Electron screening in the ^{3}He(d, p)^{4}He reaction

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A reanalysis of data for the ^{3}He(d, p)^{4}He reaction obtained using the Trojan-horse method, together with data from a direct measurement, leads to an electron-screening potential that is not consistent with the adiabatic limit, but it is consistent with a previous value from different data.

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La Cognata *et al*. [1] (LC) use the Trojan-horse method (THM) to obtain the bare-nucleus S factor $S_b(E)$ for the ^{3}He(d, p)^{4}He reaction, and combine an R-matrix fit to their results with a direct measurement [2] of the screened S factor $S(E)$ to obtain a value of the electron-screening potential, $U_e = 126 \pm 29$ eV. [LC describe this fit as more realistic and more precise than an alternative polynomial fit that gives $U_e = 155 \pm 34$ eV.] This R-matrix value is in agreement with the theoretical adiabatic limit of 115 eV [1], but not with the value $U_e = 200$ eV obtained in a previous R-matrix fit [3] to the same low-energy data [2] combined with different data in the resonant region [4].

We consider the reasons for this discrepancy in the U_e values. The LC procedure for determining the value of U_e depends on various steps:

(i) Separation of quasifree (QF) and sequential decay (SD) contributions. In the THM, only the QF contribution is of interest. LC obtain it by subtracting the SD contribution, assumed to be due to the 2^+ first-excited state of ^{8}Be. LC ascribe the major contribution to the uncertainties in their values of $S_b(E)$ to this source, but it is not considered any further here.

(ii) Normalization of experimental QF values. The THM does not provide absolute values. LC normalized their experimental values to direct data in the resonant region for E (the c.m. energy in the ^{3}He + d channel) between 100 and 600 keV. These direct data are essentially those of Geist *et al*. [4], whose measurements extend from 147 to 411 keV. The resonance peaks in LC and in Ref. [4], which are due to a $3/2^+$ level of ^{5}Li, have different widths, as is indicated by the different maximum $S(E)$ values: 14.5 MeV b in LC and about 18 MeV b from Ref. [4].

(iii) R-matrix fit to normalized values. LC say that they use a two-level R-matrix fit, but they actually use three levels (with values of the eight adjustable parameters given in their Table III). Of these three levels, two are essentially background levels, so their parameter values would not be well determined.

(iv) One-parameter fit to direct data [2]. With $S_b(E)$ values given by the R-matrix fit in (iii), LC varied the electron-screening potential U_e to best fit the low-energy $S(E)$ values of Aliotta *et al*. [2], which cover the range $E = 5$–60 keV. It is obvious from Fig. 15 of LC that the R-matrix fit is not consistent with these data, even in the higher-energy part of this range where electron screening should not be significant (in Fig. 15, the high-energy points with error bars are not from Ref. [2]).

Here we initially follow the LC procedure, with modifications. We first fit the normalized $S_b(E)$ values of LC, using a two-level R-matrix approximation [3]. The upper level is essentially responsible for the resonance peaking at $E \approx 245$ keV, while the lower background level, which is about 2.4 MeV below the ^{3}He + d threshold, is suggested by shell-model calculations. The channel radii are chosen as in Ref. [3]. There are five adjustable parameters: the energy of the upper level and the proton and deuteron reduced-width amplitudes of each level. The eigenenergy of the lower level is fixed at $E_1 = -3.2$ MeV for $B_c = S_c(E_2)\,(c = p, d)$; the results are not sensitive to this choice of E_1.

The best fit to the 15 data points of LC gives $\chi^2 \equiv \chi^2_{\rm LC} = 6.05$; so the reduced χ^2/degree of freedom (χ^2_ν) is 0.605, slightly less than the LC value of $4.66/(15-8) = 0.666$. The best fit of LC gave $S_b(0) = 6.8$ MeV b; however, the present fit gives an appreciably higher value, $S_b(0) = 7.9$ MeV b. Table I (row A, $N = 1.00$) gives the corresponding values of the resonance energies and of the reduced-width amplitudes calculated at the resonance energies.

With $S_b(E)$ given by this R-matrix fit, the best fit to the 48 $S(E)$ values of Aliotta *et al*. [2], obtained by varying only the one parameter U_e, gives $U_e = -41$ eV, which is inadmissible. Also the fit is poor, with $\chi^2 \equiv \chi^2_A = 1140$. U_e is negative because the assumed $S_b(E)$ values are too large at the energies of Ref. [2]. We therefore renormalize the LC measured values (and uncertainties) by a factor $N < 1$ and repeat the R-matrix fit and then the one-parameter fit.

