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p-Wave Strength in the Low-energy ^{7}Li(p, γ_0)^{8}Be Cross Section

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Abstract

Recent fits to low-energy ^{7}Li(p, γ_0)^{8}Be angular distribution and analysing power data suggested a large p-wave strength. It is shown that acceptable fits to the data can be obtained by attributing the p-wave $M1$ contributions to the tails of the 17·64 and 18·15 MeV 1^+ levels of ^{8}Be, with p-wave strengths much less than those obtained previously, but only if some of the spectroscopic amplitudes have signs opposite to those suggested by shell model calculations and/or a fit to higher-energy data.

1. Introduction

Chasteler *et al.* (1994) (hereafter referred to as CWTP) have recently studied the ^{7}Li(p, γ_0)^{8}Be reaction using 80 keV polarised and unpolarised protons on thick ^{7}Li targets. They found a substantial anisotropy of the angular distribution (±20%) and a large analysing power (up to about 40%). Their analysis of the data indicated appreciable p-wave strength, in addition to s-wave strength. Previously it had generally been assumed that the low-energy cross section would be due predominantly to s-wave protons and $E1$ γ rays. This was based on observed angular distributions that were approximately isotropic (within 10%) in the energy region of interest (Cecil *et al.* 1992) or appeared to be approaching isotropy in that region (Mainsbridge 1960). These earlier measurements are therefore in disagreement with those of CWTP.

CWTP point out that the presence of p-wave strength would lead to a reduced value of the zero-energy astrophysical S factor for the ^{7}Li(p, γ_0)^{8}Be reaction compared with that obtained assuming pure s-wave protons, although the experimental uncertainties mean that the reduction is not very significant. Of more significance would be a similar reduction that CWTP suggested in the zero-energy S factor for the ^{7}Be(p, γ)^{8}B reaction, because of its importance in the solar neutrino problem.

In fitting their data by adjusting values of the relative transition matrix elements (four adjustable parameters), CWTP found identical best fits for four solutions using s-wave $E1$ and p-wave $M1$ radiations, with p-wave strengths 58·5, 66·7, 86·4 and 93·3% of the total strength, and for two solutions with s-wave $E1$ and p-wave $E2$ radiations, with p-wave strengths 20·7 and 95·0%. We find the best $E1 + M1$ fits with somewhat different p-wave strengths of 41·8, 47·2,

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86·7 and 92·7%, and four $E1+E2$ fits with p-wave strengths of 15·0, 27·4, 79·7 and 94·8%. All these solutions give $\chi^2 = 18{\cdot}76$, for 17–4 = 13 degrees of freedom (DOF). These values differ from the published values of CWTP, but agree with their revised values (Chasteler 1995, personal communication). The data represent averages over $E_p = 0$–80 keV; CWTP estimated that 84% of the yield occurred in the 60–80 keV range, so we assume that the strengths are roughly those appropriate to $E_p = 70$ keV.

Rolfs and Kavanagh (1994) (hereafter referred to as RK) have attempted to explain the CWTP data assuming $E1+M1$ radiations, with the $E1$ component due to s-wave direct capture and the $M1$ component to the low-energy tails of the 1^+ levels of ^{8}Be at $E_p = 441$ and 1030 keV ($E_x = 17{\cdot}64$ and 18·15 MeV). RK say that the $M1$ resonance amplitudes from the two levels do not interfere with each other due to different isospin assignments; this is incorrect (see the argument on isospin mixing in Kumar and Barker 1971), but might be thought to be unimportant because RK found the contribution from the 1030 keV level to be only about 5% of that from the 441 keV level. Using known partial widths of the levels from Ajzenberg-Selove (1988), RK calculated the magnitude of the angular distribution coefficient $A_1(E_p)$ to be of order 0·4 in the range $E_p = 0$–80 keV, which may be compared with CWTP's experimental value of about 0·2. The formula that RK give for A_1 is, however, not correct, since they have not used the requirement that the $E1$ and $M1$ amplitudes interfere only if they have the same channel spin. The s-wave $E1$ component must have channel spin 1; the p-wave $M1$ component can have channel spin 1 or 2, and the channel spin 2 dominates in the 441 keV resonance by a factor $R \equiv \sigma(2)/\sigma(1) = 3{\cdot}2 \pm 0{\cdot}5$ (Ajzenberg-Selove 1988). Consequently the factor 2 in RK's formula for $A_1(E_p)$ should be replaced by about 1·2, giving an A_1 comparable with the experimental value. One should not, however, discuss values of A_1 alone. Since the phases $\Phi_i(E_p)$ from the formula given by RK are almost zero at $E_p \leq 80$ keV, RK obtain a large $|A_1|$ and consequently a large forward–backward asymmetry of the angular distribution, but they would obtain almost zero analysing power. All the data, including both the angular distribution and analysing power, were analysed by CWTP, who found solutions in terms of $E1$ and $M1$ strengths and relative phases. The best-fit p-wave strength varies from 42 to 93% [the 18% quoted by RK is for a somewhat poorer fit obtained by assuming that the $M1$ component in j–j coupling is pure $p_{1/2}$ (no $p_{3/2}$), for which $R = 5{\cdot}0$]. Fig. 1 of RK shows that their model gives a maximum $M1$ strength in the 0–80 keV region of about 7%, in disagreement with all the $E1+M1$ solutions of CWTP.

