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A COMMENT ON THE $^7Be(p,\gamma)^8B$ CROSS SECTION AND THE SOLAR NEUTRINO PROBLEM

F.C. Barker and R.H. Spear

Research School of Physical Sciences
The Australian National University
Canberra.

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F.C. Barker and R.H. Spear

Research School of Physical Sciences
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Abstract

Evidence is presented which indicates that the accepted value for the cross section of the $^7Be(p,\gamma)^8B$ reaction at stellar energies is probably too large. It is suggested that the accepted value of the $^7Li(d,p)^8Li$ cross section, which has been used for normalization purposes, is too large; that the accepted value for the ratio of the $^7Be(p,\gamma)^8B$ and $^7Li(d,p)^8Li$ cross sections is too large; and that the energy dependence used to extrapolate to stellar energies from the higher energies at which measurements have been made is inaccurate. The consequent reduction of the $^7Be(p,\gamma)^8B$ cross section by about 30% would not be sufficient to resolve the solar neutrino problem but would significantly lessen the discrepancy between observation and calculation.

Subject headings: nuclear reactions - neutrinos - Sun : interior

I. Introduction

The discrepancy by a factor of about three between the observed flux of solar neutrinos (2.1 ± 0.3 SNU, 1σ error) and the currently accepted calculated value (5.8 ± 2.2 SNU, 3σ error) constitutes the solar neutrino problem (Bahcall et al. 1985). The calculated flux depends on the rates for the various nuclear reactions contributing to neutrino production in the sun. In the past few years, much effort has been expended on studying one of these reactions, $^{3}He(\alpha,\gamma)^{7}Be$ (see Alexander et al. 1984, Skelton and Kavanagh 1984, and references therein), without leading to any appreciable change in the calculated flux, whereas another important reaction, $^{7}Be(p,\gamma)^{8}B$, has received comparatively little attention. The decay of the ^{8}B produced in this reaction provides high-energy neutrinos that contribute 74% of the calculated neutrino capture rate in the ^{37}Cl detector (Bahcall et al. 1985). This calculated capture rate depends sensitively on the low-energy cross section of the $^{7}Be(p,\gamma)^{8}B$ reaction, essentially through the zero-energy cross section factor $S_{17}(0)$, but measurements are not practicable at the low energies required and existing models are not trusted for an accurate calculation. The normal procedure has been to use a calculated energy dependence to extrapolate to low energies the cross section measured at higher energies.

Several years ago, Barker (1980) gave reasons for believing that the then-adopted value of $S_{17}(0) = 0.030 \pm 0.0027$ keV b was too high and consequently exaggerated the discrepancy in the solar neutrino problem. Since then the adopted value has come down to its present value of $S_{17}(0) = 0.0238 \pm 0.0023$ keV b (Filippone et al. 1983b; Bahcall et al. 1985), leading to a reduction of about 1 SNU in the calculated flux. Most of the reduction in $S_{17}(0)$ can be attributed to a reduction in the $^{7}Li(d,p)^{8}Li$ cross section, which has been used for normalizing most measurements of the $^{7}Be(p,\gamma)^{8}B$ cross section. Values of the $^{7}Li(d,p)^{8}Li$ cross section are usually quoted for the resonance at $E_d \approx 0.77$ MeV and are denoted by σ_{dp}. The currently accepted value of $S_{17}(0)$ is based on the value $\sigma_{dp} = 157 \pm 10$ mb (Filippone et al. 1983b). The energy dependence assumed for extrapolation purposes has been that calculated by Tombrello (1965).

In the next section we discuss values of the $^7Li(d,p)^8Li$ cross section σ_{dp}. Section III considers the ratio of the $^7Be(p,\gamma)^8B$ cross section to the $^7Li(d,p)^8Li$ cross section, and section IV the calculated energy dependence of the $^7Be(p,\gamma)^8B$ cross section. We finally discuss the significance of these considerations.