Table I (part A) gives some results. As N decreases, $\chi^2_{\rm LC}$ barely changes, $S_b(0)$ decreases at about the same rate as N, while χ^2_A decreases rapidly to reach a minimum of about 80 at $N \approx 0.84$, with $S_b(0) \approx 6.7$ MeV b and $U_e \approx 135$ eV. These are close to the LC values (6.8 MeV b and 126 eV). This fit (for $N = 0.84$) is shown by the solid curve in Fig. 1, together with the renormalized LC data (triangles) and the Aliotta *et al*. data (pluses). The corresponding values of $S_b(E)$ are shown by the short-dashed curve. The fit to the Aliotta *et al*. data is rather poor, though better than that shown in Fig. 15 of LC.

TABLE I. Parameter values for two-level R-matrix fits to ^{3}He$(d, p)^4$He S-factor data from La Cognata *et al*. [1] and Aliotta *et al*. [2] ($a_p = 5.0$ fm, $a_d = 6.0$ fm).

	N	E_{1r} (MeV)	γ_{1p} (MeV$^{1/2}$)	γ_{1d} (MeV$^{1/2}$)	E_{2r} (MeV)	γ_{2p} (MeV$^{1/2}$)	γ_{2d} (MeV$^{1/2}$)	$\chi^2_{\rm LC}$	$S_b(0)$ (MeV b)	χ^2_A	U_e (eV)
A	1.00	−2.38	1.70	−0.501	0.590	0.432	0.618	6.05	7.91	1140	−41
	0.90	−2.35	1.74	−0.502	0.584	0.445	0.631	6.09	7.13	241	73
	0.85	−2.30	1.80	−0.517	0.591	0.440	0.639	6.11	6.75	87	126
	0.84	−2.29	1.81	−0.517	0.591	0.441	0.642	6.12	6.67	81	135
	0.83	−2.30	1.80	−0.515	0.589	0.436	0.646	6.12	6.60	83	147
	0.80	−2.23	1.88	−0.535	0.602	0.465	0.664	6.14	6.36	144	179
B	1.09	−3.01	1.96	−0.012	0.716	0.713	0.925	19.1	6.07	22.4	193
C	1.09	−3.07	0.410	0.179	0.386	0.177	0.879	18.8	6.05	22.1	194

We now use the alternative procedure recommended in Ref. [3], in a combined fit to the $S_b(E)$ values of LC and the $S(E)$ values of Aliotta *et al*., allowing the level parameters and U_e to vary simultaneously, as well as allowing for a renormalization of the LC data. Starting from the parameter values for $N = 0.85$ in Table I, we find a best fit with total $\chi^2 \equiv \chi^2_{\rm LC} + \chi^2_A = 41.5$ and the other parameter values given in Table I, row B; this fit is shown in Fig. 1 by the dashed curve [and dotted curve for the corresponding $S_b(E)$]. The renormalized LC data are shown by squares (without error bars). The fit to the Aliotta *et al*. data is much better, as seen from Fig. 1 and from the χ^2_A values in Table I, at the expense of a poorer fit to the LC data. The fit peak is appreciably narrower than the LC experimental peak. We note that this fit gives values of $S_b(0)$ and U_e close to the values 5.96 MeV b and 200 eV found in Ref. [3] from fits that used the same low-energy data [2].

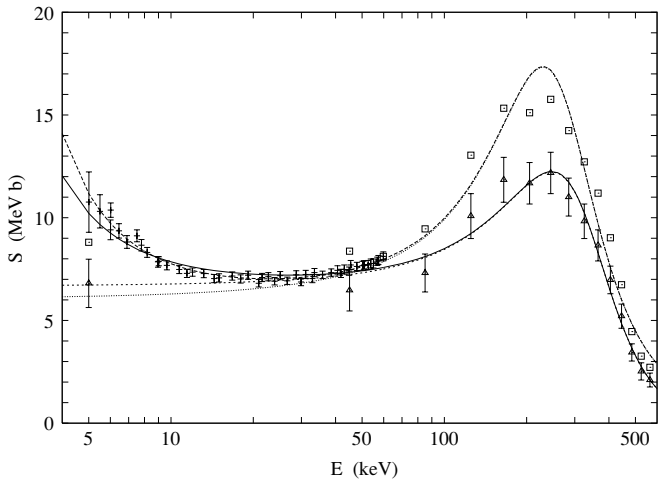

FIG. 1. S factor for ^{3}He$(d, p)^4$He reaction as a function of the ^{3}He $+ d$ c.m. energy. The experimental points with error bars are from Aliotta *et al*. [2] (pluses) and from LC (renormalized by a factor $N = 0.84$) (triangles). The solid curve shows a best fit to these data (Table I, part A, $N = 0.84$), and the short-dotted curve is the corresponding bare S factor. The experimental points without error bars (squares) are from LC (renormalized by a factor $N = 1.09$), and the dashed curve is a best combined fit to these LC data and the Aliotta *et al*. data (Table I, row B), with the dotted curve giving the corresponding bare S factor.