Here we consider the alternative $E1+E2$ solutions to the CWTP data, which were not mentioned by RK, and also reconsider the $E1+M1$ solutions.

2. Fits to CWTP data

The elements of the transition matrix may be written as $U^{J_i}_{s\ell,L\pi J_f}$, where the transition is from an initial state J_i, formed from ^{7}Li+p with channel spin s and relative orbital angular momentum ℓ, to a final state J_f, and L is the multipolarity of the transition with $\pi = 0(1)$ for electric (magnetic) radiation. Since $J_f = 0$ here, we have $L = J_i$ and $\pi = |\, J_i - 1 - \ell \,|$, so the matrix element

may be abbreviated to $U_{s\ell}^{J_i}$. The fits to the data of CWTP give values of the ratios

$$U_{s1}^{J_i}/U_{10}^{1} = r_s^{J_i} \exp\left(i\psi_s^{J_i}\right) \qquad (J_i = 1,2;\ s = 1,2). \tag{1}$$

Values of $r_s^{J_i}$ and $\psi_s^{J_i}$ for our best fits to the data of CWTP are given in Table 1. Absolute magnitudes of the $U_{s\ell}^{J_i}$ may be obtained by fitting the value of the S factor, $S = 2{\cdot}5 \times 10^{-4}$ MeV b, which was obtained by Cecil *et al.* (1992) for the ^{7}Li(p,γ_0)^{8}Be reaction over the range $E_{\rm cm} = 35 - 150$ keV.

We first consider the $E1 + E2$ solutions. The R-matrix formulae for the $U_{s\ell}^{J_i}$ may be obtained from the general formulae for EL transitions given by Barker and Kajino (1991). These are extensions of the formulae of Lane and Thomas (1958), and contain channel contributions. Alternatively, for U_{10}^{1}, a direct-capture potential model may be used as in Cecil *et al.* (1992). They assumed a central Woods–Saxon potential with conventional radius and diffuseness parameters, the potential depth being adjusted to fit the binding energy of the final p-wave state; apparently the same depth was used for the initial s-wave state. They also assumed a unit spectroscopic factor for the final 0^+ state. Then the s-wave $E1$ contribution agreed with their observed low-energy S factor.

Table 1. Relative transition matrix elements from fits to CWTP data

All solutions give $\chi^2 = 18{\cdot}76$, with 13 degrees of freedom

Case	J_i	Solution	$r_1^{J_i}$	$\psi_1^{J_i}$ (deg)	$r_2^{J_i}$	$\psi_2^{J_i}$ (deg)
$E1 + M1$	1	1	0·37	68	0·76	158
		2	0·41	−68	0·85	50
		3	1·08	−55	2·32	95
		4	1·50	41	3·22	69
$E1 + E2$	2	1	0·24	108	0·22	−154
		2	0·34	−105	0·33	−72
		3	1·09	−107	1·08	−96
		4	2·35	122	2·32	−67

