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The ^{7}Be(p, γ)^{8}B Cross Section at Low Energies

F. C. Barker

Department of Theoretical Physics, Research School of Physical Sciences,
Australian National University, P.O. Box 4, Canberra, A.C.T. 2600.

Abstract

The nonresonant part of the ^{7}Be(p, γ)^{8}B cross section at low energies is recalculated by means of a direct-capture potential model, using parameter values determined by fitting ^{7}Li(n, n)^{7}Li and ^{7}Li(n, γ)^{8}Li data. Standard values of the potential parameters and spectroscopic factors give values of the ^{7}Li(n, γ) cross section that are too large. Modified values that fit the thermal-neutron capture cross section predict ^{7}Be(p, γ) cross sections that are much less than the experimental values. Also, shell model calculations predict resonant ^{7}Be(p, γ) cross sections that are smaller than the experimental values. It is suggested that the accepted experimental values of the ^{7}Be(p, γ) cross section may be too large, perhaps due partly to an overlarge accepted value for the ^{7}Li(d, p)^{8}Li cross section, which has been used for normalization purposes. A decrease in the ^{7}Be(p, γ) cross section would reduce the calculated detection rate of solar neutrinos and lessen the discrepancy with the measured value.

1. Introduction

The ^{7}Be(p, γ)^{8}B cross section at low energies is of fundamental importance in the calculation of the detection rate of solar neutrinos with a ^{37}Cl detector of the Davis type (Davis *et al.* 1968). The low energy cross section ($E_p \lesssim 20$ keV) has been obtained by extrapolating experimental values recorded at higher energies ($E_p \gtrsim 165$ keV). Several calculations (Tombrello 1965; Aurdal 1970; Robertson 1973) have been used as a basis for this extrapolation but each has apparent defects. The present calculation is intended to avoid these defects, although it uses some features of each of the above calculations.

In each of the earlier calculations, it is assumed that the ^{7}Be(p, γ)^{8}B reaction at low energies proceeds by direct capture, and that this may be described by an optical potential. Except in the calculation by Robertson (1973), it is assumed that, apart from the Coulomb potential, the optical potential parameters and spectroscopic factors to be used in the ^{7}Be(p, γ)^{8}B calculation are the same as those required to fit data for the mirror reaction ^{7}Li(n, γ)^{8}Li and ^{7}Li + n scattering. Some justification for this assumption, namely that the properties of mirror direct-capture reactions can be well described by optical potentials that use the same parameter values for the two reactions, has been sought by testing it for the mirror reactions ^{6}Li(n, γ)^{7}Li and ^{6}Li(p, γ)^{7}Be; the results of this test are reported by Switkowski *et al.* (1979) and in the preceding paper (Barker 1980; present issue pp. 159–76). Although standard values of the potential parameters and spectroscopic factors gave cross sections that were too small for both the ^{6}Li(n, γ) and ^{6}Li(p, γ) reactions, modified values of these parameters that fitted the (n, γ) cross section also gave good agreement with the (p, γ) cross section, and to that extent this test supported the validity of the assumption.

Measurements of the ^{7}Be(p, γ)^{8}B cross section are summarized in Section 2 below. This section also discusses measurements of the ^{7}Li(d, p)^{8}Li cross section, since this has been used for normalization of the ^{7}Be(p, γ) cross section, and experimental data from ^{7}Li(n, γ)^{8}Li and ^{7}Li+n elastic scattering, since these are used for determining potential parameters and spectroscopic factors. Section 3 discusses the earlier calculations and gives the modifications used here. The results are presented in Section 4 and discussed in Section 5, including their relevance to the solar-neutrino problem.

2. Experimental Data

There have been only five relevant measurements of the ^{7}Be(p, γ)^{8}B cross section, and four of these used the ^{7}Li(d, p)^{8}Li cross section for normalizing the absolute cross section. The reason for this is that it avoids the difficulty of a direct measurement of the ^{7}Be target thickness; the two cross sections can be obtained using the same target, since ^{7}Be decays to ^{7}Li, and the same detection system, since ^{8}B and ^{8}Li both β-decay to ^{8}Be, which breaks up into two α particles, and either the β particles or the delayed α particles can be detected. In the remaining experiment, a direct measurement of the ^{7}Be(p, γ)^{8}B absolute cross section was made, but discussion of this is left to Section 5, both because the existence of this experiment was unknown until the remainder of the present work was essentially completed and because of confusion about its results.

Kavanagh (1960) measured the ^{7}Be(p, γ)^{8}B cross section $\sigma_{p\gamma}$ at $E_p = 800$ and 1400 keV. Parker (1966) measured $\sigma_{p\gamma}$ at eight energies between 483 and 1932 keV. Kavanagh *et al.* (1969) extended the measurements to lower energies, covering the range from 165 to 1020 keV; details have not been published but the cross section values are given by Kavanagh (1972), who includes further measurements up to $E_p = 10$ MeV. Vaughn *et al.* (1970) measured $\sigma_{p\gamma}$ from 953 to 3281 keV.

