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Electron screening in $^{7}\mathrm{Li}(p,\alpha)\alpha$ and $^{6}\mathrm{Li}(p,\alpha)^{3}\mathrm{He}$ for different environments ☆

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Abstract

The electron screening in the $^{7}\mathrm{Li}(p,\alpha)\alpha$ reaction has been studied at $E_p = 30$ to 100 keV for different environments: Li_2WO_4 insulator, Li metal, and PdLi alloys. For the insulator a screening potential energy of $U_e = 185 \pm 150$ eV was observed, consistent with previous work and the atomic adiabatic limit. However, for the Li metal and the PdLi alloys we find large values of $U_e = 1280 \pm 60$ and 3790 ± 330 eV, respectively: the values can be explained by the plasma model of Debye applied to the quasi-free metallic electrons in these samples. Similar results have been found for the $^{6}\mathrm{Li}(p,\alpha)^{3}\mathrm{He}$ reaction supporting the hypothesis of the isotopic independence of the electron screening effect. The data together with previous studies of $d(d,p)t$ and $^{9}\mathrm{Be}(p,\alpha)^{6}\mathrm{Li}$ in metals verify the Debye model scaling $U_e \propto Z_t$ (charge number of target).

1. Introduction

The cross section of a charged-particle-induced nuclear reaction is enhanced at sub-Coulomb energies by the electron clouds surrounding the interacting nu-

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clides, with an enhancement factor [1,2]

$$f_{\rm lab}(E) = E(E+U_e)^{-1} \times \exp\bigl(-2\pi\eta(E+U_e)+2\pi\eta(E)\bigr), \quad (1)$$

where E is the center-of-mass energy, $\eta(E)$ the Sommerfeld parameter, and U_e the screening potential energy. The electron screening in $d(d,p)t$ was studied previously for deuterated metals, insulators, and semiconductors, i.e., 58 samples in total [3–5]. As compared to measurements performed with a gaseous D_2 target ($U_e = 25$ eV [6]), a large screening was observed in all metals (of order $U_e = 300$ eV), while a small (gaseous) screening was found for the insulators and semiconductors. An explanation of the large screening was suggested [4] calculating the screening according to the Debye plasma model applied to the quasi-free metallic electrons. The electron Debye radius around the deuterons in the lattice is given by

$$R_D = \bigl(\varepsilon_o kT/e^2 n_{\rm eff}\rho_a\bigr)^{1/2} = 69(T/n_{\rm eff}\rho_a)^{1/2}\ [\rm m] \quad (2)$$

with the temperature T of the free electrons in units of K, $n_{\rm eff}$ the number of valence electrons per metallic atom, and the atomic density ρ_a in units of atoms/m^3. With the Coulomb energy of the Debye electron cloud and a deuteron projectile at R_D set equal to $U_e \equiv U_D$, one obtains

$$U_D = (4\pi\varepsilon_o)^{-1}e^2/R_D = 2.09\times10^{-11}(n_{\rm eff}\rho_a/T)^{1/2}\ [\rm eV]. \quad (3)$$

A comparison of the calculated and observed U_e values led to $n_{\rm eff}$, which was for most metals of the order of one. The acceleration mechanism of the incident positive ions leading to the high observed U_e values is thus the Debye electron cloud at the small radius R_D, about one tenth of the Bohr radius. The $n_{\rm eff}$ values were compared with those deduced from the known Hall coefficient [7]: within 2 standard deviations the two quantities agreed for all metals. A critical test of the Debye model is the predicted temperature dependence $U_D \propto T^{-1/2}$, which was verified experimentally [5].

