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The influence of electron screening on half-lives

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Electron screening strongly changes nuclear reaction cross sections at energies below 1000 times the screening energy U_e. It has been found that U_e can be one order of magnitude larger than predicted by theory [1] if the target atoms are hosted in a metallic environment. As a consequence, a change of lifetimes of low-energy β and α emitters may also be considered if they are situated in a metal. In addition, a temperature dependence of the screening effect has been proposed [2], dramatically changing some half-lifes if the metal is cooled [3, 5]. We checked these claims experimentally by measuring the decay rate of ^{22}Na in a piece of aluminum activated by a 70 MeV proton beam. We observed the ^{22}Na activity both at room temperature and when cooled down to nearly LN_2 temperatures. As a result, a 10% increase as proposed by [3] can be clearly excluded. Furthermore, a $1/\sqrt{T}$ temperature dependence of U_e as it was proposed by [3, 5] when the Debye-Hückel model is applied is unlikely.

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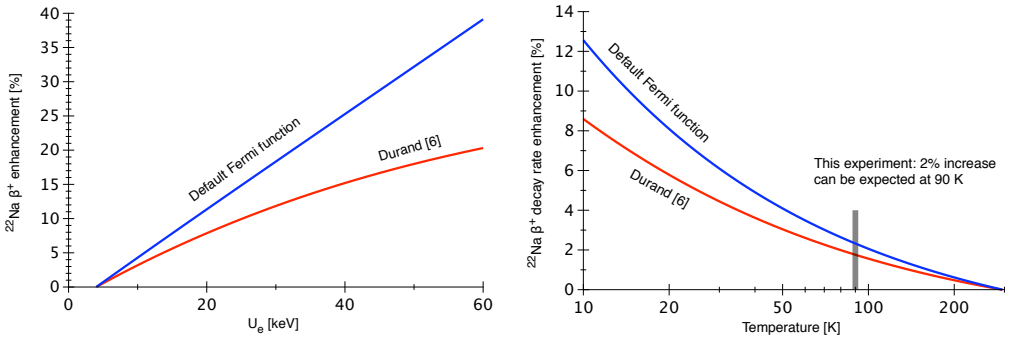

Figure 1: Left: Screening enhancement vs. screening energy U_e for the ^{22}Na β^+ decay. The screening model of Durand [6] best describes the effect. Right: Enhancement of the ^{22}Na β^+ decay rate vs. temperature.

1. Theory of the β decay electron screening

The number of end states per energy interval for the the β decay can be described by a product of a phase space factor, the Coulomb penetration function $P(E)$, and the nuclear matrix element $|M|^2$:

$$\frac{dN}{dE} \sim (E+mc^2)(E-Q)^2\sqrt{E^2+2Emc^2} \times P(E) \times |M|^2,$$

where E is the kinetic energy of the emitted β particle, Q the Q-value of the decay, and m the rest mass of the electron. In a simple picture, the electron screening can be described by an enhancement of the energy of the emitted β by replacing $P(E)$ with $P(E \pm U_e)$ where U_e is the screening energy and $+$ is for β^+ and $-$ for β^- decay, respectively. Therefore, the decay rate is enhanced for the β^+ decay and reduced for β^- decay. However, even for very low energies the β particles must be treated relativistically and this simple picture of an "energy boost" fails. In a more detailed description [6] the Dirac or Klein-Gordon equation (if the spin plays no rule) must be solved for the Coulomb potential modified by the electron shell. This leads to the enhancement curves for the ^{22}Na decay shown in Fig. 1, left, for the $E_{\rm max} = Q$ =545-keV β^+ transition to the 1274-keV level of the ^{22}Ne daughter nucleus. The default Fermi function that is usually used for β decay analyses can only be used for very small screening values.

2. Temperature effect

We are interested in possible temperature effects if the decaying β^+ emitter is hosted in a metallic environment. If the screening energy U_e scales with $1/\sqrt{T}$ where T is the absoulute temperature, the β^+ decay rate should increase if the metal is cooled down. In the experiment (see below), ^{22}Na was hosted in Aluminum. The screening energy at room temperature can be estimated by multiplying the d + d screening value for Al by the charge number of the ^{22}Ne daughter nucleus. Since there are large deviations for U_e between [1] and [2] for d + d screening we use a mean value of 400 eV here.