For the $E2$ amplitudes U_{s1}^{2} ($s = 1,2$), it may be noted that the formulae of Barker and Kajino (1991) with $J_f = 0$ show that the nonresonant channel capture requires $s = 1$ and so does not contribute to U_{21}^{2}. The same is true for the resonant channel capture for all p-wave channels. Since the solutions in Table 1 all have $r_1^2 \approx r_2^2$ (due essentially to the small experimental value of the angular distribution coefficient A_2), it therefore appears that channel contributions are not dominant. Indeed, because of the high binding energy of the final state (17·25 MeV), one would expect the channel contributions to be small (Barker and Kajino 1991). The other contribution to U_{s1}^{2} comes from resonant capture through 2^+ states of ^{8}Be. The 2^+ levels nearest to the energy region of interest are the $E_x = 16{\cdot}6, 16{\cdot}9$ and 20·1 MeV levels (Ajzenberg-Selove 1988), which have known proton and alpha reduced width amplitudes (Barker 1972). An estimate of the gamma widths may be obtained by noting that the combined contribution of the 16·6 and 16·9 MeV levels for capture to ^{8}Be ground state is about 20 times smaller than to the first excited state (Garvey *et al.* 1977), for which the total isovector $M1$ width is about 6 eV and the isoscalar and isovector $E2$ widths each about 0·3 eV (Bowles and Garvey 1978). Thus the combined $E2$ width

of the 16·6 and 16·9 MeV levels for ground-state capture should be about 0·3 eV. With the ratio of $E2$ widths taken from a shell model calculation [using the (8–16) POT interaction of Cohen and Kurath (1965)], the $E2$ ground-state width of the 20·1 MeV level is then about 0·1 eV. The calculated contribution at $E_p = 70$ keV due to $E2$ transitions from the 16·6 and 16·9 MeV levels is then about 5×10^{-3} times the observed S factor of Cecil *et al.* (1992), and for the 20·1 MeV level the ratio is about 1×10^{-5}. These are less than the amounts required to fit the CWTP data by at least a factor of 30. Thus it seems most unlikely that $E1 + E2$ capture can account for the CWTP data.

We now return to the $E1 + M1$ solutions. For convenience we omit the label $J_i = 1$ on $r_s^{J_i}, \psi_s^{J_i}$. We first assume that the $M1$ contribution comes solely from the tail of the 17·64 MeV level ($E_p = 441$ keV). Then one should take $r_2/r_1 = R^{\frac{1}{2}} = 1{\cdot}79$, assuming $R = 3{\cdot}2$; this value of R was obtained from ^{7}Li(p, γ_0)^{8}Be angular distribution data alone (Meyer *et al.* 1961). Since shell model values of the spectroscopic amplitudes for the lowest $1^+, T = 1$ state of ^{8}Be have the same sign for $s = 1$ and $s = 2$ (Cohen and Kurath 1965; Barker 1966; Kumar 1974; van Hees and Glaudemans 1983, 1984), and the same is true when isospin mixing with the lowest $1^+, T = 0$ state is included (Barker 1966), we take $\psi_2 - \psi_1 = 0$. Then with only two free parameters, a reasonable fit to the CWTP data can be obtained with $\chi^2 = 21{\cdot}7$, and with an $M1$ strength of 8·4% (or 91% for an alternative solution). This fit may be compared with CWTP's fit in which the $M1$ component is pure $p_{1/2}$, for which they found a similar χ^2 but an $M1$ strength more than twice as large. This difference is due only slightly to the different value of R (5·0 instead of 3·2), but mainly to the different value of $\psi_2 - \psi_1$ (180° instead of 0°, because the spectroscopic amplitudes have opposite signs for $s = 1$ and $s = 2$ in the $p_{1/2}$ case). With $\psi_2 - \psi_1 = 180°$, the two contributions to the analysing power coefficient B_1 tend to cancel, whereas for $\psi_2 - \psi_1 = 0°$ they are of the same sign so that the same value of B_1 can be obtained for a smaller $M1$ strength. The assumption that the 441 keV level is responsible for the $M1$ strength gives, however, additional restrictions on the parameter values. With the level parameters used by RK, we calculate the $M1$ strength at $E_p = 70$ keV due to the 441 keV level to be 6·9%, in agreement with RK. With the strength restricted to this value ($r_1^2 + r_2^2 = 0{\cdot}074$), the one-parameter fit to the CWTP data gives $\chi^2 = 25{\cdot}0$. Furthermore, one may calculate the actual values of ψ_1 and ψ_2, and not just their difference. These phases are given by

$$\psi_s = \sigma_1 - \phi_1 + \arctan\left(\frac{\frac{1}{2}\Gamma}{E_r - E}\right) - \sigma_0 + \phi_0 + n_s\pi\,, \tag{2}$$