Since the absolute values determined for $\sigma_{p\gamma}$ depend on the values of the ^{7}Li(d, p)^{8}Li cross section, we discuss measurements of this first. This cross section has a peak at $E_d \approx 770$ keV, and values given for the peak cross section σ_{dp} are 230 mb (Baggett and Bame 1952), 150 ± 38 mb (Bashkin 1954), 176 ± 15 mb (Kavanagh 1960), 211 ± 15 mb (Parker 1966), 138 ± 20 mb (McClenahan and Segel 1975) and 181 ± 8 mb (Schilling *et al.* 1976). These show considerable variation. In the first two measurements, β particles from the ^{8}Li decay were detected during bombardment; Bashkin used a technique that enabled background due mainly to neutron-capture γ rays to be eliminated, and commented that the result of Baggett and Bame was believed to be too high because of the inadequately corrected influence of background in their data. In the remaining measurements, timing cycles separated the detection periods from the bombardment periods. Kavanagh (1960) and McClenahan and Segel detected β particles, while Parker and Schilling *et al.* detected delayed α particles. With lithium targets, stability and composition are particular problems and the accuracy of absolute cross section measurements is often limited by the determination of the target thickness. Only McClenahan and Segel, who measured cross sections for a variety of reactions with lithium targets, mentioned that they checked the stability of their targets. They used two different nuclear physics methods in determining target thickness, to which they attributed an uncertainty of 10%. Schilling *et al.* claimed 2·5% uncertainty in their target thickness, accepting the value quoted by the supplier of their targets; their own measurement of the total mass of ^{7}Li in one target with 5% error could not give a target thickness with better than 5% accuracy. They also imply that their current integration was accurate to better than 0·06%. It seems that the accuracy of about 4% claimed for their cross section is unrealistic. Parker claimed 5% accuracy in his target thickness, from flame-photometry techniques. Kavanagh's (1960) absolute cross section was obtained by normalization relative to the ^{7}Li+p elastic scattering cross section, assumed known to 5% from earlier measurements.

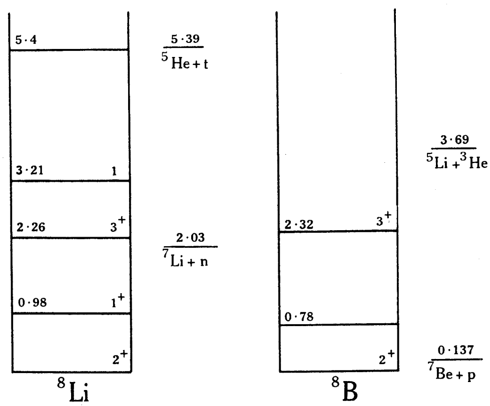

Fig. 1. Energy levels of ^{8}Li and ^{8}B (Ajzenberg-Selove 1979).

A value of $\sigma_{\mathrm{dp}} = 193 \pm 15$ mb, obtained by averaging the values of Kavanagh (1960) and Parker (1966), has been adopted in several determinations of the ^{7}Be(p, γ) cross section (Parker 1968; Kavanagh *et al.* 1969; Vaughn *et al.* 1970). For the sake of consistency, we also use this value of σ_{dp}, but note that at least one apparently reliable measurement gives an appreciably lower value; this is discussed further in Section 5. With this normalization, the experimental values of $\sigma_{\mathrm{p}\gamma}$ obtained by Parker (1968) and by Kavanagh *et al.* (1969) agree well, but the earlier measurements of Kavanagh (1960) are some 40% lower and the values of Vaughn *et al.* (1970) are about 30% lower (see Fig. 3 below).

The measurements of the ^{7}Be(p, γ) cross section show both resonant and nonresonant contributions. Although the nonresonant contributions, which we interpret as being due to direct capture, are of primary importance in extrapolation to low energies, the resonant contributions are also of interest. This is because they provide values of radiation widths for transitions between the low-lying states of ^{8}B, and these may be compared with shell model values and with the radiation widths for the corresponding transitions in the mirror nucleus ^{8}Li (see Fig. 1). The resonance observed at $E_{\mathrm{p}} \approx 730$ keV corresponds to the first excited state of ^{8}B (assumed to be 1^+), which decays by M1 radiation to the 2^+ ground state. Parker (1966) from his measurements estimated the radiation width $\Gamma_\gamma(1^+)$ to be $0\cdot050\pm0\cdot025$ eV, later renormalized (Parker 1968) to $0\cdot045\pm0\cdot023$ eV. From the cross section of Kavanagh *et al.* (1969), as given by Kavanagh (1972), one can estimate $\Gamma_\gamma(1^+) = 0\cdot047$ eV, with an error of order 10%. A resonance is also observed at $E_p \approx 2500$ keV, corresponding to the 3^+ second excited state of ^{8}B, which also decays by M1 radiation to the ground state. From the fits of Vaughn *et al.* (1970) to their data (as given in their Fig. 7), one estimates $\Gamma_\gamma(3^+) \approx 0\cdot15$ eV. Kavanagh (1972) also shows some evidence for a resonance at about this energy, but it is much broader than the known width of the 3^+ level (Ajzenberg-Selove 1979); it suggests $\Gamma_\gamma(3^+) \lesssim 0\cdot2$ eV.

Experimental data from the ^{7}Li(n, γ) and ^{7}Li(n, n) reactions are required in order to provide values of the potential parameters for the continuum states. The thermal-neutron capture cross section is

$$\sigma_{n\gamma}(E_{th}) = 45\cdot4\pm3 \quad \text{mb}, \tag{1}$$

with a branching ratio to the first excited state of ^{8}Li of

$$\mathscr{R} = (10\cdot6\pm1)\% \tag{2}$$

(Ajzenberg-Selove and Lauritsen 1974). A lower limit has been placed on the fraction W_+ of the thermal-neutron capture that proceeds via the initial channel spin $s = 2$:

$$W_+ \gtrsim 86\% \tag{3}$$

(Gul'ko *et al.* 1968). The capture cross section has been measured by Imhof *et al.* (1959) for $E_n = 40$–1000 keV (see Fig. 2 below). For the elastic scattering of thermal neutrons on ^{7}Li, the cross section is $\sigma = 1\cdot07\pm0\cdot04$ b and the coherent scattering length (bound) is $\bar{b} = -2\cdot1\pm0\cdot1$ fm (Ajzenberg-Selove 1979). From

$$\sigma = 4\pi\big(\tfrac{3}{8}a_1^2 + \tfrac{5}{8}a_2^2\big), \qquad \bar{b} = \tfrac{8}{7}\big(\tfrac{3}{8}a_1 + \tfrac{5}{8}a_2\big), \tag{4}$$

where a_s is the s-wave scattering length for channel spin s ($s = 1, 2$), we get

$$a_1 = 1\cdot09\pm0\cdot20 \text{ fm}, \qquad a_2 = -3\cdot59\pm0\cdot06 \text{ fm}. \tag{5}$$

