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Delayed Alpha Spectra from the Beta Decay of ^{8}Li and ^{8}B

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Abstract

Many-level R-matrix fits are made to the α–α scattering d-wave phase shift and to α-spectra from ^{8}Li and ^{8}B β-decay measured by Wilkinson and Alburger (1971). With the requirement that the parameter values are the same in the fits to the phase shift and the α-spectra data, the best overall fits are obtained for a channel radius of about 6·5 fm, implying a broad 2^+ intruder state of ^{8}Be at about 9 MeV. There is satisfactory agreement between the Gamow–Teller matrix elements extracted from the fits and shell model values.

1. Introduction

Measurements of ^{8}Li and ^{8}B β-decay have in the past been significant in investigations of second-class currents and conserved vector current theory, in the calculation of the flux of solar neutrinos, and also in studies of the structure of ^{8}Be. The allowed β-transitions populate 2^+ states of ^{8}Be, which then decay into two α-particles. Several measurements of the delayed α-spectra have been made, and of these the measurements of Wilkinson and Alburger (1971), details of which were published only recently by Warburton (1986), have by far the best statistics.

The α-spectra show a pronounced peak at $E_\alpha \approx 1 \cdot 5$ MeV, corresponding to the 2^+ first excited state of ^{8}Be at $E_x \approx 3 \cdot 0$ MeV (Ajzenberg-Selove 1984). It has long been realised, however, that attempts to fit the data using a one-level approximation fail to give enough yield at high energies (Griffy and Biedenharn 1960; Alburger *et al.* 1963). Barker (1969) proposed R-matrix formulae in the many-level, one-channel approximation and used them to fit the then-available delayed α-spectra. Warburton (1986) used the same formulae to fit the α-spectra measured by Wilkinson and Alburger (1971). Both Barker and Warburton made fits to the α–α scattering d-wave phase shift δ_2 as well as to the α-spectra; however, there were differences in the way they applied the R-matrix formulae. The adjustable parameters in the formulae include the channel radius a_2, the boundary condition parameter B_2, and the eigenenergies E_λ, reduced width amplitudes γ_λ and Gamow–Teller matrix elements $A_{\lambda G}$ for the various 2^+ levels λ. For a range of values of a_2 and suitable choice of B_2, Barker obtained values of E_λ and γ_λ that best fitted δ_2, and then used these values in fits to the α-spectra in order to obtain values

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Table 1. The α-spectra of Wilkinson and Alburger (1971) collected following ^8Li and ^8B β–decay using the thin catcher

			$^8Li(\beta^-)^8Be$				
I	$N(I)$	I	$N(I)$	I	$N(I)$	I	$N(I)$
1	(0)	40	50104	79	5158	118	566
2	(0)	41	45720	80	4932	119	551
3	(1)	42	41892	81	4533	120	422
4	(8)	43	38469	82	4499	121	434
5	(27)	44	35492	83	4307	122	439
6	(67)	45	32891	84	4025	123	365
7	(141)	46	30265	85	3928	124	339
8	(262)	47	28175	86	3726	125	341
9	(448)	48	26652	87	3496	126	270
10	(718)	49	24418	88	3310	127	263
11	(1096)	50	23070	89	3127	128	272
12	(1611)	51	21639	90	3025	129	217
13	(2298)	52	20356	91	2842	130	199
14	(3201)	53	19275	92	2768	131	182
15	(4373)	54	18055	93	2657	132	199
16	(5885)	55	17155	94	2476	133	157
17	8441	56	16126	95	2204	134	131
18	10756	57	15275	96	2199	135	127
19	13808	58	14343	97	2095	136	126
20	17321	59	13809	98	1987	137	116
21	22447	60	13141	99	1822	138	89
22	28189	61	12398	100	1689	139	66
23	35888	62	11685	101	1631	140	66
24	44982	63	11197	102	1556	141	45
25	54635	64	10919	103	1454	142	44
26	65332	65	10003	104	1423	143	50
27	76566	66	9611	105	1340	144	39
28	85617	67	9235	106	1205	145	32
29	92962	68	8648	107	1225	146	32
30	97121	69	8540	108	1096	147	25
31	98836	70	7963	109	1036	148	16
32	96943	71	7607	110	911	149	18
33	91895	72	7090	111	945	150	13
34	86258	73	6914	112	860	151	11
35	79135	74	6508	113	738	152	9
36	73250	75	6293	114	744	153	6
37	66851	76	5880	115	663	154	3
38	60915	77	5681	116	615	155	4
39	54799	78	5382	117	613		

Table 1. (*Continued*)

$^{8}B(\beta^{+})^{8}Be$

I	$N(I)$	I	$N(I)$	I	$N(I)$	I	$N(I)$
1	(0)	44	41124	87	4926	130	535
2	(0)	45	37801	88	4549	131	469
3	(2)	46	35104	89	4473	132	446
4	(11)	47	33170	90	4221	133	430
5	(34)	48	30965	91	4125	134	405
6	(81)	49	28596	92	3944	135	357
7	(164)	50	27047	93	3714	136	337
8	(298)	51	25487	94	3636	137	305
9	(500)	52	23991	95	3383	138	297
10	(792)	53	22479	96	3268	139	268
11	(1199)	54	21348	97	3092	140	246
12	(1753)	55	20460	98	2995	141	258
13	(2491)	56	19278	99	2770	142	222
14	(3463)	57	18098	100	2673	143	215
15	(4728)	58	17051	101	2600	144	173
16	(6363)	59	16481	102	2547	145	182
17	8863	60	16031	103	2302	146	148
18	11403	61	15180	104	2203	147	136
19	14583	62	14433	105	2177	148	116
20	18847	63	13610	106	2091	149	107
21	24314	64	13061	107	1957	150	125
22	30989	65	12415	108	1721	151	87
23	39507	66	11846	109	1688	152	101
24	49739	67	11412	110	1736	153	81
25	60464	68	10978	111	1657	154	78
26	72683	69	10435	112	1507	155	68
27	84989	70	10090	113	1419	156	48
28	94709	71	9536	114	1355	157	64
29	102464	72	9261	115	1264	158	49
30	107779	73	8927	116	1269	159	34
31	109309	74	8439	117	1123	160	38
32	106903	75	8121	118	1123	161	28
33	102799	76	7802	119	1078	162	18
34	96536	77	7456	120	942	163	17
35	89273	78	7242	121	959	164	10
36	82056	79	6943	122	855	165	20
37	74466	80	6444	123	800	166	14
38	68385	81	6161	124	751	167	20
39	62550	82	6049	125	683	168	16
40	57226	83	5889	126	657	169	15
41	52165	84	5469	127	609	170	31
42	47837	85	5340	128	590	171	7
43	44026	86	4980	129	577	172	2