where n_s is an integer, and σ_ℓ and $-\phi_\ell$ are the Coulomb and hard-sphere phase shifts. For simplicity, we have omitted the R-matrix level-shift term in the p-wave resonant phase shift, and have assumed the corresponding s-wave phase shift to be zero. In their formula for the relative phase, $\Phi_i(E_p)$, RK omitted the σ_ℓ and ϕ_ℓ terms. At $E_p = 70$ keV, the ϕ_ℓ and resonant phase shift are negligible compared with $\sigma_1 - \sigma_0 = \arctan\eta = 61°$. Fits to the CWTP data with $\psi_1 = \psi_2 = 61°$, and adjustable $M1$ strength, give $\chi^2 = 28{\cdot}8$, with 8·5% $M1$ strength. With these values of ψ_s and 6·9% $M1$ strength, one finds $\chi^2 = 32{\cdot}5$.

Table 2. Parameter values from $E1$+$M1$ fits to CWTP data with $M1$ contribution from (a) 441 keV level alone and (b–d) 441 and 1030 keV levels

In (b), the reduced width amplitudes $\gamma_{\lambda s}$ have shell model signs. In (c), the sign of γ_{b1} has been changed from the shell model value; in (d), the sign of γ_{b2} has been changed from the shell model value. All solutions assume $\psi_1 = \psi_2$

	R	Fixed values $M1$ strength (%)	ψ_1 (deg)	r_1	ψ_1 (deg)	r_2	ψ_2 (deg)	χ^2	DOF
(a)	3·2			0·148	53	0·264	53	21·7	15
	3·2	6·9		0·132	53	0·237	53	25·0	16
	3·2		61	0·149	61	0·266	61	28·8	16
	3·2	6·9	61	0·132	61	0·237	61	32·5	17
	4·4			0·138	50	0·289	50	21·7	15
	4·4	6·9		0·117	50	0·245	50	28·6	16
	4·4		61	0·135	61	0·283	61	35·2	16
	4·4	6·9	61	0·117	61	0·245	61	40·4	17
(b)	1·7	5·6		0·149	57	0·192	57	28·2	16
	1·7	5·6	61	0·149	61	0·192	61	29·8	17
(c)	6·3	4·1		0·076	50	0·192	50	74·6	16
	6·3	4·1	61	0·076	61	0·192	61	84·3	17
(d)	3·5	9·2		0·149	52	0·281	52	22·0	16
	3·5	9·2	61	0·149	61	0·281	61	31·0	17

Details of these fits are given in section (a) of Table 2.

We now consider the contributions from the other 1^+ level at 18·15 MeV (E_p = 1030 keV). The influence of this level was apparent in the analysis of ^{7}Li(p,γ_0)^{8}Be angular distribution and analysing power data for E_p = 380–960 keV that was made by Ulbricht *et al.* (1977); they found $R = 3{\cdot}3 \pm 0{\cdot}3$ for the 441 keV level and their results suggest $R \approx 1{\cdot}5$ for the 1030 keV level. There are errors, however, in the analysis of Ulbricht *et al.*; reanalysis (Barker 1979), again assuming only s-wave $E1$ and p-wave $M1$ contributions, gave $R \approx 4{\cdot}4$ for the 441 keV level and $R \approx 1{\cdot}5$ for the 1030 keV level. From analysis of ^{7}Li+p elastic scattering data, Brown *et al.* (1973) found R = 3–5 for the 1030 keV level, but reanalysis of their data suggested a value much closer to unity. The value $R = 4{\cdot}4$ for the 441 keV level agrees well with the CWTP solutions in Table 1. Section (a) of Table 2 contains parameter values for some fits, in which the $M1$ strength is from the 441 keV level alone, with $R = 4{\cdot}4$ instead of $R = 3{\cdot}2$.

To include contributions from both the 441 and 1030 keV levels, we use the R-matrix two-level, two-channel ($s = 1, 2$) approximation (Lane and Thomas 1958; Kumar and Barker 1971) with a conventional channel radius $a = 1{\cdot}45(7^{\frac{1}{3}} + 1)$ fm = 4·22 fm, and with $R = 4{\cdot}4$ for the 441 keV level and $R = 1{\cdot}5$ for the 1030 keV level. We also use the partial widths used by RK. Since the contributions from the two levels are coherent, the relative signs of the reduced width amplitudes (or spectroscopic amplitudes) are significant. Initially we choose these in accordance with the shell model calculations, including two-state isospin mixing (Barker 1966). With the 441 and 1030 keV levels labelled a and b respectively, the reduced width amplitudes $\gamma_{\lambda s}$ have the signs: $\gamma_{a1}, \gamma_{a2}, \gamma_{b2}$ all positive, γ_{b1} negative. Also $\gamma_{b\gamma}/\gamma_{a\gamma} < 0$. Then the calculated $M1$ strength at E_p = 70 keV is 5·6%, and