These values are consistent with the measurements of Roubeau *et al.* (1974), who give $a_2 - a_1 = -4\cdot5\pm0\cdot2$ fm and $-4\cdot7\pm0\cdot2$ fm, thus ruling out an alternative solution for a_s from equations (4). The values (5) are somewhat different from those used in earlier calculations (Tombrello 1965; Aurdal 1970), but this does not affect our arguments.

3. Methods of Calculation

In each of the earlier calculations by Tombrello (1965), Aurdal (1970) and Robertson (1973), the ^{7}Be(p, γ)^{8}B cross section was calculated by assuming that the reaction proceeds by direct capture only, and that the initial and final states of the system can each be described by a simple single-particle model of a proton moving in an optical potential that represents its interaction with the ^{7}Be ground state. Formulae for the integrated cross section, which is all that is required, have been given by Tombrello and by Robertson. In the notation of the preceding paper

(Barker 1980), the integrated cross section for E1 capture of s-wave and d-wave protons to a final ^8B state of spin J is

$$\sigma_{\text{tot},J} = \frac{7\pi}{256}\frac{Me^2\kappa^3(2J+1)}{\hbar^2 k^3}\sum_s \mathscr{S}_{Js}\big(|\gamma^1_{Js0}|^2 + 2|\gamma^1_{Js2}|^2\big). \tag{6}$$

The parameters that need to be specified are those describing the potentials, and also the spectroscopic factors $\mathscr{S}_{Js}$ corresponding to the breakup of the ^8B state into $^7Be(g.s.)+p$, with channel spin s. The different calculations differ in their methods of determining the values of these parameters.

Tombrello (1965) and Aurdal (1970) both assumed only s-wave proton capture and E1 radiation. Tombrello used a real central Woods–Saxon potential with fixed values of the radius and diffuseness parameters, plus the Coulomb potential of a uniformly charged sphere of the same radius, and showed that the potential depths required to fit the energies of the ground and first two excited states of ^8B are almost the same as those required to fit the corresponding levels in the mirror nucleus ^8Li with a $^7Li(g.s.)+n$ model. Thus for the initial s-wave state of the ^7Be+p system he assumed the potential parameters to be the same as those required to fit experimental data on scattering and capture of low energy neutrons by ^7Li. Tombrello chose the smallest potential depths that fitted the data, corresponding to 1s neutrons. Aurdal pointed out that it is more reasonable to choose deeper potentials that also fit the data but correspond to 2s neutrons. In both calculations, spectroscopic factors for the breakup of the ^8Li ground and first excited states into ^7Li+n were chosen to fit the $^7Li(n,\gamma)$ data, and the same values were assumed for $^8B \to {}^7Be+p$.

Robertson (1973) showed that, although s-wave proton contributions dominate at solar energies, contributions from d-wave protons (also with E1 radiation) can be appreciable at laboratory energies and therefore need to be taken into account in fitting the data. He also considered resonant M1 contributions due to p-wave protons; these add incoherently to the E1 contributions in the integrated cross section. Robertson used a direct-capture potential model for the resonant as well as the nonresonant contributions. His potential included a Thomas spin–orbit term. The potential depths for $p_{3/2}$ protons were chosen to fit the observed energies of the three lowest states of ^8B. Robertson did not, however, relate the potential depths for s-wave protons to those for s-wave neutrons scattered on ^7Li because of the possible influence of compound nucleus effects in the latter, and instead he chose them equal to the mean $p_{3/2}$ potential depth. The same depth was also used for $p_{1/2}$, $d_{3/2}$ and $d_{5/2}$ protons. The spectroscopic factors for the ^8B ground state were taken from the shell model calculations of Cohen and Kurath (1967).

In the present calculation, the potential is assumed to be of the central Woods–Saxon form used by Tombrello (1965), and the s-wave potential depths are determined in a similar way from ^7Li+n data, except that they correspond to 2s neutrons, as assumed by Aurdal (1970). The objection of Robertson (1973) to this does not seem to be valid, since in other cases where compound nucleus effects are as likely to be important as in the present case, e.g. the $1/2^+$ first excited states of ^{13}C and ^{13}N (Lane 1953), the s-wave potentials required to fit the level energies and low-energy neutron scattering properties are very similar for the mirror nuclei. Also, if Robertson's method were used for the ^6Li+p case, treated in the preceding paper (Barker 1980), and the s-wave potential depths were taken equal to the mean p-wave depth required to fit the binding energies of the two lowest states of ^{7}Be, then the amount of cancellation in the s-wave radial integrals would be much reduced and the predicted cross sections would be much increased (for the basic parameter set they would then be an order of magnitude too large). For the d-wave E1 capture of both neutrons and protons, we take the potential depth equal to the average s-wave depth, since this is approximately true for other cases (Tombrello 1966) and since the d-wave contributions to the cross sections at bombarding energies below a few MeV depend only slightly on the depth.