of $A_{\lambda G}$. The best simultaneous fits to δ_2 and the α-spectra were obtained for $a_2 \approx 6 \cdot 7$ fm. For this value of a_2, the second 2^+ state is at about 9 MeV, with a width of about 10 MeV; this is an intruder state in the sense that it must belong to a higher shell model configuration because of its large α-particle reduced width. In contrast, Warburton did not impose the condition that the parameters should have the same values in fits to the α-spectra as in the fit to δ_2. Consequently he was able to avoid a low-lying intruder state by using a smaller channel radius $a_2 = 4 \cdot 5$ fm. Arguments for and against these different approaches have been discussed by Barker (1988).

There is another matter of some concern regarding the analysis by Warburton (1986). The measurements by Wilkinson and Alburger (1971) were made primarily in order to obtain accurate *relative* α-spectra for ^{8}Li and ^{8}B (as a test for second-class currents). It did not matter if possible corrections had large uncertainties as long as the difference of the corrections for ^{8}Li and ^{8}B was known accurately. One such correction was for the α-particle energy loss in the catcher in which the ^{8}Li and ^{8}B came to rest before decaying. Measurements were made with both a 'thin' catcher and a 'thick' catcher, with thicknesses of 35 and 60 keV respectively for $5 \cdot 5$ MeV α-particles. Warburton (1986) gave and fitted only the *thick* catcher data. For these his α-particle energy losses were appreciable, being of the order of 100 keV in the region of the peak. Since the validity of some of the assumptions underlying the calculation of these energy losses is not clear, it would seem to be preferable to make use of the thin catcher data, where the energy losses are smaller and the corrections for them less significant.

In the present paper, we fit the thin catcher data of Wilkinson and Alburger (1971). The method used is similar to that in Barker (1969), in that the α-spectra and phase shift δ_2 are fitted simultaneously with the same parameter values.

2. Experimental Data

The experimental values and errors of the α–α d-wave phase shift are essentially the same as those used by Barker (1969) and Warburton (1986). No attempt is made to use phase shift values in the region of the narrow $16 \cdot 6$ and $16 \cdot 9$ MeV 2^+ levels of ^{8}Be, because Hinterberger *et al.* (1978) have already analysed α–α scattering data in this energy region and extracted parameter values for these levels.

The α-particle spectra for ^{8}Li and ^{8}B β-decay measured by Wilkinson and Alburger (1971) with their thin catcher, together with details of calibration runs and the procedure that they used for correcting for α-particle energy loss in the catcher, have been provided by Warburton (personal communication 1986). These thin catcher spectra are listed in Table 1 in a form comparable to that of Table V of Warburton (1986), which gives the spectra measured with the thick catcher. The original data extended from channels $I = 12$ to 155 (^{8}Li) and 11 to 172 (^{8}B), but data for $I \leq 16$ are not included in the fits for the same reason that Warburton (1986) did not include them. The values (in parentheses) for channels 1–16 in Table 1 are calculated values. The total counts summed over all channels are $2 \cdot 176 \times 10^6$ (^{8}Li) and $2 \cdot 507 \times 10^6$

(^{8}B); the statistics are therefore similar to those for the thick catcher. The energy calibrations comparable with those given in equations (A1) and (A3) of Warburton (1986) are

$$E_\alpha(\mathrm{Li}) = (-43\cdot 8 + 49\cdot 625I - 0\cdot 00034I^2)\ \mathrm{keV},$$

$$E_\alpha(\mathrm{B}) = (-27\cdot 8 + 49\cdot 425I + 0\cdot 00017I^2)\ \mathrm{keV}, \tag{1}$$

with channel energy $E = 2E_\alpha$ and excitation energy $E_\mathrm{x} = E - 92$ keV.

These calibrations contain an allowance for the average energy loss of the α-particles in leaving the catcher. Several assumptions underlie this calculation. Because only 22% of the ^{8}B nuclei that struck the thin catcher came to rest in it, Wilkinson and Alburger suggested that the ^{8}B depth distribution must be rather uniform. Then the average energy loss is taken as half the maximum energy loss, multiplied by an obliquity factor of $1\cdot 18$ to allow for the mean angle at which the α-particles reach the detector. Also the carbon component of the catcher is assumed to be exactly $20\,\mu\mathrm{g\,cm^{-2}}$, the gold component being determined by the requirement that the total energy loss for $5\cdot 5$ MeV α-particles should be 35 keV. This leads to an average α-particle energy loss

$$\Delta E_\alpha(\mathrm{B}) = (51\cdot 3 - 0\cdot 463I + 0\cdot 00164I^2)\ \mathrm{keV}. \tag{2}$$

For the ^{8}Li case, the energy loss is assumed to have the same I-dependence, the proportionality factor being chosen to make the difference of the measured peak energies equal to that expected because of the different Fermi functions; this gives

$$\Delta E_\alpha(\mathrm{Li})/\Delta E_\alpha(\mathrm{B}) = 0\cdot 688. \tag{3}$$