$R = 1{\cdot}7$. The small $M1$ strength and small value of R are due to destructive interference between the contributions from the two levels in the $s = 2$ channel. The calculated phases ψ_s are essentially unchanged from before. Fits to the CWTP data with these restrictions are given in section (b) of Table 2. The values of χ^2/DOF suggest that these are acceptable fits.

There is, however, a problem with the shell model signs of the $\gamma_{\lambda s}$, which was pointed out previously (Barker 1979). These signs predict the p-wave matrix elements U^1_{s1} in the region between the 441 and 1030 keV levels to show destructive interference for $s = 1$ and constructive interference for $s = 2$. Analysis of the higher-energy data of Ulbricht *et al.* (1977) does not show this destructive interference, and so suggests $\gamma_{b1} > 0$. Constructive interference in the region between the levels implies, however, destructive interference below the lower level, and so a small $M1$ strength. With the sign of γ_{b1} changed, we find an $M1$ strength at $E_p = 70$ keV of only $4{\cdot}1\%$. Consequently the fits to the CWTP data are very poor, as is shown in section (c) of Table 2.

If the signs of the $\gamma_{\lambda s}$ are chosen to give the maximum $M1$ strength at $E_p = 70$ keV, by taking γ_{b1} and γ_{b2} both negative, the fits shown in section (d) of Table 2 are obtained; in particular, the fit with adjustable ψ_s is very good with χ^2/DOF even less than for the best four-parameter fits. This fit to the CWTP data is shown in Fig. 1. These signs of $\gamma_{\lambda s}$ would, however, imply destructive interference in the region between the levels for both $s = 1$ and $s = 2$, contrary to the accepted fit to the higher-energy data (Barker 1979). As in the fits to the CWTP data, there are at each of the higher energies four independent solutions for the matrix elements that give identical best fits (Ulbricht *et al.* 1977 found at most two of these solutions), and these vary more or less smoothly with energy without any ambiguities due to crossing. In two of the solutions, the 441 keV resonance is produced by s-wave protons, while in the other two it is produced by p-wave protons. Since the resonance is known to be due to a 1^+ level, only the latter two solutions are admissible. In one of these, the phase differences ψ_s ($s = 1, 2$) both increase by about 180° as the 441 keV resonance is crossed, in the other they decrease by about 180°. Only the former of these solutions has the behaviour expected for a p-wave resonance, and this is the solution accepted in Barker (1979). In this solution ψ_1 and ψ_2 increase monotonically and are approximately equal in the region between the levels, and r_2/r_1 decreases monotonically. The same behaviour is found if d-wave $E1$ contributions, calculated from a direct-capture potential model, are included (Barker 1979). This solution is inconsistent with destructive interference in the region between the levels for either or both $s = 1$ and $s = 2$.

From Tables 1 and 2, it is seen that acceptable fits to the CWTP data can be obtained for parameter values very different from those giving the best fits. It may then be the case at higher energies that, although the best-fit solutions are quite distinct, a crossover from one solution to another may be possible via acceptable fits. To test this, fits to the data should be made directly in terms of level parameters, instead of using the transition matrix elements as intermediaries.

3. Discussion

The present study of the ^{7}Li(p,γ_0)^{8}Be reaction at low energy suggests that the recent CWTP data cannot be understood in terms of $E1 + E2$ transitions,