II. The $^7Li(d,p)^8Li$ cross section

Measured values of σ_{dp} together with the values used by Filippone et al. (1982,1983b) in obtaining the adopted mean value are given in Table 1. Filippone et al. excluded the early measurements (Baggett and Bame 1952; Bashkin 1954) because of their large uncertainties, and the measurement of Parker (1966) because it lies 2.8 standard deviations above the weighted mean. The measured value from Kavanagh (1960) was reduced by 7.5% to take account of changes in the $^7Li(p,p)^7Li$ cross section (Warters et al. 1953), which Kavanagh had used for normalizing his results, due to a renormalization (Ford 1964; Brown et al. 1973) and a remeasurement (Lerner and Marion 1969). The precision claimed by Schilling et al. (1976) was considered by Filippone et al. (1982) to be unreasonably high, and the uncertainty that they quoted was doubled. The weighted mean of these values is then 157 ± 6 mb, and Filippone et al. (1983b) increased the uncertainty to 10 mb to take account of systematic errors.

Some comments on the earlier measured values in Table 1 (Baggett and Bame 1952; Bashkin 1954; Kavanagh 1960; Parker 1966; McClenahan and Segel 1975; Schilling et al. 1976) have already been made (Barker 1980).

Additional comments follow. Almost all the (used) values of σ_{dp} in Table 1 are based ultimately on the measurement by Bader et al. (1956) of the absolute stopping cross section for protons in lithium. The connections are shown in Figure 1. McClenahan and Segel (1975) presumably used the same stopping cross section in obtaining the Li content of their LiF target, although they do not say so. Schilling et al. (1976) took their target thickness as that quoted by the supplier of their targets, but give no information on how this was obtained.

Bader et al. (1956) claimed an accuracy of 3% in their measurements. Apparently no other absolute measurements of the stopping cross section for hydrogen in lithium have been made; however, Andersen and Ziegler (1977) comment that the values of Bader et al. for many (but not all) other targets appear to be high. One would not expect the lithium results to be exceptional in their reliability, since lithium targets are notorious for stability and composition problems.

Recently there has been a determination of the ^{7}Li(d,p)^{8}Li cross section by Haight et al. (1985), which avoided the problem of lithium targets by using a ^{7}Li beam and a deuterated polyethylene target. They obtained $\sigma = 155 \pm 20$ mb at $E_{^7Li} = 12.2 \pm 1.3$ MeV, corresponding to $E_d = 3.4 \pm 0.4$ MeV. Previous measurements at these energies were made by McClenahan and Segel (1975), who found $\sigma \approx 195$ mb, and Mingay (1979), with $\sigma \approx 255$ mb. (Bashkin 1954 does not claim reliability for his measurements for $E_d \gtrsim 2.1$ MeV.) Now these measurements, and other measurements where they overlap in energy (Baggett and Bame 1952; Kavanagh 1960; Schilling et al. 1976), have essentially the same energy dependence, differing only in absolute magnitude (see Mingay 1979, Figure 6); if this energy dependence is used to extrapolate the measured value of Haight et al. down to $E_d = 0.77$ MeV, one finds $\sigma_{dp} \approx 110 \pm 15$ mb, which is very much less than the adopted value.

In summary, most if not all of the conventional measurements of σ_{dp} used to obtain the currently accepted value depend on the accuracy of the absolute stopping cross sections of Bader et al. (1956). The most recent and apparently the most reliable of these measurements (Elwyn et al. 1982; Filippone et al. 1982) give values of σ_{dp} lower than the accepted value, as does the one independent measurement (Haight et al. 1985). The average of these three measurements is $\sigma_{dp} = 138 \pm 8$ mb, some 12% less than the accepted value.

III. Ratio of the $^7Be(p,\gamma)^8B$ and $^7Li(d,p)^8Li$ cross sections

Most measurements of the $^7Be(p,\gamma)^8B$ cross section (Kavanagh 1960; Parker 1966, 1968; Kavanagh et al. 1969; Kavanagh 1972; Vaughn et al. 1970; Filippone et al. 1983a,b) have obtained absolute values by normalization to the $^7Li(d,p)^8Li$ cross section σ_{dp}. Of the others, Wiezorek et al. (1977) determined the ^7Be areal density in their target by measuring the yield of 478 keV γ-rays, which are emitted following the radioactive decay of ^7Be to the first excited state of ^7Li, and Filippone et al. (1983a,b) also used this method as well as one dependent on σ_{dp}. In Figure 2, all the measurements made relative to σ_{dp} are shown, as values of the S factor, normalized to the same value $\sigma_{dp} = 157$ mb.[1] The error bars do not contain any contribution

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[1]The values in Figure 2 attributed to Filippone et al. (1983a,b) are 1.06 times those given in Figure 3 of Filippone et al. (1983a) and Figure 8 of Filippone et al. (1983b), which correspond to $\sigma_{dp} \approx 148$ mb.