The experimental spectra of Table 1 should be corrected for smearing due to various causes. Warburton (1986) has considered two of these—the energy resolution of the detector (FWHM = 34 keV) and the electron–neutrino recoil. From our calculations, corrections due to recoil are about $-0\cdot 42\%$ at $I = 17$ ($E_\mathrm{x} \approx 1\cdot 5$ MeV), $+0\cdot 34\%$ at $I = 30$ ($E_\mathrm{x} \approx 2\cdot 8$ MeV) and $-0\cdot 12\%$ at $I = 42$ ($E_\mathrm{x} \approx 4\cdot 0$ MeV), while those due to resolution are an order of magnitude smaller. These corrections reduce the FWHM of the 3 MeV peak by about 8 keV ($0\cdot 5\%$), and we conclude, as did Warburton, that they may be neglected. Other contributions to energy loss and smearing are considered in Section 4.

In the fits, the error in the value $N(I)$ is taken as $[N(I)]^{1/2}$.

The data of Matt *et al.* (1964) on the high-energy end of the α-spectrum from ^{8}B β-decay are used, as in Barker (1969), to give information on the β-decay matrix elements for the $16\cdot 6$ and $16\cdot 9$ MeV levels.

3. Procedure for Fitting and Derivation of Gamow–Teller Matrix Elements

The R-matrix formulae used to fit the data are the same as in Barker (1969). The procedure of using these formulae is slightly different, because the present α-spectra data are of comparable quality to the δ_2 data, so that we do not determine any of the parameter values from preliminary fits to δ_2

alone. We include contributions to δ_2 from three 2^+ levels (labelled $\lambda = 1,2,3$), $\lambda = 1$ corresponding to the first excited state of ^{8}Be at about 3 MeV and $\lambda = 3$ to a background state well above the energy range being fitted. Contributions to the α-spectra are from these three states and also from the 16·6 and 16·9 MeV states, labelled a and b respectively. These two states are also expressed as mixtures of pure $T = 0$ and 1 states, labelled 0 and 1′.

The formulae are essentially given by equations (A12), (A14) and (A15) of Barker (1969). The parameters are a_2 and B_2, E_λ, γ_λ and $A_{\lambda G}$ ($\lambda = 1,2,3,0$), $E_{1'}$ and the Fermi matrix element $A_{1'F}$. From Barker (1969), we assume that $A_{1'G} = 0$ and that $A_{1'F}$ is given by equation (13) below with $M_{1'F}^2 = 2$. Since the values of E_λ, γ_λ and $A_{\lambda x}$ for a given fit depend on the choice of B_2, we use $E_\lambda^{(\mu)}$ to denote the value of E_λ appropriate to $B_2 = S_2(E_\mu^{(\mu)})$, and similarly for other parameters (cf. Barker 1971). The values $E_a^0 = 16\cdot715$ MeV, $E_b^0 = 17\cdot017$ MeV, $\Gamma_a^0 = 0\cdot1077$ MeV and $\Gamma_b^0 = 0\cdot0744$ MeV are taken from Hinterberger *et al.* (1978), the superscript 0 here indicating $K = 0$ (see equation 5 below); these values are appropriate to $B_2 = S_2(E_0^{(0)})$, where $E_0^{(0)}$ is an average energy for the 16·6, 16·9 MeV doublet:

$$E_0^{(0)} = (\Gamma_a^0 E_a^0 + \Gamma_b^0 E_b^0)/(\Gamma_a^0 + \Gamma_b^0) = 16\cdot838 \text{ MeV}. \tag{4}$$

The procedure for fitting the data is, for a chosen value of a_2, to take starting values of $E_\lambda^{(1)}$ and $\gamma_\lambda^{(1)}$ ($\lambda = 1,2,3$). The corresponding values $E_\lambda^{(0)}$ and $\gamma_\lambda^{(0)}$ ($\lambda = 1,2,3$) are calculated using the formulae of Barker (1972). The value of K is then obtained from (Barker 1969)

$$K = P_2(E_0^{(0)}) \sum_{\lambda=1}^{3} \gamma_\lambda^{(0)2}/(E_\lambda^{(0)} - E_0^{(0)}). \tag{5}$$

Then we get

$$\gamma_0^{(0)2} = (1 + K^2)\Gamma_0^0/2P_2(E_0^{(0)}), \tag{6}$$

where $\Gamma_0^0 = \Gamma_a^0 + \Gamma_b^0$. From these values of $E_\lambda^{(0)}$ and $\gamma_\lambda^{(0)}$ ($\lambda = 1,2,3,0$), we calculate values of $E_\lambda^{(3)}$ and $\gamma_\lambda^{(3)}$. The values of $A_{\lambda G}^{(3)}$ ($\lambda = 1,2,0$) are then varied in order to best fit the α-spectrum, subject to the condition $A_{3G}^{(3)} = 0$ (i.e. the background level is not fed in the β-decay). This procedure is repeated with adjusted values of the $E_\lambda^{(1)}$ and $\gamma_\lambda^{(1)}$ (except that the energy $E_3^{(1)}$ of the background level is kept fixed) in order to obtain a best simultaneous fit to δ_2 and the α-spectrum. This is done separately for the α-spectra from ^{8}Li and from ^{8}B, and is repeated for a range of values of a_2 in order to obtain the best overall fit.