Table 1. Values of spectroscopic factors for states of ^{8}Li and ^{8}B

Spectroscopic factor $\mathscr{S}$	J	s	Calculated values[A] CK[a]	B[b]	K[c]	Experimental values[A] Resonance ^{8}Li	Resonance ^{8}B	Stripping ^{8}Li
$\mathscr{S}_{Js}$	2	1	0·282	0·251	0·250			
	2	2	0·751	0·765	0·751			
	1	1	0·140	0·159	0·206			
	1	2	0·306	0·295	0·221			
	3	2	0·338	0·300	0·308			
$\mathscr{S}_J$	2		1·03	1·02	1·00			0·88[d], 0·87[e]
	1		0·45	0·45	0·43		0·58±0·20[f]	0·47[d], 0·48[e]
	3		0·34	0·30	0·31	0·19±0·04[g]	0·20±0·03[h]	0·25[d]

[A] References: (*a*) Cohen and Kurath (1965, 1967); (*b*) Barker (1966); (*c*) Kumar (1974); (*d*) Macfarlane and French (1960), for ^{7}Li(d, p)^{8}Li, PWBA, $\theta_0^2 = 0{\cdot}06$; (*e*) Schiffer *et al.* (1967), for ^{7}Li(d, p)^{8}Li, DWBA; (*f*) Ajzenberg-Selove (1979), with $\Gamma^0_{\rm cm} = 40 \pm 10$ keV; (*g*) Ajzenberg-Selove (1979), with $\Gamma^0_{\rm cm} = 33 \pm 6$ keV; (*h*) Ajzenberg-Selove (1979), with $\Gamma^0_{\rm cm} = 350 \pm 40$ keV.

In our calculation, the values of the spectroscopic factors $\mathscr{S}_{Js}$ in equation (6), which we use for both ^{7}Li(n, γ) and ^{7}Be(p, γ) direct capture, are initially taken from shell model calculations. These values are given in Table 1, together with calculated and experimental values of $\mathscr{S}_J = \Sigma_s \mathscr{S}_{Js}$. The resonance values are derived from observed widths, using the one-level approximation with both ground state and first excited state channels included, a conventional value for the channel radius $a_c = 1{\cdot}45(7^{\frac{1}{3}} + 1^{\frac{1}{3}})$ fm $= 4{\cdot}22$ fm, and the shell model value of the spectroscopic factor for the excited state channel. There is moderate agreement between the calculated and experimental values of $\mathscr{S}_J$. In his calculation, Tombrello (1965) obtained values of $\mathscr{S}_{Js}$ ($\equiv \theta_s^2$) by fitting the ^{7}Li(n, γ) data of Imhof *et al.* (1959), assuming $\mathscr{S}_{Js}$ to be the same for $J = 2$ and 1. He considered the two cases (i) $\mathscr{S}_{J1} = 0$, $\mathscr{S}_{J2} = 0{\cdot}55$, and (ii) $\mathscr{S}_{J1} = 0{\cdot}22$, $\mathscr{S}_{J2} = 0{\cdot}39$, corresponding to the ratio $\mathscr{S}_{J1}/\mathscr{S}_{J2}$ taking on the extreme values allowed by the observed value of W_+. These values do not correspond very well with the shell model values in Table 1. In agreement with Robertson (1973), we find that, although we can reproduce Tombrello's results when we use his parameter values, the same is not true for the results of Aurdal (1970), so that we do not discuss the latter results further. Robertson used the values of $\mathscr{S}_{Js}$ in column CK of Table 1.

Although the values of $\mathscr{S}_J$ in Table 1 show that the 2^+ ground state of ^{8}B looks like ^{7}Be(g.s.)+p, the 1^+ and 3^+ excited states do not and so, in contrast to Robertson (1973), we do not calculate the resonant p-wave capture for a potential model but make use of shell model wavefunctions. From these we calculate values of the radiation widths of the excited states, and compare them with values extracted from the experimental cross sections.

In each of the previous calculations, the same values $R = 2 \cdot 95$ fm and $a = 0 \cdot 52$ fm were used for the radius and diffuseness parameter of the Woods–Saxon nuclear potential. The corresponding value of r_0, in $R = r_0 A^{\frac{1}{3}}$, is $r_0 = 1 \cdot 54$ fm. These values of R and a were obtained by Tombrello (1965) by interpolation in the mass number A from optical model analyses of the scattering of 180 MeV protons on various

Table 2. Potential depths for ^{7}Li+n and ^{7}Be+p systems

The potentials listed are for the standard values $r_0 = 1 \cdot 25$ fm ($R = 2 \cdot 39$ fm) and $a = 0 \cdot 65$ fm

States			Potential depth (MeV) for reaction		
J	l	s	^{7}Li+n	^{7}Be+p	Both reactions
Bound states					
2			46·42	46·62	
1			43·34	—	
Continuum states					
	0	1			45·52
	0	2			56·18
	2	1,2			50

targets (Johansson *et al.* 1961). Tombrello (1965) apparently used values of the optical model parameters calculated by Johansson *et al.*, whereas they obtained best fits to their data with parameter values for the real central part of the potential of $r_0 = 1 \cdot 1$ fm for both lithium and beryllium targets (the corresponding Coulomb parameter being $1 \cdot 3$ fm), and $a = 0 \cdot 4$ fm for lithium targets and $0 \cdot 5$ fm for beryllium. Widely different (and energy-dependent) values of r_0 and a are suggested by other optical model analyses of nucleon scattering on light nuclei (Satchler *et al.* 1968; Werby *et al.* 1971).

