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*Short note*

# Loss of $^8$Li recoil nuclei in $^7$Li(d,p)$^8$Li and implications on the $^7$Be(p,$\gamma$)$^8$B cross section*

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**Abstract.** The loss of $^8$Li recoil nuclei in $^7$Li(d,p)$^8$Li has been measured using different backings and $^7$LiF target thicknesses as well as different deuteron energies. The results confirm essentially recent TRIM calculations. The losses are large (about 13%) for the combination of thin targets and heavy backings at $E_d = 0.80$ MeV and increase with decreasing deuteron energy. The implications on the cross sections for $^7$Li(d,p)$^8$Li and $^7$Be(p,$\gamma$)$^8$B are discussed.

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The absolute cross section $\sigma_{17}(E)$ of the $^7$Be(p,$\gamma$)$^8$B reaction influences sensitively the calculated flux of high-energy neutrinos from the sun, where the reaction takes place at the thermal Gamow energy $E_o = 18$ keV. Due to its importance for the solar-neutrino-puzzle, the cross section $\sigma_{17}(E)$ should be known with adequate precision, i.e. to better than 5% [1]. As the cross section drops nearly exponentially at subcoulomb energies, $\sigma_{17}(E)$ could not be measured yet at E$_o$. Instead, $\sigma_{17}(E)$ was determined at higher energies and extrapolated to $E_o$ with the help of nuclear reaction models. All direct measurements [2–8] used a relatively thin radioactive $^7$Be target ($T_{1/2} = 53.29$ d), which was produced by hot chemistry on a heavy backing (always Pt). The cross section was determined from the yield of the $^8$B recoils, which was deduced either from the $\beta$-decay of $^8$B or - in the majority of cases - from the $\beta$-delayed $\alpha$-decay of $^8$B ($T_{1/2} = 770$ ms). In this approach the $^7$Be target was irradiated by protons for a time period of a few half-lives $T_{1/2}(^8B)$. The target was then moved quickly in front of a Si particle detector, where the $^8$B-decay was observed for a few $T_{1/2}(^8B)$. Finally, the target was placed back into the irradiation position and the cycle was continued until sufficient $^8$B-counts were accumulated in the detector. The absolute cross section $\sigma_{27}(E)$ of the $^7$Li(d,p)$^8$Li reaction, near the broad resonance at center-of-mass energy $E = 0.61$ MeV, is also of interest, since it served as a normalisation for the majority of measurements of the $^7$Be(p,$\gamma$)$^8$B cross section. The $^8$Li recoils ($T_{1/2} = 840$ ms) exhibit similar kinematics in their $\beta$-delayed $\alpha$-decay via $^8$Be. Changing from a proton beam

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**Table 1.** LiF target thicknesses and backings used in the measurement of the $^8$Li recoil losses in $^7$Li(d,p)$^8$Li at $E_d$ = 0.80 MeV

| Target[a] | $^7$LiF layer [$\mu$m] | Backing material | $^8$Li recoil loss [%] |
|---|---|---|---|
| 1 | 1.20 | Pt | 0.9 |
| 2 | 0.315 | Cu | 1.4 |
| 3 | 0.014 | Pt | 12.5 |
| 4 | 0.014 | Cu | 1.1 |
| 5 | 0.014 | Al | 0.2 |

[a] Targets 3 to 5 were produced in a single process

to a deuteron beam in the same setup, the amount of $^7$Li nuclides which were produced by the on-going $^7$Be decay in the target could be measured, leading to an in-situ measurement of the $^7$Be target density. The reported $\sigma_{17}(E)$ data - covering the energy range $E$ = 0.12 to 8.75 MeV - show however a considerable scatter, both in the absolute values and to some extend also in their energy dependences. Although the large scatter is not understood, it may be caused in part by the complicated stoichiometry of the $^7$Be targets and different $\sigma_{27}(E)$ values used for normalisation. Recent measurements have led to a recommended $\sigma_{27}(E)$ value [9,10]. However, even using this value as a standard in the $\sigma_{17}(E)$ evaluations, a considerable scatter of the $\sigma_{17}(E)$ values still remains.

Weissman et al. [11] suggested recently that a significant backscattering of the recoiling nuclides ($^8$Li and $^8$B) out of the target could occur affecting significantly the deduced cross section values for both reactions. Applying TRIM simulations to the case of $^7$Li(d,p)$^8$Li at $E$ = 0.61 MeV, a loss of $^8$Li recoils up to 15% was found depending on the backing material (large effects for heavy backings such as Pt) and on the thickness of the LiF target (large effects for thin targets). We report here on the measurement of these $^8$Li recoil losses in $^7$Li(d,p)$^8$Li using different backings and LiF target thicknesses (Table 1) as well as different deuteron energies.