Because the 2^+ levels of ^{8}Be are broad and contributions from them to the α-spectra are coherent, it is not possible to derive from the fits unique β-decay branching ratios, log*ft* values or Gamow–Teller matrix elements. We define the transition probability w_λ to level λ as that obtained from the total transition probability w [given by equations (A12) and (A13) of Barker (1969)] by assuming that only level λ is fed. This definition was used by Warburton (1986) and Barker and Warburton (1988), but is different from that used by

Barker (1969). Then equation (A16) of Barker (1969) is replaced by

$$w_\lambda = C^2(g^2_{\lambda F} + g^2_{\lambda G})\gamma^2_\lambda \int_0^\infty \frac{f_\beta P_2 \,\mathrm{d}E}{(E_\lambda - E)^2 |1 - (S_2 - B_2 + \mathrm{i} P_2)\Sigma_{\lambda'}\gamma^2_{\lambda'}/(E_{\lambda'} - E)|^2}, \tag{7}$$

where

$$C^2 g^2_{\lambda x}\gamma^2_\lambda = (\ln 2/N t_{1/2}) A^2_{\lambda x} \tag{8}$$

from equation (A15) of Barker (1969). An approximate branching ratio is then given by

$$\begin{aligned} \mathrm{BR}_\lambda &\equiv w_\lambda / w \\ &= N^{-1}(A^2_{\lambda F} + A^2_{\lambda G}) \int_0^\infty \frac{f_\beta P_2 \,\mathrm{d}E}{(E_\lambda - E)^2 |1 - (S_2 - B_2 + \mathrm{i} P_2)\Sigma_{\lambda'}\gamma^2_{\lambda'}/(E_{\lambda'} - E)|^2}, \end{aligned} \tag{9}$$

but $\Sigma_\lambda \mathrm{BR}_\lambda \neq 1$. The mean value, f_λ, of f_β for level λ is defined by writing the integral in equation (7) as $f_\lambda I_\lambda$, where

$$I_\lambda = \int_0^\infty \frac{P_2 \,\mathrm{d}E}{(E_\lambda - E)^2 |1 - (S_2 - B_2 + \mathrm{i} P_2)\Sigma_{\lambda'}\gamma^2_{\lambda'}/(E_{\lambda'} - E)|^2}. \tag{10}$$

Then we have

$$(ft_{1/2})_\lambda = N t_{1/2} / (A^2_{\lambda F} + A^2_{\lambda G}) I_\lambda . \tag{11}$$

This may be compared with the usual formula

$$(ft_{1/2})_\lambda = B/(M^2_{\lambda F} + M^2_{\lambda G}), \tag{12}$$

where $B = 6166$ s, and $M_{\lambda F}$ and $M_{\lambda G}$ are the Fermi and Gamow–Teller matrix elements as defined by Warburton (1986); these are related to the matrix elements used in Barker (1969) by $M^2_{\lambda F} = |\int \mathbf{1}|^2_\lambda$ and $M^2_{\lambda G} = R|\int \boldsymbol{\sigma}|^2_\lambda$. Then we get

$$M_{\lambda x} = (B I_\lambda / N t_{1/2})^{1/2} A_{\lambda x} . \tag{13}$$

This is essentially the same as equation (A22) of Barker (1969). Values of BR_λ, $\log(ft_{1/2})_\lambda$ and $M_{\lambda G}$ are calculated from equations (9), (11) and (13), using parameter values corresponding to $B_2 = S_2(E^{(\lambda)}_\lambda)$. In the relation (13) between M_{0G} and A_{0G} we use for I_0, given by equation (10), the narrow-level approximation* (Barker 1969)

$$I_\lambda = \pi \gamma^{(\lambda)-2}_\lambda (1 + \gamma^{(\lambda)2}_\lambda \,\mathrm{d}S_2/\mathrm{d}E)^{-1}_{E^{(\lambda)}_\lambda}, \tag{14}$$

and then take $\gamma^{(0)2}_0 (\mathrm{d}S_2/\mathrm{d}E)_{E^{(0)}_0} \ll 1$.

* The minus sign in equation (A19) of Barker (1969) is incorrect and should be replaced by a plus.

The data of Matt *et al.* (1964) were fitted by Barker (1969) with $|\int \boldsymbol{\sigma}|_0^2 = 2\cdot 60$, using $B = 6240$ s and $R = 1\cdot 39$. Since $A_{\lambda G}^2 \propto R|\int \boldsymbol{\sigma}|_\lambda^2/B$, the same value of A_{0G}^2 is obtained for $B = 6166$ s and $R^{1/2} = 1\cdot 2635$ (Warburton 1986) with $|\int \boldsymbol{\sigma}|_0^2 = 2\cdot 24$, or $M_{0G}^{(0)} = 1\cdot 89$.

4. Fits to Data

In fits to the phase shift δ_2 alone, the minimum value of χ_D^2 (χ^2 per degree of freedom) is about $0\cdot 5$ (see Table 1 of Barker 1969, where $X_2 = \chi_D^2/1\cdot 2$). Separate fits to the α-spectra of Table 1 with the energy calibrations (1) give minimum χ_D^2 values of about $1\cdot 7$ for both the ^{8}Li and ^{8}B cases [compare Tables I and III of Warburton (1986) for fits to the thick catcher data]. In simultaneous fits to δ_2 and the α-spectra, we therefore give weight factors of $1\cdot 0$ and $0\cdot 3$ to their respective contributions to χ_D^2.

Table 2. Values of χ_D^2 for best simultaneous fits to δ_2 and the α-spectra of Table 1 with the calibrations (1)

a_2 (fm)	5·25	5·5	6·0	6·5	6·75	7·0	7·5
Li	6·34	5·18	4·32	3·80	3·54	4·08	10·28
B	5·65	4·47	3·80	3·17	3·19	4·05	12·80

The resultant values of χ_D^2 for a range of values of a_2 are given in Table 2. The minimum values of χ_D^2, which occur for $a_2 \approx 6\cdot 5$ fm, are much larger than $1\cdot 0$ ($1\cdot 0\times 0\cdot 5+0\cdot 3\times 1\cdot 7$), suggesting that the phase shift data and the α-spectra data are not very consistent. Another way of expressing this is that the parameter values that best fit δ_2 and those that best fit the α-spectra are significantly different, as was found by Warburton (1986) for the thick catcher data. His conclusion was that this is to be expected in R-matrix theory; we believe that the parameter values should be the same, and so we look more carefully at the data to see if greater consistency is possible.