The electron screening in the $^7{\rm Li}(p,\alpha)\alpha$ reaction has been studied previously using a gaseous H_2 target (inverse kinematics) leading to an atomic screening potential energy $U_A = 300 \pm 160$ eV [8] consistent with the adiabatic limit (175 eV [1]). The Debye radius scales inversely with the nuclear charge Z_t of the target atoms [2], $R_D \propto (Z_t(Z_t+1))^{-1/2}$, and thus $U_D \propto (Z_t(Z_t+1))^{1/2}$. For the $^7{\rm Li}(p,\alpha)\alpha$ reaction with $n_{\rm eff}({\rm Li}) = 0.8 \pm 0.2$ [7] at $T = 20\,^\circ$C one expects $U_D = 820 \pm 100$ eV for a Li metal and therefore $U_e = U_A + U_D = 1120 \pm 260$ eV assuming a linear addition of both acceleration mechanisms. If an alloy such as $PdLi_x$ is used with a few percent Li admixture x (maintaining essentially the metallic character of Pd), one has $n_{\rm eff}({\rm Pd}) = 6.3 \pm 1.2$ [4] and thus $U_D = 2800 \pm 280$ eV leading to the prediction $U_e = U_A + U_D = 3100 \pm 440$ eV. Kasagi et al. [9] performed studies in a $PdLi_x$ alloy ($x = 5$–7%) finding $U_e = 1500 \pm 310$ eV, but no explanation of this observation was given. We report on experimental $^7{\rm Li}(p,\alpha)\alpha$ studies testing the predictions for the different environments: a Li_2WO_4 insulator, a Li metal, and two $PdLi_x$ alloys. We report also on the results of the electron screening in the $^6{\rm Li}(p,\alpha)^3{\rm He}$ reaction for these environments. Details not contained here can be found in [10].

2. Equipment and procedures

The equipment, procedures, and data analyses have been described elsewhere [3,4]. Briefly, we used infinitely thick Li targets of natural isotopic content (92.58% ^{7}Li, 7.42% ^{6}Li), which allowed us to study concurrently both $^7{\rm Li}(p,\alpha)\alpha$ and $^6{\rm Li}(p,\alpha)^3{\rm He}$ reactions. The Li_2WO_4 samples (360 μg/cm^2 thickness, $\Phi = 40$ mm) were fabricated by vacuum-evaporation on a steel backing. The surface of the Li metal sheet (2 mm thick, $\Phi = 40$ mm) was cleaned mechanically in Ar gas to a silvery color and transferred also in Ar gas into the target chamber. Finally, the $PdLi_x$ alloy (0.2 mm thick, $\Phi = 30$ mm, silvery color) was produced by plasma discharge techniques and annealed in vacuum at 850 °C for one hour. NRA studies using the $E_\alpha = 953$ keV resonance in $^7{\rm Li}(\alpha,\gamma)^{11}{\rm B}$ demonstrated that the Li content in the $PdLi_x$ alloys started at the surface with a homogeneous depth distribution.

The observed thick-target yield curve was differentiated to arrive at a thin-target yield curve, which was fitted using 2 free parameters [3]: the absolute yield provided information on the absolute cross section and the energy dependence of the data gave the screening potential energy U_e. For a given sample, we carried out several runs (up to 13) between $E_p = 30$ and 100 keV,

where all targets remained stable in yield to better than 10% at the reference energy $E_p = 100$ keV. Inspection of the samples after the irradiations revealed no change in color or resistance. The exception was the Li metal, which showed a dark color at the beam spot area indicating a beam hydration: a hydrogen solubility of 8.6% was observed via NRA using the $E_N = 8.40$ MeV resonance in $^1\mathrm{H}(^{15}\mathrm{N},\alpha\gamma)^{12}\mathrm{C}$, which was taken into account in the analysis.

The beam direction and spot on target (beam diameter $\Phi = 10$ mm) were defined by 2 apertures, one of $\Phi = 6$ mm at a distance $d = 62$ cm from the target and the other of $\Phi = 10$ mm at $d = 280$ cm. An electric quadrupole triplet placed between the 2 apertures was used to focus the beam. The beam current on target was kept below 20 μA.

3. Results for $^7\mathrm{Li}(p,\alpha)\alpha$

At the effective energy [2] $E = 83.3$ keV we find a cross section $\sigma = 57 \pm 3$ and 44 ± 3 μb for the Li_2WO_4 and Li targets, respectively, where the quoted errors arise from the quadratic addition of uncertainties in thin-target yields (2%), current (2%), solid angle (2%), and stopping power (5%), where the stopping power was calculated using SRIM (see [10]). The weighted average $\sigma = 51 \pm 6$ μb is in good agreement with previous work [8], 56 ± 6 μb: we adopted $\sigma = 54 \pm 4$ μb as a standard. A comparison of the observed yield for the two $PdLi_x$ alloys with that for the Li metal led to a ^{7}Li atomic content $x = 0.01\%$ and 1%. For the bare $S(E)$ factor we adopted the expression

$$S_b(E) = 0.055 + 0.21E - 0.31E^2 \text{ [MeV b]} \quad (4)$$

(E in MeV) as derived from data of the Trojan horse method [11].