As initial values of r_0 and a, we take the values customarily used for optical model descriptions of bound states, namely $r_0 = 1 \cdot 25$ fm and $a = 0 \cdot 65$ fm, which were obtained by Bjorklund and Fernbach (1958) from analysis of neutron scattering on heavier targets. Values of the potential depths corresponding to these values of r_0 and a are given in Table 2. For the final bound states of ^{8}Li and ^{8}B, the depths are obtained by fitting the observed binding energies of these states, as shown in Fig. 1. The near equality of the depths for the ground states of ^{8}Li and ^{8}B may be noted. For the ^{7}Li+n initial s-wave continuum states, the depths are chosen to fit the scattering lengths of equations (5), and the same depths are assumed to be valid for ^{7}Be+p. Variations of these values of r_0 and a, and of the values of the spectroscopic factors, are subsequently considered in order to improve the fits to the neutron-capture data, principally the thermal-neutron cross section.

4. Results

(*a*) *Resonant p-wave Capture*

Calculated and experimental values of the radiation widths of the 1^+ and 3^+ excited states of ^{8}Li and ^{8}B for M1 transitions to the 2^+ ground states are given in

Table 3. Although the experimental errors are large in most cases, and there is considerable variation in the calculated values for the 3^+ states, it seems fair to say that there is satisfactory agreement between theory and experiment for the transitions in ^{8}Li, but for ^{8}B the experimental values appear to be about twice the calculated values.

Table 3. M1 radiation widths of excited states of ^{8}Li and ^{8}B

Nucleus	J^π	Calculated widths[A] (eV) CK[a]	B[b]	K[c]	Experimental widths[A] (eV)	
^{8}Li	1^+	0·048	0·049	0·053	$0{\cdot}065^{+0{\cdot}053}_{-0{\cdot}020}$[d]	$0{\cdot}047^{+0{\cdot}026}_{-0{\cdot}012}$[e]
	3^+	0·088	0·060	0·043	$0{\cdot}07 \pm 0{\cdot}03$[f]	
^{8}B	1^+	0·019	0·019	0·021	$0{\cdot}045 \pm 0{\cdot}023$[g]	$0{\cdot}047 \pm 0{\cdot}005$[h]
	3^+	0·110	0·078	0·061	0·15[i]	$\lesssim 0{\cdot}2$[h]

[A] References: (*a*) Cohen and Kurath (1965); (*b*) Barker (1966); (*c*) Kumar (1974); (*d*) Throop *et al.* (1971); (*e*) Costa *et al.* (1972); (*f*) Imhof *et al.* (1959); (*g*) Parker (1966, 1968); (*h*) Kavanagh (1972); (*i*) Vaughn *et al.* (1970).

Table 4. Experimental and calculated values for ^{7}Li(n, γ)^{8}Li and ^{7}Be(p, γ)^{8}B

Parameter modified	Change in parameter[A]	$\sigma_{n\gamma}(E_{th})$ (mb)	$\mathscr{R}$ (%)	W_+ (%)	$\sigma_{n\gamma}(600)$ (μb)	$S_{p\gamma}(300)$ (keV b)	$S_{p\gamma}(0)$ (keV b)
		Standard parameter set					
—	—	64·1	9·0	89·3	7·4	0·0209	0·0225
		Modified parameter sets (a)					
$\mathscr{S}_{Js}$	B→CK	63·9	9·1	88·3	7·5	0·0212	0·0228
	B→K	62·2	7·9	88·5	7·3	0·0206	0·0221
a_1 (fm)	1·09→1·29	63·7	9·0	89·9	7·4	0·0209	0·0225
a_2 (fm)	−3·59→−3·53	63·5	9·1	89·2	7·4	0·0209	0·0225
V_2 (MeV)	50→30	64·1	9·0	89·3	7·4	0·0209	0·0225
r_{hc} (fm)	0→1·0	70·8	9·2	88·8	7·9	0·0248	0·0268
$r_{hc,p}$ (fm)	0→1·0	79·7	8·7	89·3	9·2	0·0250	0·0269
		Modified parameter sets (b)					
$\mathscr{S}_{Js}$	×0·708	45·4	9·0	89·3	5·3	0·0148	0·0159
$\mathscr{S}_{2s}$	×0·678	45·4	12·8	89·0	5·3	0·0142	0·0152
r_0 (fm)	1·25→0·53	45·4	9·1	90·0	5·5	0·0134	0·0144
a (fm)	0·65→0·27	45·4	8·8	90·1	5·7	0·0126	0·0135
r_{co} (fm)	0→4·75	45·4	10·5	87·5	4·6	0·0202	0·0223
Experimental values:		45·4±3	10·6±1	$\gtrsim$86	6±1	0·030±0·002	

[A] Change in modified parameter from the value for the standard set; in the set (*a*) the spectroscopic factors $\mathscr{S}_{Js}$ of (B) Barker (1966) are changed to those of (CK) Cohen and Kurath (1967) or (K) Kumar (1974).

(*b*) *Nonresonant s-wave and d-wave Capture in* ^{7}Li(n, γ)^{8}Li

Initially we calculate the ^{7}Li(n, γ)^{8}Li cross section and related quantities using the spectroscopic factors of Barker (1966) given in Table 1 and the potential parameters given in Table 2. The resulting values are given in Table 4, where they are referred to as the standard parameter set. As well as the quantities for which experimental values are given in equations (1)–(3), we also include $\sigma_{n\gamma}(600)$, the total $^7Li(n, \gamma)$ cross section at $E_n = 600$ keV, as being representative of the nonresonant part of the cross section. The last two columns in Table 4 refer to the $^7Be(p, \gamma)^8B$ reaction, and these are discussed in subsection (*c*) below. The complete $^7Li(n, \gamma)$ cross section is shown in Fig. 2; the experimental points are from Imhof *et al.* (1959) and the full curve gives the calculated values. Only for $\sigma_{n\gamma}(E_{th})$ is there a clear discrepancy between calculation and experiment, although the calculated value of $\mathscr{R}$ is a little low and that of $\sigma_{n\gamma}(600)$ a little high.