The parameter values that give a best fit to δ_2 predict α-spectra that have a peak that is narrower (by about 15%) and at a somewhat higher channel energy (by about 60 keV) than the measured peak, while the parameter values that best fit the α-spectra predict δ_2 values that rise more slowly than the measured values in the region of the 3 MeV level. It is unlikely that any experimental conditions would enhance the rate of increase of a phase shift near resonance, but anything that led to a spreading of the α-particle energies would cause a broadening of the peak in the α-spectrum and could reduce the energy of the peak. We therefore reconsider the possible causes of α-particle energy smearing and loss in the α-spectra.

Smearing due to detector resolution and lepton recoil has already been discussed in Section 2 and dismissed as unimportant. An allowance for the average α-particle energy loss in escaping from the catcher, due to the distribution in depth of the decaying ^{8}Li or ^{8}B and the spread in the angle of

Table 3. Values of χ_D^2 and other quantities for best simultaneous fits to δ_2 and the α-spectra of Table 1 with the calibrations (15)

Quantity	Case	a_2 (fm) 5.25	5.5	6.0	6.5	6.75	7.0	7.5
χ_D^2	Li	4.86	3.70	3.12	2.62	2.61	3.20	9.85
	B	4.17	3.24	2.69	2.30	2.67	3.49	12.58
$E_1^{(1)}$	Li	3.026	2.984	2.891	2.798	2.752	2.714	2.607
(MeV)	B	3.031	2.990	2.902	2.804	2.759	2.712	2.624
$\gamma_1^{(1)}$	Li	0.809	0.741	0.651	0.591	0.569	0.551	0.530
(MeV$^{1/2}$)	B	0.799	0.733	0.645	0.588	0.566	0.550	0.526
$E_2^{(2)}$	Li	14.91	13.56	10.72	8.85	8.12	7.45	6.36
(MeV)	B	15.01	13.59	10.71	8.87	8.01	7.42	6.24
$\gamma_2^{(2)}$	Li	1.198	1.173	0.986	0.880	0.835	0.792	0.725
(MeV$^{1/2}$)	B	1.199	1.164	0.997	0.884	0.845	0.807	0.722
$\gamma_0^{(0)}$	Li	0.565	0.324	0.138	0.109	0.109	0.114	0.135
(MeV$^{1/2}$)	B	0.594	0.318	0.140	0.109	0.108	0.114	0.130
$M_{1G}^{(1)}$	Li	0.126	0.124	0.116	0.108	0.104	0.101	0.093
	B	0.118	0.117	0.110	0.102	0.098	0.095	0.088
$M_{2G}^{(2)}$	Li	−0.576	−0.378	−0.218	−0.181	−0.171	−0.161	−0.149
	B	−0.740	−0.402	−0.221	−0.180	−0.166	−0.158	−0.141
$M_{0G}^{(0)}$	Li	2.53	2.37	2.08	1.77	1.59	1.44	1.19
	B	2.45	2.16	1.96	1.64	1.60	1.41	1.28
$\log(ft)_1$	Li	5.59	5.60	5.66	5.72	5.76	5.78	5.86
	B	5.65	5.65	5.71	5.77	5.80	5.84	5.91
$\log(ft)_2$	Li	4.27	4.64	5.11	5.27	5.32	5.38	5.45
	B	4.05	4.58	5.10	5.28	5.35	5.39	5.49
$\log(ft)_a$	Li	3.47	3.30	3.29	3.36	3.42	3.48	3.62
	B	3.47	3.34	3.32	3.41	3.42	3.49	3.56
$\log(ft)_b$	Li	2.99	3.13	3.29	3.40	3.45	3.48	3.51
	B	3.02	3.20	3.32	3.43	3.45	3.49	3.50
BR_1	Li	80.1	79.1	75.3	69.1	65.8	62.8	54.8
(%)	B	78.0	76.6	72.6	66.2	62.7	59.2	52.2
BR_2	Li	171.4	80.9	31.2	27.9	28.6	30.0	35.3
(%)	B	209.8	83.3	34.6	30.0	31.7	33.0	37.7
BR_0	Li	152.7	45.2	6.2	2.8	2.2	2.1	2.3
(%)	B	188.4	43.1	6.6	2.8	2.7	2.4	3.1

emission of the alphas, is included in the presently-used energy calibrations (1). These depth and angle distributions would also cause smearing of the α-spectra. While it is reasonable that this should have been neglected in the work of Wilkinson and Alburger (1971), its effect on the present analysis should be considered. The assumptions of Wilkinson and Alburger regarding the depth distributions are given in Section 2. The angle distribution depends on the target–catcher–detector geometry. The diameter of the active area of the catcher was about 8 mm and that of the detector about 14 mm, and the separation of the catcher and detector surfaces was about 6 mm (Alburger, personal communication 1988). With the assumption of uniform distributions of the ^{8}Li and ^{8}B nuclei over the active area of the catcher, although this assumption is not critical, the smearing due to the depth and angle distributions has been calculated and found to be inappreciable.

There is a different source of energy loss and smearing mentioned by Alburger *et al.* (1963) but not taken into account by Warburton (1986). This is the dead layer on the front of the detector, the thickness of which is given as 10–15 keV for 5·5 MeV α-particles. If we assume the value 15 keV, then the calibrations are changed from (1) to

$$E_\alpha(\mathrm{Li}) = (-4\cdot 9 + 49\cdot 140 I + 0\cdot 00090 I^2)\ \mathrm{keV},$$

$$E_\alpha(\mathrm{B}) = (11\cdot 0 + 48\cdot 940 I + 0\cdot 00141 I^2)\ \mathrm{keV}. \tag{15}$$

The peak energies are each increased by about 50 keV, so giving better agreement with what is expected from the fit to δ_2. Additional smearing is also produced. The total effect of smearing is still negligible, however, since that due to α-particle energy loss, including the effects of both the depth and angle distributions and of the dead layer, is small compared with that due to lepton recoil.