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due to uncertainty in the value of σ_{dp}. Thus any discrepancies in Figure 2 are due to differences in the measured ratio of the $^7Be(p,\gamma)^8B$

and $^7Li(d,p)^8Li$ cross sections. The curves in Figure 2 are discussed in the next section.

All the measurements in Figure 2 seem to be more or less consistent with the same energy dependence. The absolute measurements of Parker (1966,1968) and of Kavanagh et al. (1969) and Kavanagh (1972) are in good agreement with one another, while those of Kavanagh (1960), Vaughn et al. (1970), and Filippone et al. (1983a,b) are also in agreement with one another, but the values of the first group are about 30% greater than those of the second group. This applies to the resonant contribution at $E_p \approx 0.73$ MeV as well as to the non-resonant contribution. The size of the resonant contribution may be represented by the radiation width Γ_γ for the M1 transition from the first excited state of ^8B to the ground state, the values of which for the present normalization are $\Gamma_\gamma = 0.037 \pm 0.019$ eV (Parker 1966,1968) and 0.038 ± 0.003 eV (Kavanagh et al. 1969; Kavanagh 1972) from the first group, and $\Gamma_\gamma = 0.025 \pm 0.004$ eV (Filippone et al. 1983a,b) from the second group. The non-resonant contribution may be represented by the values of $S_{17}(0)$, provided the same energy dependence is assumed, say that of Tombrello (1965), and such values are given[2] in Table 1 of Filippone

[2]Vaughn et al. (1970) analysed their data in two ways, in which different assumptions were made about the resonant contributions. Filippone et al. (1983a,b) use only the result of the first analysis $S_{17}(0) = 0.0214 \pm 0.0022$ keV b ; the corresponding value from the second analysis $S_{17}(0) = 0.0184 \pm 0.0035$ keV b is omitted without comment, in spite of the fact that Vaughn et al. considered it the better value; Kavanagh (1982) also omitted it in a similar summary. Actually we agree that the

second value should not be used, because it was based on the assumption of a broad s-wave resonance at $E_p = 3.8$ MeV, additional to the nonresonant part that was assumed to have the Tombrello energy dependence; such a resonance would also contribute to $S_{17}(0)$, and the analogue resonance in the mirror $^7Li + n$ system would invalidate the fits to data made by Tombrello (1965).

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et al. (1983a) and Figure 9 of Filippone et al. (1983b); however the values as presented obscure the discrepancies between the various measurements because the uncertainties shown all include a common component which allows for the uncertainty in the normalizing cross section σ_{dp}.

Of the two measurements not based on the value of σ_{dp}, that of Filippone et al. (1983a,b) may be considered as an indirect measurement of σ_{dp}; equating the ^7Be areal densities that Filippone et al. obtained by their two different methods gives $\sigma_{dp} = 147 \pm 19$ mb, in excellent agreement with their own direct measurements (Elwyn et al. 1982; Filippone et al. 1982) and consistent with the adopted mean (see Table 1). In the other measurement, Wiezorek et al. (1977) found $S_{17}(E_p = 0.36$ MeV$) = 0.039 \pm 0.010$ keV b, which is seen to lie well above the other measurements in Figure 2. Comments on the analysis of this experiment have been made by Barker (1980) and Kavanagh (1982).