In the two-level (five-parameter) fits to the LC data alone, there are strong correlations between some of the parameters. In fact, the errors on the data, particularly at energies below the resonance, are so large that only three parameters can be well determined from the energy, width, and height of the peak. We therefore now use a one-level R-matrix approximation to fit the LC data. The three adjustable parameters are the level energy and the proton and deuteron reduced widths. This is the model used in Ref. [5] to study and fit the properties of the analog $3/2^+$ level of ^{5}He (and to some extent the $3/2^+$ level of ^{5}Li, using the experimental data then available).

The level parameters from the best one-level fit to the 15 LC data points (with $N = 1.0$) are given in Table II, row A. This has $\chi^2_{\rm LC} = 7.19$ or $\chi^2_\nu = 0.599$, about the same as for the two-level fit. There are, however, objections to this fit; the partial observed widths Γ^0_c calculated at E_m, the peak energy of the S factor, have $\Gamma^0_p > \Gamma^0_d$, contrary to the results of Ref. [5]. In a more direct comparison with experiment, these parameter values predict the real part of the ^{3}He $+ d$ phase shift to decrease across the resonance and that of the ^{4}He $+ p$ phase shift to increase, contrary to observation [6,7]. We therefore seek a fit to the LC data that has $\Gamma^0_p < \Gamma^0_d$. There is a local minimum in χ^2 for the parameter values given in row B of Table II. This gives $\chi^2_\nu = 1.12$. For comparison, results from the best fit to the 60 data points from Geist *et al*. [4] are given in row C of Table II ($\chi^2_\nu = 2.34$). The parameter values in rows B and C predict ^{3}He $+ d$ and ^{4}He $+ p$ phase shifts in reasonable agreement with experiment.

All the sets of parameter values in Table I, parts A and B, appear to be similar to the values in Table II, row A, and so to be inconsistent with the elastic-scattering data. We therefore return to a two-level fit to the combined LC and Aliotta *et al*. data, allowing all parameters to vary simultaneously, but starting from the level parameters in Table II, row B, for the upper level. This leads to a best fit with parameter values, given in Table I, row C, that appear to be consistent with the elastic-scattering data, and with total $\chi^2 = 41.0$, essentially the same as before (in Table I, row B). The fit curve everywhere differs from the dashed curve in Fig. 1 by less than 1%. This fit

TABLE II. Parameter values for one-level R-matrix fits to ^{3}He$(d, p)^4$He S-factor data from La Cognata *et al*. [1] or from Geist *et al*. [4] ($a_p = 5.0$ fm, $a_d = 6.0$ fm).

	Data	E_r (MeV)	γ_p (MeV$^{1/2}$)	γ_d (MeV$^{1/2}$)	χ^2	E_m (MeV)	Γ_p^0 (MeV)	Γ_d^0 (MeV)	Γ^0 (MeV)	$S_b(0)$ (MeV b)
A	LC	0.307	0.209	0.364	7.19	0.241	0.264	0.054	0.319	7.13
B	LC	0.400	0.172	0.913	13.40	0.231	0.102	0.185	0.287	6.38
C	Geist	0.427	0.225	1.394	133.5	0.200	0.093	0.173	0.266	

gives $U_e = 194$ eV, which is close to the value 200 eV in Ref. [3] obtained from fitting other resonance data [4]. An increase in χ^2 by 1 corresponds to an uncertainty in U_e of ± 12 eV. [An even better fit to the combined LC and Aliotta *et al*. data, with $\chi^2 = 34$ and $U_e = 218$ eV, has been found, but it is based on unrealistic parameter values, including $E_{1r} \approx -0.13$ MeV and $\gamma_{1p}/\gamma_{2p} \approx 0.05$; model calculations [5] require $\gamma_{1p} \gg \gamma_{2p}$.]

It seems that fits to the data of LC and Aliotta *et al*. [2] lead to values of U_e consistent with the adiabatic limit if the LC fitting procedure is used, but much better fits can be obtained when all parameters are allowed to vary simultaneously, giving larger values of U_e and parameter values consistent with elastic-scattering data. Provided the resonance data are normalized to the low-energy data [2], as was done in Ref. [3] and also here, it is the low-energy data that essentially determine the value of U_e. Fitting different low-energy data could, of course, lead to different values of U_e [3].

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