The increase of the decay rate vs. the temperature is shown in Fig. 1, right. Since the absolute amount of implanted ^{22}Na is not very well known only changes at different temperatures can be

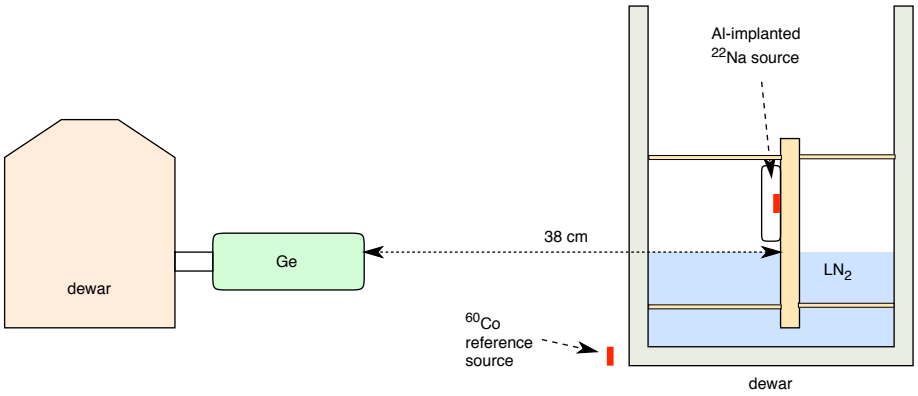

Figure 2: The set-up for the ^{22}Na lifetime measurement.

observed. Therefore, the curves are normalized to the enhancement at room temperature (295 K). About 2% increase of the rate can be expected at 90 K.

3. The experiment

The ^{22}Na source was produced at TRIUMF by sending a 70-MeV proton beam through an aluminum disk. Via the reaction ^{27}Al(p,^{6}Li) most of the ^{22}Na is produced deep in the metal, as required by the claim in [3]. The source produced this way had an activity of 670 kBq.

The activated Al/^{22}Na probe was then mounted on a copper bar which was fixed with screwable rods at the walls of a dewar (see Fig.2). A ^{60}Co reference source was placed directly before the dewar. The γ-rays were detected with a Germanium detector. With a thermocouple mounted directly at the cover of the ^{22}Na source, the temperature could be determined. Measurements have beend done several times with and without LN_2 in the dewar. The temperature at the source with LN_2 filled in was about 90 K. After these measurements the dewar was rotated by 180° to exclude a change of the rate by a possible displacement of the source caused by mechanical stress and the measurements have been repeated.

4. Results

The results for both ^{22}Na lines are shown in Fig.3. When cooled to 90 K, a small decrease of the 511-keV rate can be observed. However, similar fluctuations can also be seen at room temperature. The reason may be that 511-keV γ-rays can be produced by many other sources and are not unique to ^{22}Na. (The measurements have been performed in the ISAC hall where many other experiments are running). However, the 1274-keV line is clearly tied to our source. No correlation with the temperature can be seen for this line. If the 5 measurements at room temperature and the 3 measurements at 90 K are summarized each a small increase of (0.70$\pm$0.45)% can be observed. Therefore, an increase of 10% as it follows from a 40% increase at 10 K as claimed by [3] can be clearly excluded. Comparing this result with the expected enhancement at 90 K of 2% for the model by Durand and the non-relativistic screening enhancement, a visible effect is also unlikely (note that the default Fermi function is not suitable for high screening values as they are used here).

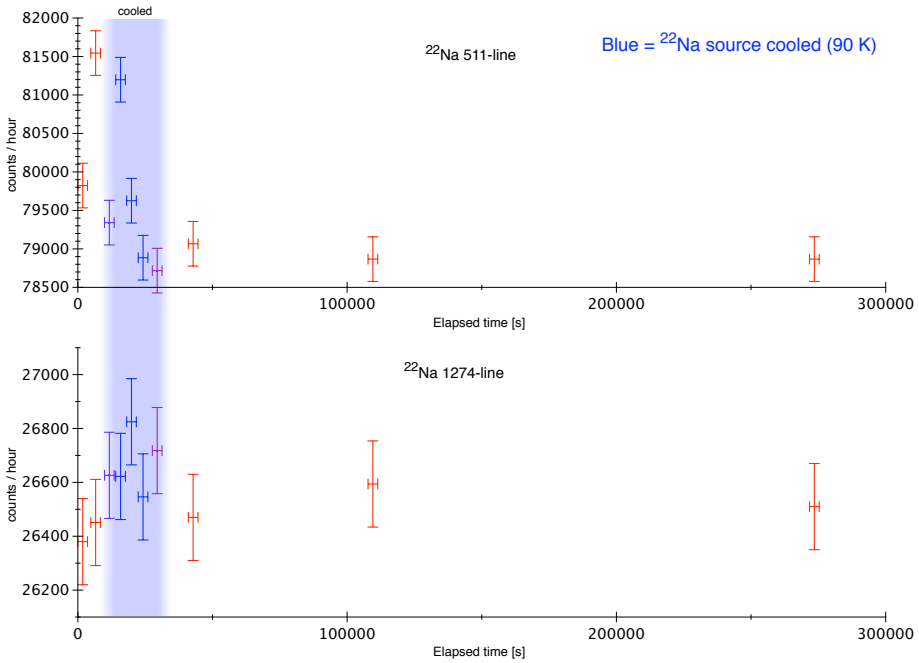

Figure 3: Results of the ^{22}Na lifetime measurement.

Concluding, high screening values at low temperatures as they result from a $1/\sqrt{T}$ dependence as predicted by the Debye-Hückel model could not be observed within 3 standard deviations. The results are within 1.5 standard deviations in agreement with the expected Thomas-Fermi screening for dense electron plasmas predicting no temperature dependence.

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