In discussing the $^7Be(p,\gamma)^8B$ cross section measurements, Bahcall et al. (1982) commented that the target matrix in the experiment of Vaughn et al. (1970) was much thicker and the α-particle resolution much poorer than in the experiments of Parker (1966) or Kavanagh et al. (1969), giving data that were "more difficult to analyse cleanly and reliably". This, together with the good agreement between the results of Parker and Kavanagh et al., led to the results of Vaughn et al. being omitted from the averaging process by Bahcall et al. (1982) and even, in earlier discussions by Parker (1973,1978), to them being neglected entirely. In the recent experiment by Filippone et al. (1983a,b), the ^{7}Be areal density of the target was about ten times that for the experiment of Parker (1966), enabling shorter runs and consequently less severe problems from background and from carbon buildup on the target (≤ 3 keV as compared with 77 keV). Thus one would expect the results of Filippone et al. to be more reliable than those of Parker. The fact that the work of Kavanagh et al. (1969), apart from its results (Kavanagh 1972), is still unpublished makes it more or less immune from detailed criticism. It has been accepted because of the reputation and authority of its authors and the institute to which they belong.

The accepted value of $S_{17}(0)$ was obtained by using for the ratio of the $^{7}Be(p,\gamma)^{8}B$ and $^{7}Li(d,p)^{8}Li$ cross sections an average value from both groups of measurements, in spite of the fact that the magnitudes in the two groups are apparently inconsistent with one another. Bahcall et al. (1982) selected only the upper group; it now seems preferable to select the lower group, which contains the measurement (Filippone et al. 1983a,b) that appears to be the most reliable, so obtaining a reduction of $S_{17}(0)$ from the accepted value by about 10%.

IV. Energy dependence of the $^{7}Be(p,\gamma)^{8}B$ cross section

Almost all extrapolations of the measured $^{7}Be(p,\gamma)^{8}B$ cross section to low energies have been made assuming that the non-resonant contribution has the energy dependence calculated by Tombrello (1965). He used a direct-capture model in which the optical-potential parameters for the initial $^{7}Be + p$ system and the spectroscopic factors of the final ^{8}B state were assumed to be the same as for the mirror $^{7}Li + n$ system, so that they could be obtained by fitting experimental data for the reactions $^7Li(n,n)^7Li$ and $^7Li(n,\gamma)^8Li$. Tombrello included contributions from s-wave protons only. Some criticisms of this calculation have been made previously. Aurdal (1970) pointed out that it is more reasonable to choose deeper potentials corresponding to 2s nucleons rather than 1s nucleons as assumed by Tombrello. Robertson (1973) showed that, although s-wave proton contributions dominate the $^7Be(p,\gamma)^8B$ cross section at solar energies, contributions from d-wave protons can be appreciable at laboratory energies and therefore need to be taken into account in fitting the data. Both of these defects of Tombrello's calculation were corrected in the calculation by Barker (1980), which otherwise essentially used Tombrello's approach but with new ^7Li+n data. Additional comments on the calculations of Tombrello, Aurdal and Robertson are given by Barker (1980).[3]

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[3] An additional problem concerning Tombrello's numerical values of S_{17} at very low energies has been pointed out recently (Barker 1983). Fits to data using the energy dependence attributed to Tombrello have given the zero-energy logarithmic derivative of S_{17} as $(1/S\ dS/dE)_0 \equiv a = -1.0\ MeV^{-1}$ (Parker 1966; Kavanagh 1972,1982; Bahcall et al. 1982), whereas calculations using Tombrello's parameter values have given $a = -2.0\ MeV^{-1}$ (Barker 1983). The latter calculations give values of S_{17} that agree reasonably with the published values in Figure 3 of Tombrello (1965) for $E_p \geq 0.15$ MeV, but are appreciably larger as $E_p \to 0$; these calculated values agree less well with the energy dependence attributed to Tombrello by others.