Simultaneous fits to δ_2 and the α-spectra of Table 1, again with weight factors of 1·0 and 0·3 respectively but with the calibrations (15), give the values of χ^2_{D} and other quantities in Table 3. The minimum values of χ^2_{D}, which again occur for $a_2 \approx 6\cdot 5$ fm, are smaller than in Table 2, showing that better consistency between the δ_2 data and the α-spectra data is obtained with the calibrations (15) rather than (1). There is good agreement between the parameter values obtained from the ^{8}Li and the ^{8}B fits. The values of $M^{(0)}_{0\mathrm{G}}$ obtained for $a_2 = 6\cdot 5$ fm are comparable with the value 1·89 obtained from fitting the ^{8}B data of Matt *et al.* (1964). Also for this value of a_2, $\Sigma_\lambda \mathrm{BR}_\lambda$ is approximately unity; this does not occur for much smaller values of a_2 because of the approach of the level 2 to the 16·6, 16·9 MeV doublet.

The best fits to δ_2 and the α-spectra for $a_2 = 6\cdot 5$ fm and the parameter values of Table 3 are shown in Figs 1 and 2. The three contributions plotted in each part of Fig. 2 are values of $N_\lambda(\mathrm{E}) = (Nt_{1/2}/\ln 2) w_\lambda(\mathrm{E})$ for $\lambda = 1$, 2 and 0, where

$$w_\lambda = \int_0^\infty w_\lambda(\mathrm{E})\, \mathrm{d}E$$

is given by equation (7). Because the levels contribute coherently, one has

$\Sigma_\lambda N_\lambda(E) \neq N(E)$. Also $N_\lambda(E)$ is calculated with parameter values corresponding to $B_2 = S_2(E_\lambda^{(\lambda)})$. It is clear that the shapes of the contributions from the 3 MeV level and the 16 MeV doublet are very different from the corresponding contributions of Warburton (1986) as plotted in his Figs 7 and 8. The Fermi contributions to the spectra are negligible except in the ^{8}B spectrum in the immediate neighbourhood of the 16·6 MeV level.

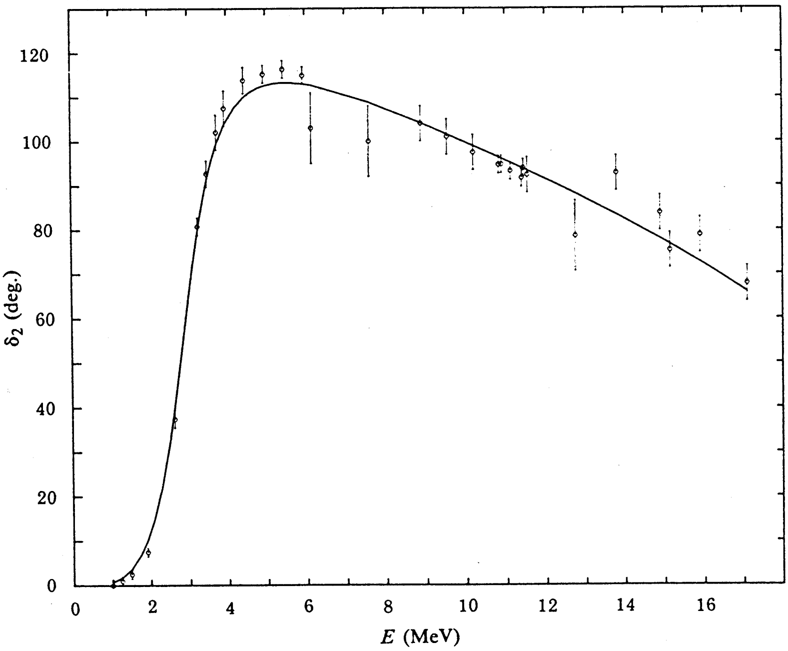

Fig. 1. The α–α scattering d-wave phase shift δ_2 as a function of the ^{8}Be channel energy E. The points are experimental values and the curve is the R-matrix three-level fit for the channel radius $a_2 = 6 \cdot 5$ fm and other parameters from Table 3 (^{8}B case).

5. Discussion

Neither the fit to δ_2 shown in Fig. 1 nor the fits to the α-spectra shown in Fig. 2 are as good as would have been obtained if δ_2 and the α-spectra had been fitted separately. The δ_2 data suggest a 3 MeV peak that is narrower than is indicated by the measured α-spectra. This discrepancy would be reduced if the smearing of the α-spectra due to α-particle energy loss were much greater than our estimate, which is uncertain because of the unknown accuracy of several of the assumptions on which it is based.

More or less independently of this smearing difficulty, the best consistent R-matrix fit of the scattering and β-decay data is obtained for a channel radius $a_2 \approx 6 \cdot 5$ fm, which is much the same as was obtained earlier from fits both to β-decay data (Barker 1969; Clark *et al.* 1969) and to ^{9}Be(p, d)^{8}Be data (Barker 1969; Barker *et al.* 1976). The implication is that there is a low-lying 2^+ intruder state in ^{8}Be at an excitation energy of about 9 MeV and with a