The results of the 3 samples are shown in Fig. 1 in form of the $S(E)$ factor (for numerical values, see [10]) leading to $U_e = 185 \pm 150, 1280 \pm 60$, and 3790 ± 330 eV for Li_2WO_4, Li, and $PdLi_{1\%}$, respectively. For the alloy $PdLi_{0.01\%}$ we find $U_e = 4100 \pm 650$ eV (not shown), consistent with the above value for $PdLi_{1\%}$. The results indicate that the metallic character of Pd remained essentially unchanged by the small Li content: weighted average $U_e = 3860 \pm 290$ eV. The U_e value of the insulator is in agreement with previous work [8] and the atomic adiabatic limit.

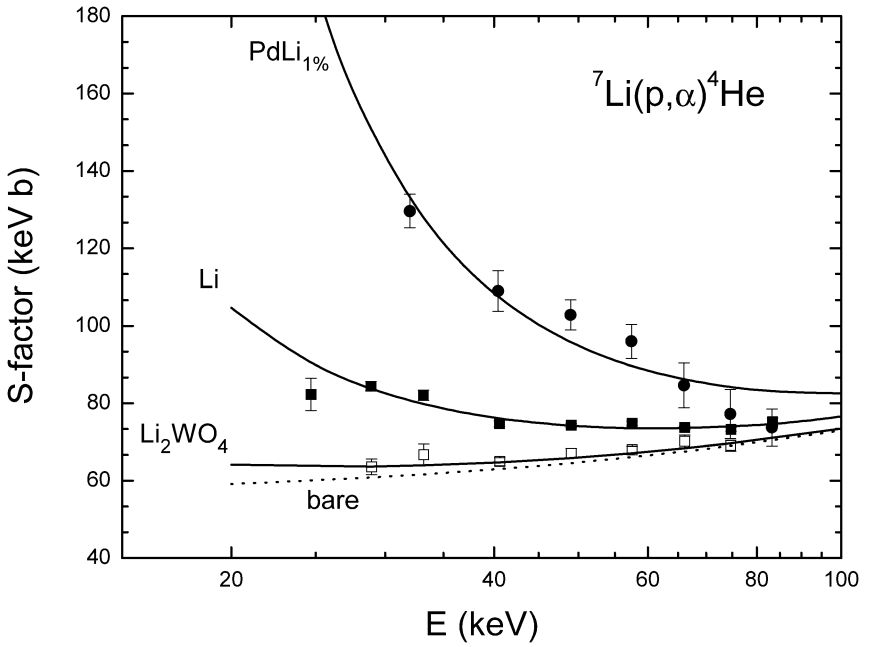

Fig. 1. Astrophysical $S(E)$ factor of $^7\mathrm{Li}(p,\alpha)\alpha$ for different environments: Li_2WO_4 insulator, Li metal, and $PdLi_{1\%}$ alloy. The solid curves through the data points include the bare $S(E)$ factor (dotted curve) and the electron screening with the U_e values given in the text.

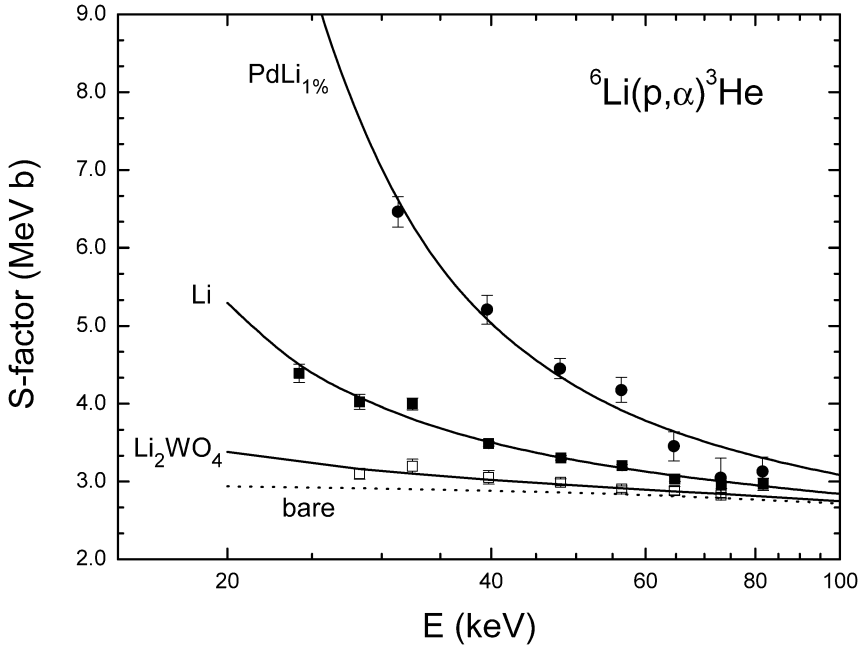

Fig. 2. Astrophysical $S(E)$ factor of $^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$ for different environments: Li_2WO_4 insulator, Li metal, and $PdLi_{1\%}$ alloy. The solid curves through the data points include the bare $S(E)$ factor (dotted curve) and the electron screening with the U_e values given in the text.