In Barker (1980), since the standard parameter set did not fit the ^7Li+n data and in particular the thermal neutron capture cross section, several modified parameter sets that did were given. These led to a variety of $^7Be(p,\gamma)^8B$ cross sections, but the differences were mainly in the absolute values while the energy dependences were rather similar. Relative to the energy dependence attributed to Tombrello, Barker's s-wave contribution decreases with increasing energy, as Robertson (1973) found in his calculations, but the total S factor increases with energy, due to the increase in the relative d-wave contribution, which is 6% at zero energy, 19% at 0.3 MeV, and 82% at 4 MeV (Barker 1980). Thus the values of $S_{17}(0)$ obtained using Barker's energy dependence are smaller than those from Tombrello's when the same data are fitted. For their data, Filippone et al. (1983b) found the reduction to be 10-15%. The curves in Figure 2 show fits to these data, which extend up to $E_p = 1.4$ MeV only, using the energy dependences of Tombrello and of Barker, the latter being for the standard parameter set with a normalization factor of 0.84. The extension of the Tombrello curve to 4 MeV uses his suggested linear extrapolation (see Vaughn et al. 1970). The data of Filippone et al. are better fitted by the energy dependence of Tombrello, but it is seen that this fails to follow the trend of the higher energy data, even when one allows for a resonance contribution at $E_p \approx 2.5$ MeV, whereas the Barker energy dependence does. Since the latter has more justification than that of Tombrello, it seems more reasonable to use it, so obtaining values of $S_{17}(0)$ smaller by about 12% than those hitherto obtained.

V. Discussion

The error assigned to the presently accepted value of $S_{17}(0)$ is about 10%. Thus changes to $S_{17}(0)$ of the order of 10% would be significant. In each of the preceding three sections, we have seen that reductions of this order are not only plausible but are eminently justifiable. These three reductions, of about 12%, 10%, and 12%, are independent, leading to a net reduction of about 30%, giving $S_{17}(0) \approx 0.017$ keV b. Such a value would reduce the capture rate of solar neutrinos from the presently predicted value (Bahcall et al. 1985) of 5.8 ± 2.2 SNU (effective 3σ limits) to about 4.5 SNU, so reducing by a significant amount the discrepancy with the observed rate (Bahcall et al. 1985) of 2.1 ± 0.3 SNU (1σ error).

In the above considerations, we have used experimental data and the calculated energy dependence of the $^7Be(p,\gamma)^8B$ cross section, but have not mentioned the calculated absolute value of this cross section. By using parameter values that fitted $^7Li + n$ data, Barker (1980) calculated $S_{17}(0)$ values ranging from 0.014 to 0.022 keV b, in good agreement with the experimental value suggested above. Also shell model values of $\Gamma_\gamma = 0.019 - 0.021$ eV (see Table 3 of Barker 1980) agree well with the similarly adjusted experimental value $\Gamma_\gamma = 0.023 \pm 0.004$ eV.

It seems unlikely that the values suggested here will be accepted before more work is done. It is to be hoped that new measurements of the $^7Be(p,\gamma)^8B$ cross section will be made using radioactive ion beam facilities (Boyd et al. 1983; Haight et al. 1983,1985). In the meantime, a new measurement should be made of the stopping cross section for hydrogen in lithium.

Table 1

Values of the $^{7}Li(d,p)^{8}Li$ cross section at the 0.77 MeV resonance

σ_{dp} (mb) Measured	Used (1)	Reference
230		2
150 ± 38		3
176 ± 15	163 ± 15	4
211 ± 15		5
138 ± 20	138 ± 20	6
181 ± 8	181 ± 16	7
174 ± 16	174 ± 16	8
146 ± 13	146 ± 13	9
148 ± 12	148 ± 12	10
	157 ± 10	Adopted mean (1)

References. - (1) Filippone et al. 1983b. (2) Baggett and Bame 1952. (3) Bashkin 1954. (4) Kavanagh 1960. (5) Parker 1966. (6) McClenahan and Segel 1975. (7) Schilling et al. 1976. (8) Mingay 1979. (9) Elwyn et al. 1982. (10) Filippone et al. 1982.

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Figure captions

Fig.1. Connections between $^7Li(d,p)^8Li$ cross section measurements and the stopping cross section measurement of Bader et al. (1956). (Lerner and Marion also determined their target thickness by weighing but gave this measurement only one third of the weight given to that based on the stopping cross section; they also referred to the calculated stopping cross sections of Williamson and Boujot 1962.)

Fig.2. 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. For the sake of clarity, the error bars on some Kavanagh et al. points are omitted. The curves are calculated nonresonant fits to the data of Filippone et al. using two different energy dependences: full curve, Tombrello (1965); dashed curve, Barker (1980).