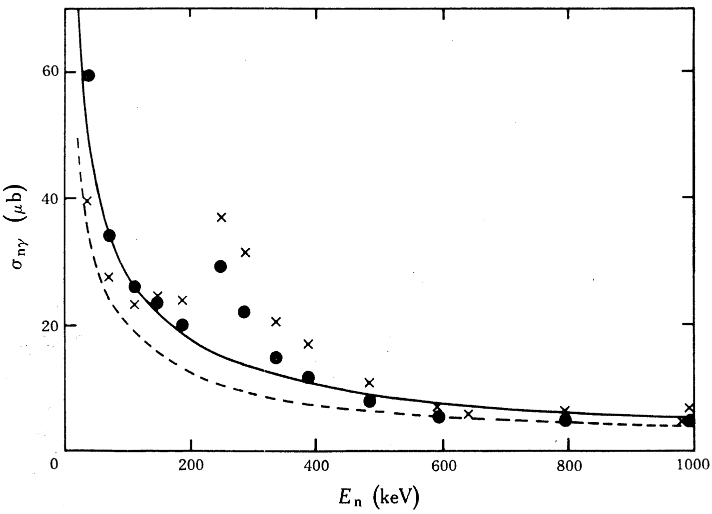

Fig. 2. Cross section $\sigma_{n\gamma}$ for $^7Li(n, \gamma)^8Li$ as a function of neutron energy E_n. The crosses and circles are experimental values derived from the same measurements but with normalizations based on the absolute cross sections of two different reactions (Imhof *et al.* 1959); a resonant contribution for $E_n \approx 250$ keV is included in these values. The curves are nonresonant contributions calculated for two different sets of parameters indicated in Table 4: full curve, standard set; dashed curve, modified set with $\mathscr{S}_{Js}$ multiplied by $0 \cdot 708$.

Only small changes in the calculated values are produced by changing the spectroscopic factors from those of Barker (1966) to those of Cohen and Kurath (1967) or of Kumar (1974), which are given in Table 1, or by changing the potential depths by fitting scattering lengths varied within the uncertainties indicated in equations (5) (see modified parameter sets (*a*) in Table 4). Reasonable changes in the d-wave potential depth V_2 have a negligible effect. Introduction of a hard-core radius r_{hc} for all states (or of $r_{hc,p}$ for the p states only) leads to increased cross sections. There are, however, several ways of obtaining appreciable decreases in the calculated cross sections, which include decreasing spectroscopic factors, decreasing r_0 and/or a, and introducing a cutoff radius in the radial integrals.

In Table 4 we show the effects of the changes just described, made one at a time. We discuss only the changes shown in the modified parameter sets (*b*) of Table 4, which enable the experimental value of $\sigma_{n\gamma}(E_{th})$ to be fitted. Decreasing uniformly the values of all spectroscopic factors $\mathscr{S}_{Js}$ renormalizes all cross sections, without changing $\mathscr{R}$ or W_+. If only $\mathscr{S}_{2s}$ is reduced then the value of $\mathscr{R}$ is significantly increased and becomes larger than the experimental value. Some reduction of $\mathscr{S}_{2s}$ is suggested by the values in Table 1, but not as much as is required to fit $\sigma_{n\gamma}(E_{th})$. A reduction of r_0 to $0\cdot53$ fm is required in order to fit $\sigma_{n\gamma}(E_{th})$, or of a to $0\cdot27$ fm, each of these being much smaller than the standard value. Introducing a cutoff radius $r_{co} \gtrsim 3$ fm decreases the radial integrals, in contrast to the situation in ^{6}Li(n, γ)^{7}Li (Barker 1980), since here there is little cancellation in the radial integrals. Alternatively, the experimental value of $\sigma_{n\gamma}(E_{th})$ could have been fitted by small simultaneous changes in more than one parameter.

The above changes have little effect on the value of W_+, which remains acceptable. Agreement for $\mathscr{R}$ can be obtained by a reasonable change in the ratio $\mathscr{S}_{2s}/\mathscr{S}_{1s}$. When $\sigma_{n\gamma}(E_{th})$ is fitted, the predicted values of $\sigma_{n\gamma}(600)$ are near the bottom of the experimental range. Now, the experimental value and error listed for $\sigma_{n\gamma}(600)$ in Table 4 came from the two values given by Imhof *et al.* (1959) for $\sigma_{n\gamma}$ for $E_n \approx 600$ keV, based on the same measurement but normalized relative to two different reactions. The higher value of $\sigma_{n\gamma} \approx 7\ \mu$b was normalized to the ^{6}Li(n, t)^{4}He absolute cross section, the lower value of $\sigma_{n\gamma} \approx 5\ \mu$b to the ^{127}I(n, γ)^{128}I cross section. The value used for the ^{6}Li(n, t) cross section at $E_n \approx 600$ keV was about $0\cdot40$ b, whereas recent measurements give lower values; e.g. Gayther (1977) gives about $0\cdot31$ b. Thus it is reasonable to reduce the higher value of $\sigma_{n\gamma}$ to about $5\cdot4\ \mu$b and there is then good agreement between the experimental and predicted values of $\sigma_{n\gamma}(600)$. As an example of the predicted $\sigma_{n\gamma}$ values for other energies, the dashed curve in Fig. 2 shows the values for the modified parameter set with $\mathscr{S}_{Js}$ decreased by a factor of $0\cdot708$; when allowance is made for the resonant contribution at $E_n \approx 250$ keV contained in the experimental points, there is satisfactory agreement. We note that the d-wave contribution is about 8% at $E_n = 600$ keV, increasing to 22% at $E_n = 1000$ keV. Tombrello (1965) neglected any d-wave contribution, and chose his $\mathscr{S}_{Js}$ values to fit the $\sigma_{n\gamma}$ values of Imhof *et al.* (1959) for $E_n = 40$–1000 keV. His parameter values give $\sigma_{n\gamma}(E_{th}) = 62$ mb (case *a*) and 55 mb (case *b*), each being higher than the experimental value.