The observed value for the Li metal gives a Debye enhancement $U_D = U_e - U_A = 1095 \pm 160$ eV and thus $n_{\mathrm{eff}}(\mathrm{Li}) = 1.4 \pm 0.4$, in fair agreement with the value from the Hall coefficient. Similarly, the results for the two $PdLi_x$ alloys give $U_D = 3675 \pm 330$ eV with $n_{\mathrm{eff}}(\mathrm{Pd}) = 11 \pm 2$, consistent with the value quoted in [4].

4. Results for $^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$

At the effective energy $E = 81.6$ keV we find a cross section $\sigma = 2.5 \pm 0.2$ and 1.8 ± 0.1 mb for the Li_2WO_4 and Li targets, respectively. The weighted average $\sigma = 2.1 \pm 0.4$ mb is in agreement with previous work [8], 2.2 ± 0.2 mb: we adopted $\sigma = 2.2 \pm 0.2$ mb as a standard. For the bare $S(E)$ factor we adopted the expression

$$S_b(E) = 3.00 - 3.02E + 1.93E^2 \ [\mathrm{MeV\,b}] \qquad (5)$$

(E in MeV) as derived from data of the Trojan horse method [12].

The results of the 3 samples are shown in Fig. 2 in form of the $S(E)$ factor (for numerical values, see [10]) leading to $U_e = 320 \pm 110$, 1320 ± 70, and 3760 ± 260 eV for Li_2WO_4, Li, and $PdLi_{1\%}$, respectively. The result for the insulator is in agreement with previous work [8], $U_e = 440 \pm 150$ eV. The observed value for the Li metal yields a Debye enhancement $U_D = U_e - U_A = 1000 \pm 130$ eV, which gives in turn $n_{\mathrm{eff}}(\mathrm{Li}) = 1.2 \pm 0.3$. Similarly, the result for the $PdLi_{1\%}$ alloy gives $U_D = 3440 \pm 280$ eV with $n_{\mathrm{eff}}(\mathrm{Pd}) = 9.5 \pm 1.5$, consistent with the value quoted in [4].

5. Discussion

Since the reported absolute cross section for both reactions [8] has been confirmed by the present work, the astrophysical consequences [2,8,11], e.g., for primordial nucleosynthesis, remain essentially unchanged.

The present data for the electron screening in the $^7\mathrm{Li}(p,\alpha)\alpha$ and $^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$ reactions for different environments give a consistent picture: (i) as suggested previously [8] the present data demonstrate clearly the isotopic independence of the electron

screening effect, i.e., the same U_e value for ^{7}Li and ^{6}Li nuclides, particularly in the cases of the Li metal and $PdLi_x$ alloys; (ii) for the Li_2WO_4 insulator the atomic electron cloud leads to one acceleration mechanism, while the Li metal and the $PdLi_x$ alloys exhibit an additional acceleration mechanism due to the quasi-free metallic electrons at the Debye radius. In comparison to the data in the $d(d, p)t$ reaction for metals [3–5], the screening potential energy scales with the charge Z_t of the target nucleus, as expected from the Debye model.

Previous studies of the reactions ^{9}Be$(p, \alpha)^6$Li and ^{9}Be$(p, d)^8$Be using a metallic Be target led to a high screening potential energy $U_e = 900 \pm 50$ eV [13], which was not understood at the time, i.e., in 1997. With $n_{\text{eff}}(\text{Be}) = 0.21 \pm 0.04$ from the Hall coefficient [4,7], $T = 20\,^\circ$C, and scaling U_D with Z_t (here $Z_t = 4$) one finds $U_D = 870 \pm 80$ eV; assuming $U_A = 240$ eV [1] one arrives at $U_e = U_D + U_A = 1110 \pm 80$ eV consistent with the above observation and supporting again the Z_t scaling of the Debye model. Clearly, an improved theory is highly desirable to explain why the simple Debye model appears to work so well. Without such a theory, one may consider the Debye model as a powerful parametrization of the data.

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