The 4 MV Dynamitron tandem accelerator at the Ruhr-Universität Bochum provided a deuteron beam at $E_d$ = 0.4 to 1.8 MeV with currents in the range 100 to 300 nA. The beam was guided to the target via two beam defining apertures of 4 and 5 mm diameter. In order to achieve a uniform illumination of the target, the ion beam was scanned over the first aperture resulting in a beam spot on target of 5.5 mm diameter. The target was mounted on a rotating wheel, which moved the target between the beam irradiation position and the $^8$Li-decay counting position (a Si detector in close geometry to the irradiated target). The detector efficiency was obtained using a calibrated $\alpha$-source mounted in the target position and rotated into the counting position. Similarly, the irradiation time interval (in this setup equal to the counting time interval) and transfer time interval were determined from the observed counts in the detector when the calibrated $\alpha$-source was rotated on the wheel for a definite number of cycles. The setup was pumped by a 360 l/s turbo pump and a LN$_2$ cryo trap, which generated together a vacuum of about $10^{-6}$ mbar in the chamber. The beam current was measured on the target as well as in a Faraday cup mounted behind the target (in the irradiation position). Proper suppression of secondary electrons was achieved by the use of an electrode placed in front of the target (Faraday cup).

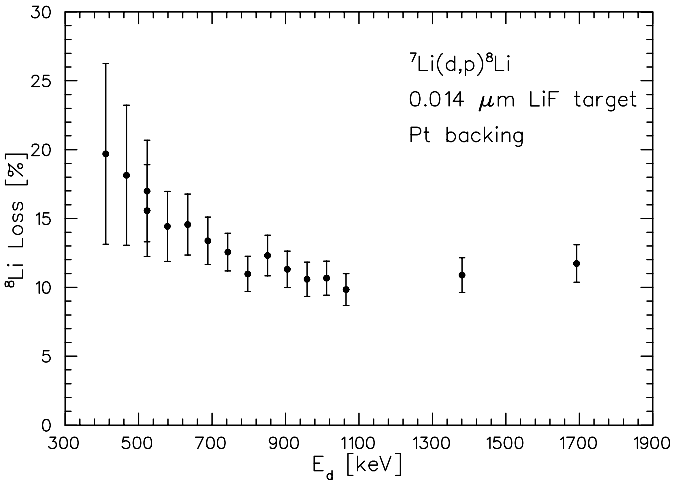

**Fig. 1.** Loss of $^8$Li recoil nuclei in the reaction $^7$Li(d,p)$^8$Li for a 0.014 $\mu$m LiF target on a Pt backing in the energy range 0.41 to 1.7 MeV

The setup was first used to determine the target thickness of the LiF targets (Table 1) via the reaction $^7$Li(d,p)$^8$Li at $E_d$ = 771 keV assuming $\sigma_{27}(E)$ = 146 mb [9]. For target #3 (Table 1) an excitation function was obtained at $E_d$ = 0.4 to 1.8 MeV to check the reliability of the setup and to provide a normalisation of the recoil backscatter losses over a wide range of deuteron energies (Fig. 1).

The setup was then modified in order to measure the yield of the $^8$Li recoils which were backscattered out of the target and thus lost in the above measurements. For this purpose the LiF target was fixed in the irradiation position and a 2.0 $\mu$m thick Al foil (thickness measured using an $\alpha$-source) was mounted on the rotating wheel (11 mm distance to the target). The incident deuteron beam passed the Al foil to reach the target; the energy loss in the foil was taken into account in the data analyses. The Al foil - with the implanted $^8$Li recoils (after loss from the target) - was moved between the irradiation and counting positions using the same time intervals as before. The detector efficiency was determined from Monte Carlo calculations, where it was assumed that the angular correlation of the $^8$Li recoils is according to the Rutherford law. This assumption was verified experimentally within about 20% using another modification of the setup: the beam passed through a hole (15 mm diameter) in the wheel, whereby only those backscattered $^8$Li recoils could be detected (in the counting position) which reached the material around the hole in the wheel during the irradiation time interval.

