted into a 50-μm-thick Pd foil. In this scheme the damage of lattice structure in metal host induced by the ^{4}He beam will be much slighter than that induced by the ^{19}F beam in the present work, since the ^{4}He beam can penetrate through the foil.

Up to now, the observed influences of metallic environments on the nuclear decay half-lives are considerably smaller than the estimated ones by using the phenomenological Debye model,[9] implying that the Debye model may miss some essential physics constituents to describe the nuclear decays in metal hosts. Further experimental and theoretical studies are required.

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