Solar Fusion Cross Sections

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We review and analyze the available information for nuclear fusion cross sections that are most important for solar energy generation and solar neutrino production. We provide best values for the low-energy cross-section factors and, wherever possible, estimates of the uncertainties. We also describe the most important experiments and calculations that are required in order to improve our knowledge of solar fusion rates.

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I. INTRODUCTION

This section describes in Sec. I A the reasons why a critical analysis of what is known about solar fusion reactions is timely and important, summarizes in Sec. I B the process by which this collective manuscript was written , and provides in Sec. I C a brief outline of the structure of the paper.

A. Motivation

The original motivation of solar neutrino experiments was to use the neutrinos "..to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars" (Bahcall, 1964; Davis, 1964). This goal has now been achieved by four pioneering experiments: Homestake (Davis, 1994), Kamiokande (Fukuda *et al.*, 1996), GALLEX (Kirsten *et al.*, 1997), and SAGE (Gavrin *et al.*, 1997). These experiments provide direct evidence that the stars shine and evolve as the result of nuclear fusion reactions among light elements in their interiors.

Stimulated in large part by the precision obtainable in solar neutrino experiments and by solar neutrino calculations with standard models of the sun, our knowledge of the low-energy cross sections for fusion reactions among light elements has been greatly refined by many hundreds of careful studies of the rates of these reactions. The rate of progress was particularly dramatic in the first few years following the proposal of the chlorine (Homestake) experiment in 1964.

In 1964, when the chlorine solar neutrino experiment was proposed (Davis, 1964; Bahcall, 1964), the rate of the ^{3}He-^{3}He reaction was estimated (Good, Kunz, and Moak, 1954; Parker, Bahcall, and Fowler, 1964) to be 5 times slower than the current best estimate and the uncertainty in the low-energy cross section was estimated (Parker, Bahcall, and Fowler, 1964) to be "as much as a factor of 5 or 10." Since the ^{3}He-^{3}He reaction competes with the ^{3}He-^{4}He reaction—which leads to high energy neutrinos—the calculated fluxes for the higher energy neutrinos were overestimated in the earliest days of solar neutrino research. The most significant uncertainties, in the rates of the ^{3}He-^{3}He, the ^{3}He-^{4}He, and the ^{7}Be-p

reactions, were much reduced after just a few years of intensive experimental research in the middle and late 1960s (Bahcall and Davis, 1982).

Over the past three decades, steady and impressive progress has been made in refining the rates of these and other reactions that produce solar energy and solar neutrinos. (For reviews of previous work on this subject, see, e.g., Fowler, Caughlan, and Zimmerman, 1967, 1975; Bahcall and Davis, 1982; Clayton, 1983; Fowler, 1984; Parker, 1986; Rolfs and Rodney, 1988; Caughlan and Fowler, 1988; Bahcall and Pinsonneault, 1992, 1995; Parker and Rolfs, 1991). An independent assessment of nuclear fusion reaction rates is being conducted by the European Nuclear Astrophysics Compilation of Reaction Rates (NACRE) (see, e.g., Angulo, 1997); the results from this compilation, which has broader goals than our study and in particular does not focus on precision solar rates, are not yet available.

However, an unexpected development has occurred. The accuracy of the solar neutrino experiments and the precision of the theoretical predictions based upon standard solar models and standard electroweak theory have made possible extraordinarily sensitive tests of new physics, of physics beyond the minimal standard electroweak model. Even more surprising is the fact that, for the past three decades, the neutrino experiments have consistently disagreed with standard predictions, despite concerted efforts by many physicists, chemists, astronomers, and engineers to find ways out of this dilemma.

The four pioneering solar neutrino experiments together provide evidence for physics beyond the standard electroweak theory. The Kamiokande (Fukuda *et al.*, 1996) and the chlorine (Davis, 1994) experiments appear to be inconsistent with each other if nothing happens to the neutrinos after they are created in the center of the sun (Bahcall and Bethe, 1990). Moreover, the well calibrated gallium solar neutrino experiments GALLEX (Kirsten *et al.*, 1997), and SAGE (Gavrin *et al.*, 1997) are interpreted, if neutrinos do not oscillate or otherwise change their states on the way to the earth from the solar core, as indicating an almost complete absence of ^{7}Be neutrinos. However, we know [see discussion of Eq. (25) in Sec. VII] that the ^{7}Be neutrinos must be present, if there is no new electroweak physics occurring, because of the demonstration that ^{8}B neutrinos are observed by the Kamiokande solar neutrino experiment. Both ^{7}Be and ^{8}B neutrinos are produced by capture on ^{7}Be ions.

New solar neutrino experiments are currently underway to test for evidence of new physics with exquisitely precise and sensitive techniques. These experiments include a huge pure water Cerenkov detector known as Super-Kamiokande (Suzuki, 1994; Totsuka, 1996), a kiloton of heavy water, SNO, that will study both neutral and charged currents (Ewan *et al.*, 1987, 1989; McDonald, 1995), a large organic scintillator, BOREXINO, that will investigate lower energy neutrinos than has previously been possible (Arpesella *et al.*, 1992; Raghavan, 1995), and a 600 ton liquid argon time projection chamber, ICARUS, that will provide detailed information on the surviving ^{8}B ν_e flux (Rubbia, 1996; ICARUS collaboration, 1995; Bahcall *et al.*, 1986). With these new detectors, it will be possible to search for evidence of new physics that is independent of details of solar model predictions. [Discussions of solar neutrino experiments and the related physics and astronomy can be found at, for example, http://www.hep.anl.gov/NDK/Hypertext/nuindustry.html, http://neutrino.pc.helsinki.fi/neutrino/, and http://www.sns.ias.edu/ jnb .]