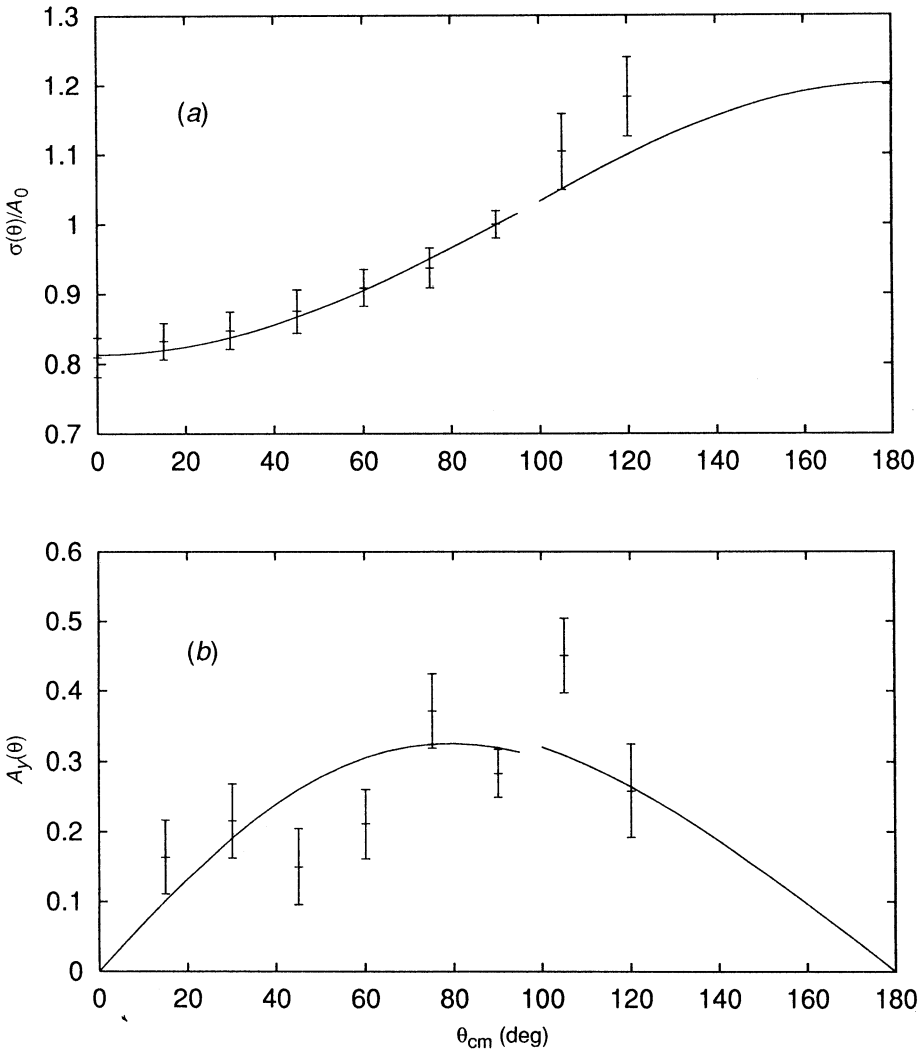

Fig. 1. Differential cross section (a) and analysing power (b) for the ^{7}Li(p,γ_0)^{8}Be reaction at $E_p \approx 70$ keV as functions of the centre-of-mass angle. The experimental data are from CWTP, and the curves are fits with the parameter values given in Table 2, section (d), first row. The breaks in the curves are due to the different detector geometry used by CWTP at angles above and below 100°, and the consequent different finite geometry correction factors.

but may be explained as due to s-wave $E1$ plus p-wave $M1$ contributions, with the $M1$ contribution attributed to the tails of the 441 and 1030 keV resonances. The previous analysis by RK, which reached the same conclusion, contained several errors. The signs of the reduced width amplitudes of the two 1^+ levels are required to be different from those suggested by a previous fit to higher-energy ^{7}Li(p,γ_0)^{8}Be data (Barker 1979) and possibly different from shell model values. The acceptable fits to the CWTP data have $M1$ strengths much less than those

for the best-fit solutions in terms of transition matrix elements, with comparable or somewhat larger values of χ^2/DOF.

As regards the ^{7}Be(p, γ)^{8}B reaction, CWTP say that isospin symmetries can be used to relate the ^{7}Li(p, γ)^{8}Be and ^{7}Be(p, γ)^{8}B reactions. This does not apply, however, to the ^{7}Li(p,γ_0)^{8}Be reaction leading to the $T = 0$ ground state of ^{8}Be, since the ^{8}B ground state has $T = 1$. Also the γ-ray energies are very different in the two reactions: 17·3 MeV for ^{7}Li(p,γ_0)^{8}Be and 0·14 MeV for ^{7}Be(p, γ)^{8}B. Even if there were large p-wave strength in ^{7}Li(p,γ_0)^{8}Be, it is difficult to see how this could be used to argue for significant p-wave strength at low energy in ^{7}Be(p, γ)^{8}B.

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