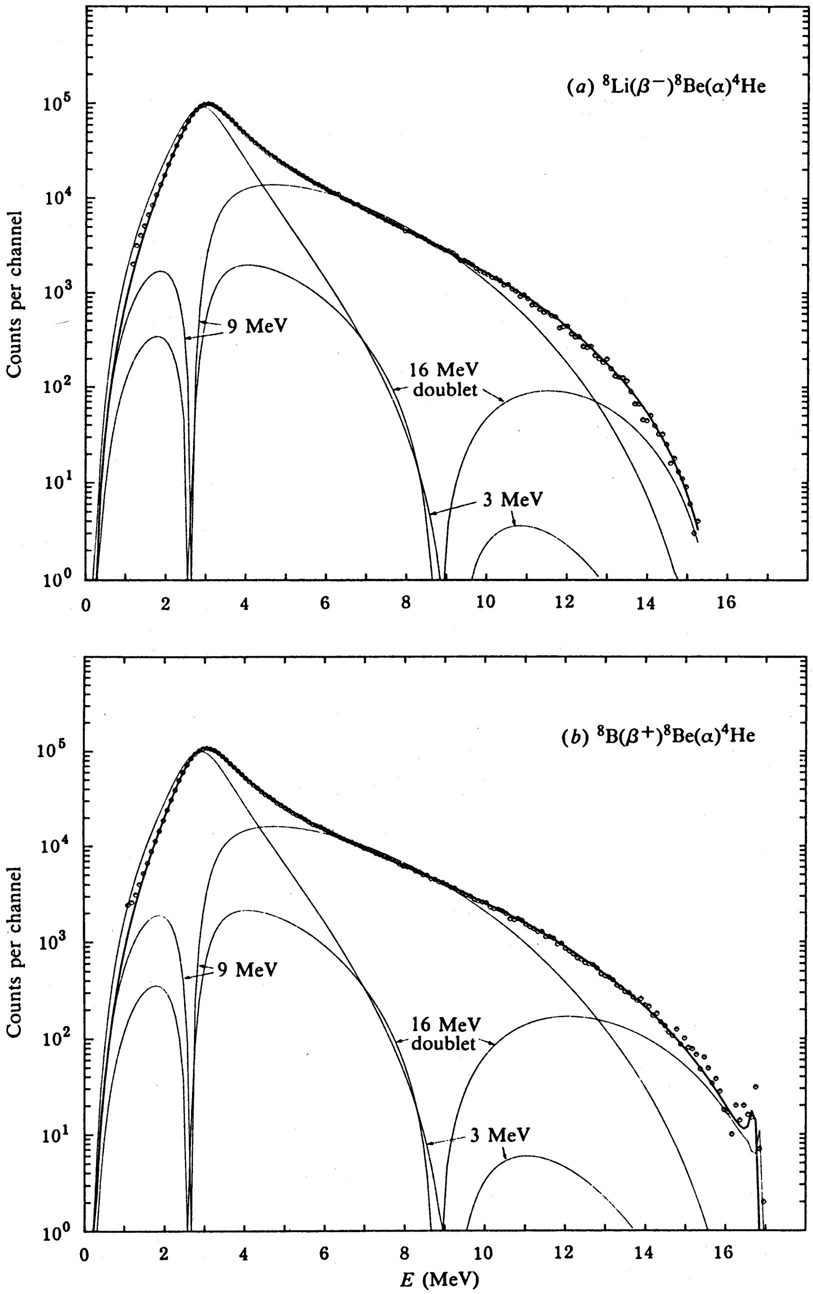

Fig. 2. Spectrum of α-particles from (*a*) $^8Li(\beta^-)^8Be(\alpha)^4He$ and (*b*) $^8B(\beta^+)^8Be(\alpha)^4He$ as a function of ^8Be channel energy E. The points are the experimental values of Wilkinson and Alburger (1971) obtained with their thin catcher; the points for $E < 1\cdot6$ MeV are not included in the fits. The heavy curve is the R-matrix fit for the channel radius $a_2 = 6\cdot5$ fm and other parameters from Table 3. The light curves show the approximate contributions from the levels $\lambda = 1$ (labelled 3 MeV), $\lambda = 2$ (9 MeV) and $\lambda = 0$ (16 MeV doublet). See text for more details.

large width. This is consistent with the finding of a broad 0^+ intruder state at about 6 MeV (Barker *et al.* 1968, 1976) based on quite independent data, and with expectations from the systematics of the energies of 0^+ and 2^+ intruder states in other light even nuclei.

We note that the branching ratio BR_0 to the 16·6, 16·9 MeV doublet from Table 3 is a few per cent, for both the ^{8}Li and ^{8}B cases. Warburton (1986) obtained 7–9%. In contrast, McKeown *et al.* (1980) gave the branching ratio to the 3 MeV state as 99·996%, implying $BR_0 \lesssim 0 \cdot 004\%$, and Bahcall and Holstein (1986) argued on the basis of phase space factors that BR_0 must be less than 0·01%. These small values of BR_0 result, however, from the erroneous assumption that the contribution from the 16·6, 16·9 MeV doublet is concentrated at 16·6 MeV (which would also lead to $BR_0 = 0$ for ^{8}Li), whereas the effect of the integrated Fermi function is to make this contribution peak at much lower excitation energies [as shown for example in Fig. 4 of Barker (1969) and Fig. 8 of Warburton (1986), as well as Fig. 2*b* here].

Table 4. Magnitudes of Gamow–Teller matrix elements from various sources

Source		$\|M^{(1)}_{1G}\|$ ^{8}Li	$\|M^{(1)}_{1G}\|$ ^{8}B	$\|M^{(0)}_{0G}\|$ ^{8}Li	$\|M^{(0)}_{0G}\|$ ^{8}B
Fits to Wilkinson and Alburger data					
Thin catcher:	Table 3	0·108	0·102	1·77	1·64
Thick catcher:	Warburton (1986)	0·163	0·152	2·69[A]	2·64[A]
	Present	0·108	0·102	1·78	1·66
Shell model calculations					
Cohen and Kurath (1965):	(6-16)2BME	0·188		1·94	
	(8-16)2BME	0·24			
	(8-16)POT	0·33			
Barker (1966)		0·165		1·97	
Hauge and Maripuu (1973)		0·26			
Kumar (1974)		0·213		1·74	

[A] Values of $M^{(1)}_{0G}$ [for $B_2 = S_2(E_1)$]; the corresponding values of $M^{(0)}_{0G}$ are essentially the same.

