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First hints on a change of the ^{22}Na β^+-decay half-life in the metal Pd

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Abstract. For the β^+-decay of ^{22}Na in the metallic environment Pd cooled to $T = 12$ K the ^{22}Na half-life was observed to be shorter by $1.2 \pm 0.2\%$. The result is consistent with —but lower than— the prediction of the Debye plasma model.

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The cross-section of a nuclear fusion reaction is enhanced at sub-Coulomb energies by the electron clouds surrounding the interacting nuclei, with an enhancement factor [1,2] $f_{\rm lab}(E) = E(E+U_{\rm e})^{-1}\exp(\pi\eta U_{\rm e}/E)$, where E is the center-of-mass energy, η the Sommerfeld parameter, and $U_{\rm e}$ the electron screening energy. Recently, the electron screening in d(d, p)t has been studied for deuterated metals and insulators, *i.e.* 58 samples in total [3–6]. A large screening was observed in all metals of order $U_{\rm e} = 300$ eV at a target temperature of $T = 293$ K, which was explained by the Debye plasma model applied to the quasi-free metallic electrons [7–9]: $U_{\rm e} = U_{\rm D} = 2.09\times10^{-11} Z_{\rm i} Z_{\rm t} (n_{\rm eff}\rho_{\rm a}/T)^{1/2}$ [eV], with the temperature T of the quasi-free electrons in units of K, $n_{\rm eff}$ the number of these electrons per metallic atom, the atomic density $\rho_{\rm a}$ in units of atoms/ m^3, $Z_{\rm i}$ and $Z_{\rm t}$ the integral charge number of the incident ions and target atoms, respectively.

The Debye model has been used by us to make also a prediction concerning radioactive decay of nuclides in a metallic environment. In general, for the α-decay and β^+-decay one expects a shorter half-life, while for the β^--decay and electron capture process one predicts a longer half-life. A longer half-life of the electron capture by ^{7}Be in metallic environments has been observed recently [10], somewhat lower than the expected value. Furthermore, if the β^+-decay of ^{22}Na to the 1274 keV state in ^{22}Ne ($Q = 545\,{\rm keV}; T_{1/2} = 2.602\,{\rm y}$) occurs in a metal cooled to $T = 12$ K, one arrives —for the inverse process— at $U_{\rm D} = Z_{\rm e} Z_{\rm t} U_{\rm e}({\rm d+d})(293/12)^{1/2} \approx 1\times10\times300\,{\rm eV}\times4.94 = 14.8\,{\rm keV}$, where we used a typical value of 300 eV for the d + d fusion reaction at $T = 293$ K and assumed the $U_{\rm D} \propto T^{-1/2}$ dependence to be valid for $T < 260\,{\rm K}$ [6]. A possible temperature dependence of $n_{\rm eff}(T)$ is not known from the Hall coefficient and has thus been neglected. Since the decay rate scales approximately with the fifth power of energy, one obtains an enhancement of $f_{\rm lab} \approx ((Q+U_{\rm D})/Q)^5 = 1.14$, *i.e.* a shorter half-life by 14%. At room temperature the half-life is shorter by 3% leading to a net effect of 11% between $T = 293$ and 12 K. Using the actual phase space factors in the decay rates and taking into account that the decay proceeds to 90% by β^+-decay and to 10% by electron capture, one arrives at a net effect of about 6% (the 10% electron capture process alone leads to a longer half-life by about 0.5%). The present work reports on experimental investigations of this expected lifetime change of ^{22}Na in the metal Pd.

The setup [10] consisted of a cryopump (minimum temperature $T = 12$ K), where on the head of its Cu rod the sample was installed together with a Si diode for the temperature measurement. The chamber with the cryopump was evacuated by a turbopump. We used a Ge detector placed at 0° to the cryopump axis (100% relative efficiency, front-face distance to the sample = 5 cm) to observe the 511 and 1274 keV γ-rays from the radioactive decay of ^{22}Na. The setup was surrounded by a 5 to 10 cm

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thick Pb shield to suppress the room background. A 50 Hz pulser was used to check for dead time effects ($< 0.1\%$).

The sample consisted of a $10\,\mu g/cm^2$ thick layer of LiF evaporated on a 0.2 mm thick Pd sheet. Using the reaction $^{19}F(\alpha, n)^{22}Na$ ($Q = -1.95\,MeV$) at $E_\alpha = 10$ MeV (cross-section = 0.5 b [11]), the ^{22}Na recoils produced in the LiF layer entered the Pd foil with an energy between 0 and 3.3 MeV reaching an implantation depth from zero up to $1.8\,\mu m$. The concurrently implanted ^4He ions were implanted at a different depth and diffused —as a noble gas— quickly from the Pd sheet. With a $0.5\,\mu pA$ ^4He beam from the Dynamitron-Tandem at Bochum, one expected the production of 0.5×10^{10} ^{22}Na nuclides in 8 h, which led to a ^{22}Na activity of about 45 Bq. The experimental procedure consisted of 2 steps: i) starting at room temperature ($T = 293$ K) we measured the relative γ-ray activity $A(t = 0)$ over a running period of 2 days; ii) the cryopump was then turned on ($T = 12$ K) and we measured the relative γ-ray activity $A(t)$ over a period of 3 days. In the analysis the normal decay $\exp(-t/\tau)$ has been taken into account. The dependence of the detection efficiency on temperature was monitored concurrently using a $^7Be + ^{137}Cs$ source [10] in a Li_2O matrix (= insulator).

The data for the ^{22}Na-Pd sample (relative to the $^7Be + ^{137}Cs$ source) led to a change in the ^{22}Na activity by $+1.2 \pm 0.2\%$ and thus to a correspondingly shorter ^{22}Na lifetime. The result is consistent with —but lower than— the expectation from the Debye plasma model. However, one may consider the result as a lower limit, since those ^{22}Na recoils with nearly zero energy are implanted near the surface, where the Pd foil may have an oxyd layer. Furthermore, the ^{22}Na nuclides can form —near the surface— themselves an oxyd. In both cases these ^{22}Na nuclides will be in an insulator environment with zero effect on the lifetime. An improved production process is thus desirable such as the implantation of a radioactive ^{22}Na ion beam of say 15 MeV as well as an analysis of the sample, *e.g.* using RBS.

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