The results (Table 1 and Fig. 1) show clearly the loss of $^8$Li recoils out of the target for all target and backing combinations. The loss depends on the type of backing:

negligible loss for light backings such as Al and severe loss for heavy backings such as Pt. The loss also depends on the thickness of the LiF target: the thicker the target the smaller the loss. Finally, the loss is energy dependent as observed in Fig. 1 for a thin target on a Pt backing: about 13% at $E_d = 0.77$ MeV (standard energy) and up to about 20% at $E_d = 0.40$ MeV. The results confirm in part the TRIM calculations of Weissman et al. [11].

For the recommended $\sigma_{27}(E)$ value at $E = 0.61$ MeV the situation remains essentially unchanged [9 and references therein], because the accepted values were fortunately either based on LiF targets on an Al backing, a LiF target sandwiched between thin Au layers on C or Al backings (where the Au layers were too thin for significant $^8$Li losses), or on direct measurement of proton yields from $^7$Li(d,p)$^8$Li (independent of the backscattering $^8$Li losses). Using the recommended value of 146±5 mb [9] together with the recent value of $155 \pm 8$ mb [11] one arrives at a new weighted average value of $149 \pm 4$ mb at $E = 0.61$ MeV.

The situation is different in the case of the $^7$Be(p,$\gamma$)$^8$B reaction, where all experiments were performed with a $^7$Be target (mostly of unknown chemical composition) on a Pt backing. Thus, all these measurements will have experienced in principle a loss of $^8$B recoils from the target. The cross section values derived from measurements, in which the $^7$Be target density was determined via the $^7$Be $\gamma$-activity [6–8] should be increased by the backscatter effect. Measurements, in which the $^7$Be target density was determined in situ via the $^7$Li(d,p)$^8$Li reaction [2–5,7], are sensitive to the difference of the recoil losses in the two reactions: due to different reaction kinematics the backscattering loss will be less pronounced for the case of the $^8$B recoils; as a consequence, the correct cross section values should be lower than those reported. Unfortunately, the exact $^7$Be target composition of the individual experiments are not well known hampering thus a precise correction of the reported values. One might suggest therefore that the reported absolute $\sigma_{17}(E)$ values should include an additional systematic uncertainty of the order of 15%. As suggested from the data in Fig. 1, the energy dependence of $\sigma_{17}(E)$ might be affected by the recoil losses even stronger at low energies and might thus influence severely the extrapolation of the data to the solar Gamow energy $E_o$ producing a nonnegligible influence on the solar-neutrino-puzzle. In order to reach the goal of 5% precision, new measurements of $\sigma_{17}(E)$ must include quantitative in-situ determinations of the $^8$B losses nearly at each energy.

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## References

1. J. N. Bahcall and M. H. Pinsonneault, Rev. Mod. Phys. **64**, 885 (1992)
2. R. W. Kavanagh, Nucl. Phys. **15**, 411 (1960)
3. P. D. Parker, Phys Rev. **150**, 851 (1966); Astroph. J. **153**, L85 (1968)
4. R. W. Kavanagh, T. A. Tombrello, J. M. Mosher, and D. R. Goosman, Bull. Am. Phys. Soc. **14**, 1209 (1969); R. W. Kavanagh in "Cosmology, Fusion and Other Matter", ed. F. Reines (Colorado University Press, 1972) p. 169
5. F. J. Vaughn, R. A. Chalmers, D. Kohler, and L. F. Chase, Phys. Rev. **C 2**, 1657 (1970)
6. C. Wiezorek, H. Krähwinkel, R. Santo, and L. Wallek, Z. Phys. **A 282**, 121 (1977)
7. B. W. Filippone, A. J. Elwyn, C. N. Davids, and D. D. Koetke, Phys. Rev. **C 28**, 2222 (1983)
8. F. Hammache, G. Bogaert, P. Aguer, C. Angulo, S. Barhoumi, L. Brillard, J.F. Chemin, G. Claverie, A. Coc, M. Hussonnois, M. Jacotin, J. Kiener, A. Lefebvre, J.N. Scheurer, J.P. Thibaud, E. Virassamynaiken, Phys. Rev. Lett. **80**, 928 (1998)
9. F. Strieder, L. Gialanella, U. Greife, C. Rolfs, S. Schmidt, W. H. Schulte, H. P. Trautvetter, D. Zahnow, F. Terrasi L. Campajola, A. D'Onofrio, V. Roca, M. Romano, and M. Romoli, Z. Phys. **A 355**, 209 (1996)
10. E. G. Adelberger et al., Rev. Mod. Phys. (to be published)
11. L. Weissman C. Broude, G. Goldring, R. Hadar, M. Hass, F. Schwamm, and M. Shaanan, Nucl. Phys. **A 630**, 678 (1998)