(*c*) *Nonresonant s-wave and d-wave Capture in* ^{7}Be(p, γ)^{8}B

At low bombarding energies, it is convenient to consider the S factor for the ^{7}Be(p, γ)^{8}B reaction rather than the cross section itself. These are related by

$$S_{p\gamma} = E_{cm} \exp(2\pi\eta)\, \sigma_{p\gamma},$$

where η is the Sommerfeld parameter. The values of $S_{p\gamma}$ corresponding to the cross sections measured by Kavanagh (1960), Parker (1968), Kavanagh *et al.* (1969) and Vaughn *et al.* (1970) are shown in Fig. 3 for proton energies E_p up to about 4 MeV. Resonances at $E_p \approx 730$ and 2500 keV are due to the 1^+ and 3^+ states of ^{8}B. As a measure of the nonresonant part of the cross section, we consider the value of $S_{p\gamma}(300)$, the S factor at $E_p = 300$ keV. Kavanagh *et al.* (1969) give $S_{p\gamma}(300) = 0\cdot030 \pm 0\cdot002$ keV b, and this value is entered in Table 4 as the accepted experimental value. Calculated values of $S_{p\gamma}(300)$ are also given in Table 4 for the standard and modified sets of parameter values. It is seen that the standard value is below the experimental value, and the modified values (*b*) that fit $\sigma_{n\gamma}(E_{th})$ are lower still. The curves in Fig. 3 show the calculated nonresonant contributions to $S_{p\gamma}$ for the standard set and a particular modified set that fits $\sigma_{n\gamma}(E_{th})$. The rise in $S_{p\gamma}$ at the higher energies is due to the d-wave proton contribution, which increases rapidly with proton energy, from about 6% at zero energy to 19% at 300 keV and 82% at 4 MeV. It is seen that at all energies, the predicted values of $S_{p\gamma}$ for the standard set lie below the measured values of Parker (1968) and of Kavanagh *et al.* (1969), though there is moderate agreement with those of Vaughn *et al.* (1970), while the values for the modified set lie consistently below all the measured values except the early values of Kavanagh (1960).

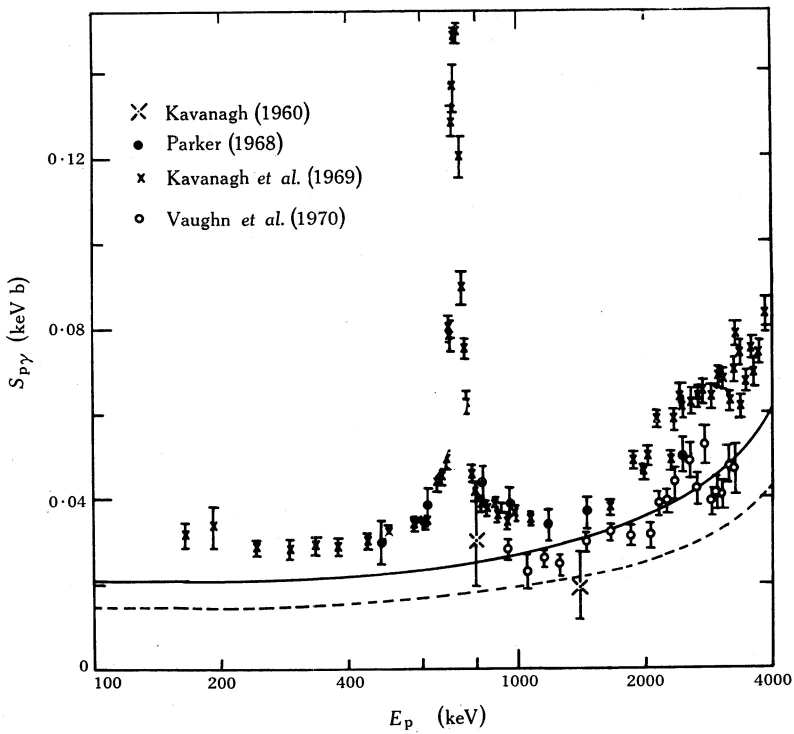

Fig. 3. S factor for $^7Be(p, \gamma)^8B$ as a function of proton energy E_p. The points are experimental values as indicated, and include resonant contributions for $E_p \approx 730$ and 2500 keV. The curves are nonresonant contributions calculated for two different sets of parameters indicated in Table 4: full curve, standard set; dashed curve, modified set with $\mathscr{S}_{Js}$ multiplied by 0·708.

The final column in Table 4 gives calculated values of the zero-energy S factor, which is of interest in the solar-neutrino problem; these are discussed in the next section.