The magnitudes of $M^{(1)}_{1G}$ and $M^{(0)}_{0G}$ from Table 3 ($a_2 = 6 \cdot 5$ fm) are compared in Table 4 with the values extracted by Warburton (1986) from fits to the thick catcher data of Wilkinson and Alburger (1971), and with various shell model values. Also given are values obtained using the present approach to fit the thick catcher data published by Warburton (1986), but with energy calibrations that allow for the effect of the detector dead layer; as for the thin catcher data, the best fits are obtained for $a_2 \approx 6 \cdot 5$ fm, and the resultant parameter values are very similar to those of Table 3. The differences between the present values and Warburton's values in Table 4 are due essentially to the use of different channel radii and also to Warburton's use of $K = 0$ in equation (6)—his values are for $a_2 = 4 \cdot 5$ fm, for which K should be 1·88 (Barker 1988). The values Warburton obtained for $a_2 = 6 \cdot 75$ fm (given in his Table III) are very little different from ours for $a_2 = 6 \cdot 5$ fm and $K = 0 \cdot 21$. The shell model values of the large matrix element $M^{(0)}_{0G}$ are fairly consistent with one another and, if quenched by a factor of 0·9 as was found to be appropriate for p-shell nuclei (Wilkinson 1973), agree reasonably with the values obtained from the present fits. On the other hand $M_{1G}^{(1)}$ is small and the shell model values vary considerably; the larger values are found for interactions that seriously underestimate the separation of the first and second 2^+, $T=0$ states of ^{8}Be, so that the smaller shell model values are probably more reliable. Even with quenching, these values are larger than the present experimental values, and this may be due to inadequate allowance for the effects of α-clustering or distortion on the wavefunction of the lower 2^+ state (Goldhammer *et al.* 1968; Kumar 1974). The question of the relative sign of $M_{0G}^{(0)}$ and $M_{1G}^{(1)}$ is discussed in Barker (1988). The value of $M_{2G}^{(2)}$ in Table 3 may be attributed to about 1% admixture of the second 2^+, $T=0$ state of the lowest configuration into the intruder state (see the discussion in Barker 1969).

6. Summary

Many-level R-matrix fits have been made to the α–α scattering d-wave phase shift and to the α-spectra from ^{8}Li and ^{8}B β-decay measured by Wilkinson and Alburger with their thin catcher (and also with their thick catcher). There are some uncertainties in correcting the measured α-spectra for α-particle energy loss and smearing in the catcher and detector. The best simultaneous fits to the phase shift and the α-spectra data require a channel radius $a_2 \approx 6 \cdot 5$ fm, implying the existence of a 2^+ intruder state of ^{8}Be at about 9 MeV with a large width. This is in contrast to the recent analysis by Warburton (1986), who fitted the phase shift and the thick catcher α-spectra with $a_2 = 4 \cdot 5$ fm and an intruder state at 26 MeV or above. The large value of a_2 and low-lying intruder state obtained here are consequences of requiring the *same* parameter values in the fits to the two types of data. There is satisfactory agreement between the Gamow–Teller matrix elements extracted from the fits and shell model values.

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References

Ajzenberg-Selove, F. (1984). *Nucl. Phys.* A **413**, 1.
Alburger, D. E., Donovan, P. F., and Wilkinson, D. H. (1963). *Phys. Rev.* **132**, 334.
Bahcall, J. N., and Holstein, B. R. (1986). *Phys. Rev.* C **33**, 2121.
Barker, F. C. (1966). *Nucl. Phys.* **83**, 418.
Barker, F. C. (1969). *Aust. J. Phys.* **22**, 293.
Barker, F. C. (1971). *Aust. J. Phys.* **24**, 777.
Barker, F. C. (1972). *Aust. J. Phys.* **25**, 341.
Barker, F. C. (1988). *Aust. J. Phys.* **41**, 743.
Barker, F. C., Crawley, G. M., Miller, P. S., and Steele, W. F. (1976). *Aust. J. Phys.* **29**, 245.
Barker, F. C., Hay, H. J., and Treacy, P. B. (1968). *Aust. J. Phys.* **21**, 239.

Barker, F. C., and Warburton, E. K. (1988). *Nucl. Phys.* A **487**, 269.
Clark, G. J., Treacy, P. B., and Tucker, S. N. (1969). *Aust. J. Phys.* **22**, 663.
Cohen, S., and Kurath, D. (1965). *Nucl. Phys.* **73**, 1.
Goldhammer, P., Hill, J. R., and Nachamkin, J. (1968). *Nucl. Phys.* A **106**, 62.
Griffy, T. A., and Biedenharn, L. C. (1960). *Nucl. Phys.* **15**, 636.
Hauge, P. S., and Maripuu, S. (1973). *Phys. Rev.* C **8**, 1609.
Hinterberger, F., Eversheim, P. D., van Rossen, P., Schüller, B., Schönhagen, R., Thenée, M., Görgen, R., Braml, T., and Hartmann, H. J. (1978). *Nucl. Phys.* A **299**, 397.
Kumar, N. (1974). *Nucl. Phys.* A **225**, 221.
Matt, E., Pfander, H., Rieseberg, H., and Soergel, V. (1964). *Phys. Lett.* **9**, 174.
McKeown, R. D., Garvey, G. T., and Gagliardi, C. A. (1980). *Phys. Rev.* C **22**, 738.
Warburton, E. K. (1986). *Phys. Rev.* C **33**, 303.
Wilkinson, D. H. (1973). *Nucl. Phys.* A **209**, 470.
Wilkinson, D. H., and Alburger, D. E. (1971). *Phys. Rev. Lett.* **26**, 1127.

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