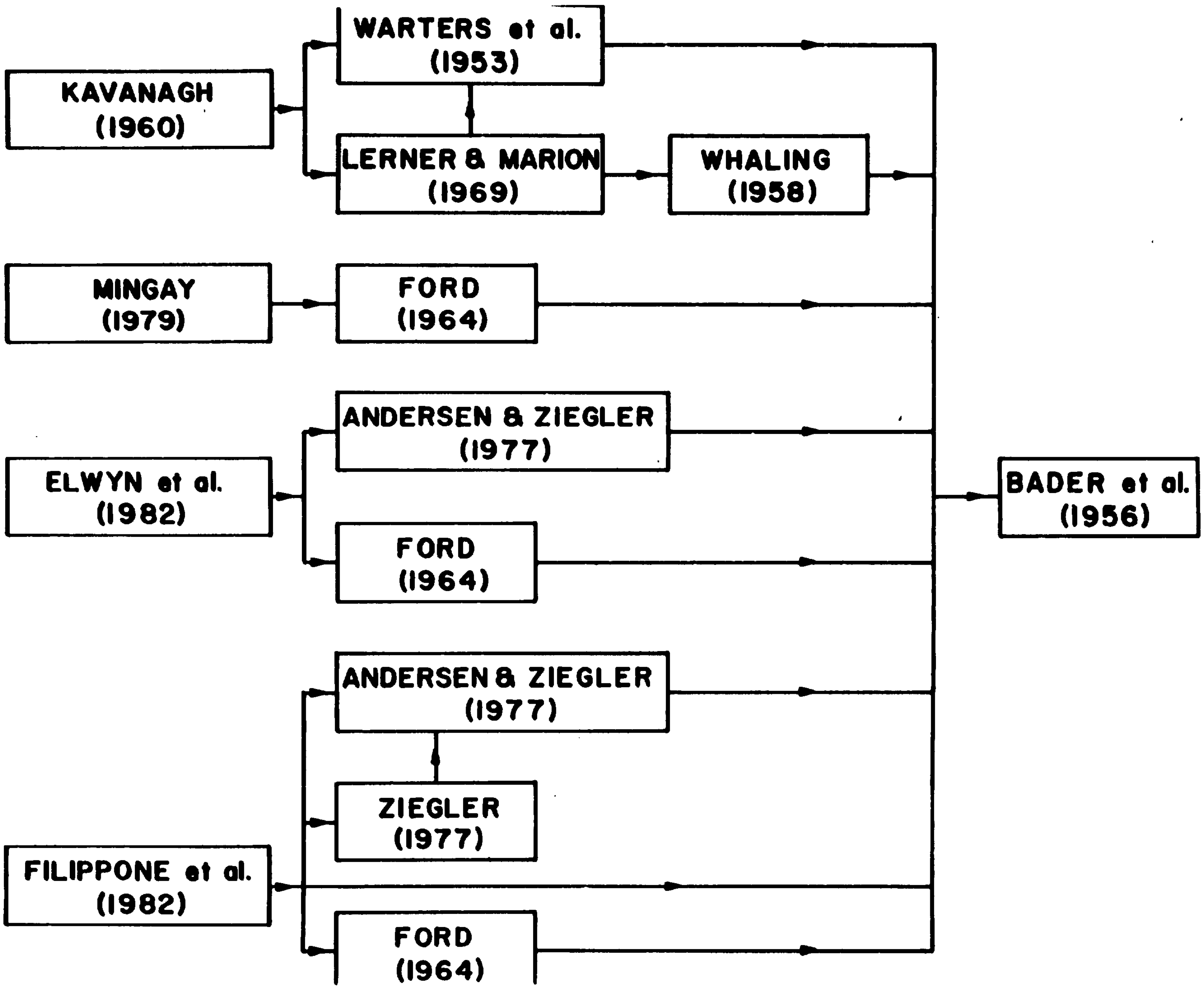
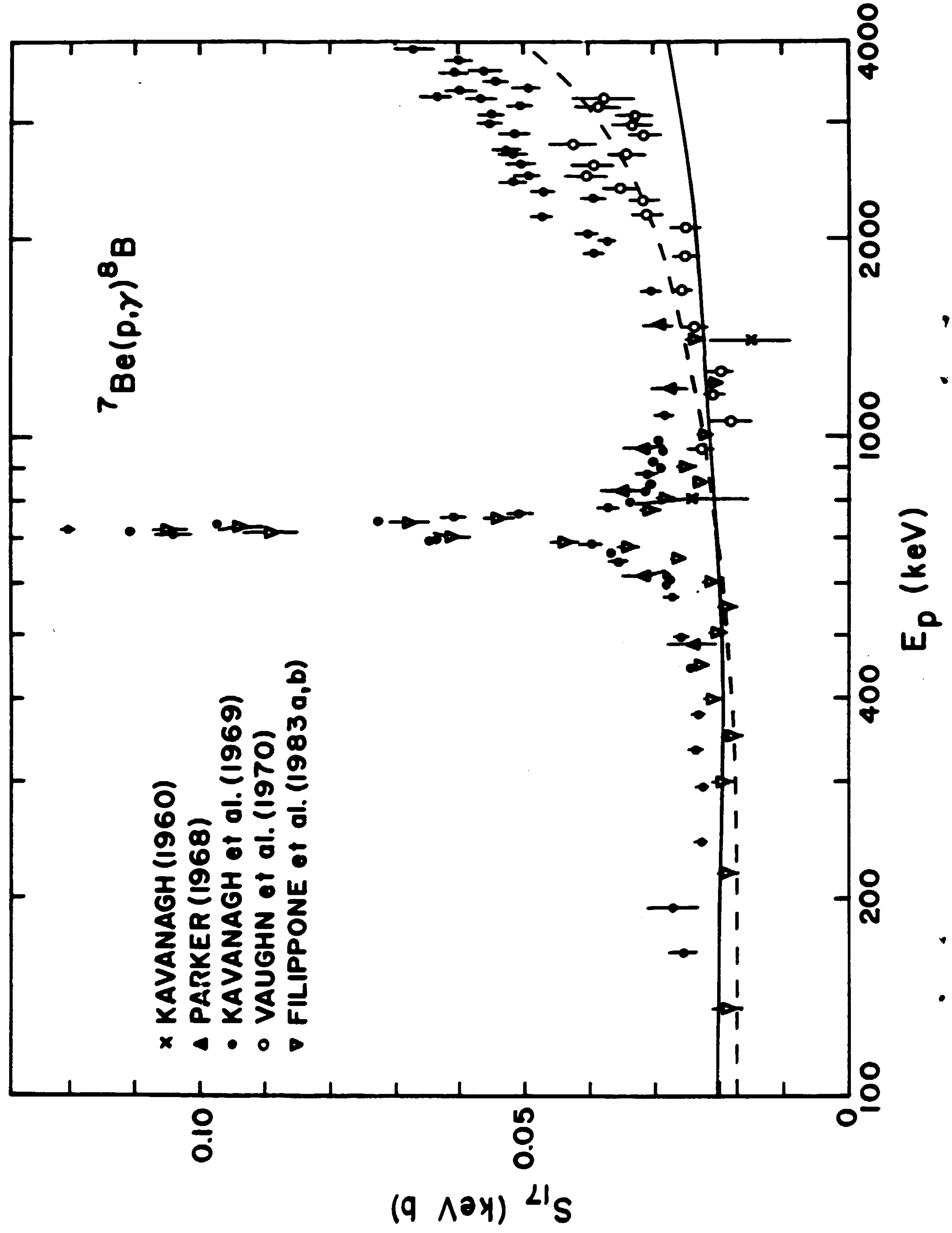

KAVANAGH (1960)
WARTERS et al. (1953)
LERNER & MARION (1969)
WHALING (1958)
MINGAY (1979)
FORD (1964)
ELWYN et al. (1982)
ANDERSEN & ZIEGLER (1977)
FORD (1964)
BADER et al. (1956)
ANDERSEN & ZIEGLER (1977)
ZIEGLER (1977)
FILIPPONE et al. (1982)
FORD (1964)

Figure 1



$^7Be(p,\gamma)^8B$
× KAVANAGH (1960)
▲ PARKER (1968)
• KAVANAGH et al. (1969)
○ VAUGHN et al. (1970)
▼ FILIPPONE et al. (1983a,b)
S_{17} (keV b)
0.10
0.05
0
100
200
400
1000
2000
4000
E_p (keV)

Figure 2