5. Discussion

The present calculation of the nonresonant $^7Be(p, \gamma)^8B$ cross section is based on the assumption that the capture is direct and may be described by an optical model potential using the same parameter values and spectroscopic factors as are required to fit experimental data for the mirror reaction $^7Li(n, \gamma)^8Li$. Use of Woods–Saxon potentials with conventional values of the radius and diffuseness parameters, together with shell model values of the spectroscopic factors, gives too large a value of the thermal-neutron capture cross section $\sigma_{n\gamma}(E_{th})$, but values of the $^7Be(p,\gamma)$ cross section $\sigma_{p\gamma}$ that are smaller than the generally accepted experimental values of Parker (1968) and Kavanagh *et al.* (1969). Various modifications of the parameter values enable the experimental value of $\sigma_{n\gamma}(E_{th})$ to be fitted, and each of these has the effect of reducing the predicted values of $\sigma_{p\gamma}$, so increasing the discrepancy with experiment.

In each of the earlier calculations (Tombrello 1965; Aurdal 1970; Robertson 1973) the calculated $^7Be(p,\gamma)$ cross sections were also lower than the experimental values, but they were renormalized to fit the data. The basic assumption of the present calculation, that the same parameter values may be used for mirror direct-capture reactions, has now been tested in another case involving $^6Li(p,\gamma)^7Be$ and $^6Li(n,\gamma)^7Li$, where adequate data are available for each reaction, and found to be justified (Switkowski *et al.* 1979; Barker 1980). Hence it seems reasonable to take seriously the discrepancy between calculation and experiment, and to investigate the possibility that the experimental values are too large. Further evidence that this may be the case is given in Section 4*a* above, where it appears that the measured resonant parts of the $^7Be(p,\gamma)^8B$ cross section may be about twice what one would expect.

We note that the measured $^7Be(p,\gamma)$ cross sections of Kavanagh (1960) and of Vaughn *et al.* (1970) are appreciably smaller than the values of Parker (1968) and of Kavanagh *et al.* (1969), when each is normalized relative to the same value of σ_{dp}, the $^7Li(d,p)^8Li$ cross section at the 770 keV peak. In addition it has been already pointed out in Section 2 that at least one apparently reliable measurement of σ_{dp} gives a value appreciably lower than the commonly accepted value. Each of these observations suggests that a reduction in the accepted experimental value of $\sigma_{p\gamma}$ may not be unreasonable. Obviously an accurate remeasurement of the $^7Li(d,p)^8Li$ cross section would be most desirable.

In Section 2 there was a brief mention of a direct measurement of the $^7Be(p,\gamma)^8B$ cross section, made without reference to the $^7Li(d,p)^8Li$ cross section. This was performed at Münster by Wiezorek *et al.* (1977) at the single energy $E_p = 360$ keV. They obtained the result $S_{p\gamma}(360) = 0{\cdot}039 \pm 0{\cdot}010$ keV b, which is seen from Fig. 3 to be higher than the experimental value of Kavanagh *et al.* (1969) and more than twice the value predicted here. However, there has been confusion concerning the result of this experiment, since the expression that Wiezorek *et al.* give for the cross section is inconsistent with their definitions; the expression can be corrected by including an extra factor t_1, which suggests a much smaller value of $S_{p\gamma}(360)$. Nevertheless the Münster group still claim that their result is correct.*

In the calculation of the flux of solar neutrinos, it is the $^7Be(p,\gamma)^8B$ cross section at low energies ($E_p \lesssim 20$ keV) that is of interest, and this is represented by the zero-

* The Münster group (R. Santo, personal communication) retain the expression for the cross section in its published form, but redefine N_p as the number of protons per second summed over all irradiation cycles; this is equivalent to including an extra factor t_1 in the expression. They point out that the quantity Q referred to in their paper (Wiezorek *et al.* 1977) as the charge accumulation (and equal to $0{\cdot}35$ C) is not a measured quantity but is related to N_p and to the actually measured charge accumulated over all irradiation cycles (Q_{t_1}) by the relations

$$Q = N_p e t_0 = (Q_{t_1}/t_1) t_0 \,,$$

where $t_0 = 1$ s and $Q_{t_1} = 0{\cdot}055$ C (neither of which is mentioned in their paper). They obtain their result by using this latter value of the accumulated charge.

energy S factor $S_{p\gamma}(0)$, more usually written S_{17}. In recent calculations the value $S_{17} = 0\cdot030$ keV b has been adopted (Bahcall and Sears 1972) with an assumed uncertainty of 9% (from Kavanagh 1972). This value of S_{17} was obtained from the measurements of Kavanagh *et al.* (1969) by assuming that the S factor is constant for $E_p \lesssim 500$ keV. Extrapolation of the data of Parker (1968) and of Kavanagh *et al.* using the energy dependence of the S factor calculated by Tombrello (1965) and by Robertson (1973) gave slightly larger values of S_{17} (0·031–0·035 keV b). In contrast, the values given in Table 4 that are predicted from the optical model calculations are appreciably smaller and range from 0·014 to 0·022 keV b.

In summary, there are many disturbing features of the present situation regarding the $^7Be(p, \gamma)^8B$ cross section. It seems that S_{17} is not known as definitely as the assumed uncertainty of 9% would imply, and several indications suggest a significant reduction in the adopted value of S_{17}. This would imply a significant reduction in the calculated detection rate of solar neutrinos in the Davis experiment, since neutrinos from ^8B contribute 73% of the total value (Bahcall 1977). Such a reduction would lessen the discrepancy between the calculated detection rate of $4\cdot7 \pm 1\cdot6$ SNU (see Fowler 1978) and the latest experimental value of $1\cdot8 \pm 0\cdot4$ SNU (Davis 1979).

It is evident that the cross section of the $^7Be(p, \gamma)^8B$ reaction, as well as that of the $^7Li(d, p)^8Li$ reaction, requires further investigation, particularly as a possible means of reducing the discrepancy in the solar-neutrino problem.

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