However, our ability to interpret the existing and new solar neutrino experiments is limited by the imprecision in our knowledge of the relevant nuclear fusion cross sections. To cite the most important example, the calculated rate of events in the Super-Kamiokande and SNO solar neutrino experiments is directly proportional to the rate measured in the laboratory at low energies for the ^{7}Be$(p,\gamma)^8$B reaction. This reaction is so rare in the sun, that the assumed rate of ^{7}Be$(p,\gamma)^8$B has only a negligible effect on solar models and therefore on the structure of the sun. The predicted rate of neutrino events in the interval 2 MeV to 15 MeV is directly proportional to the measured laboratory rate of the ^{7}Be$(p,\gamma)^8$B reaction. Unfortunately, the low-energy cross-section factor for the production of ^{8}B is the least well known of the important cross sections in the *pp* chain.

We will concentrate in this review on the low-energy cross section factors, S, that determine the rates for the most important solar fusion reactions. The local rate of a non-resonant fusion reaction can be written in the following form (see, e.g., Bahcall, 1989):

$$\langle \sigma v \rangle = 1.3005 \times 10^{-15} \left[\frac{Z_1 Z_2}{A T_6^2} \right]^{1/3} f S_{\rm eff} \ \exp\left(-\tau\right) \ {\rm cm}^3 \ {\rm s}^{-1}. \tag{1}$$

Here Z_1, Z_2 are the nuclear charges of the fusing ions, A_1,A_2 are the atomic mass numbers, A the reduced mass $A_1 A_2/(A_1 + A_2)$, T_6 is the temperature in units of 10^6 K, and the cross-section factor $S_{\rm eff}$ (defined below) is in keV b. The most probable energy, E_0, at which the reaction occurs is

$$\begin{aligned} E_0 &= \left[(\pi \alpha Z_1 Z_2 kT)^2 (m A c^2/2) \right]^{1/3} \\ &= 1.2204 (Z_1^2 Z_2^2 A T_6^2)^{1/3} \ {\rm keV}. \end{aligned} \tag{2}$$

The energy E_0 is also known as the Gamow energy. The exponent τ that occurs in Eq. (1) dominates the temperature dependence of the reaction rate and is given by

$$\tau = 3E_0/kT = 42.487 \left(Z_1^2 Z_2^2 A T_6^{-1} \right)^{1/3}. \tag{3}$$

For all the important reactions of interest in solar fusion, τ is in the range 15 to 40. The quantity f is a correction factor due to screening first calculated by Salpeter (1954) and discussed in this paper in Sec. II C. The quantity S_{eff} is the effective cross section factor for the fusion reaction of interest and is evaluated at the most probable interaction energy, E_0. To first order in τ^{-1} (Bahcall, 1966),

$$S_{\rm eff} = S(E_0)\left\{1 + \tau^{-1}\left[\frac{5}{12} + \frac{5S'E_0}{2S} + \frac{S''E_0^2}{S}\right]_{E=E_0}\right\}. \tag{4}$$

Here $S' = {\rm d}S/{\rm d}E$. In most analyses in the literature, the values of S and associated derivatives are quoted at zero energy, not at E_0. In order to relate (4) to the usual formulae, one must express the relevant quantities in terms of their values at $E = 0$. The appropriate connection is

$$S_{\rm eff}(E_0) \simeq$$
$$S(0)\left[1 + \frac{5}{12\tau} + \frac{S'\left(E_0 + \frac{35}{36}kT\right)}{S} + \frac{S''E_0}{S}\left(\frac{E_0}{2} + \frac{89}{72}kT\right)\right]_{E\,=\,0}. \tag{5}$$

In some contexts, $S_{\rm eff}(E_0)$ is referred to as simply the 'S-factor' or 'the low-energy S-factor'.

For standard solar models (cf. Bahcall, 1989), the fusion energy and the *pp* neutrino flux are generated over a rather wide range of temperatures, $8 < T_6 < 16$. The other important fusion reactions and neutrino fluxes are generated over a more narrow range of physical conditions. The ^{8}B neutrino flux is created in the most restricted temperature range, $13 < T_6 < 16$. The mass density (in g cm^{-3}) is given approximately by the relation $\rho = 0.04 T_6^3$ in the temperature range of interest.

The approximate dependences of the solar neutrino fluxes on the different low-energy nuclear cross-section factors can be calculated for standard solar models. The most important fluxes for solar neutrino experiments that have been carried out so far, or which are currently being constructed, are the low energy neutrinos from the fundamental *pp* reaction, ϕ(pp), the intermediate energy ^{7}Be line neutrinos, $\phi(^7{\rm Be})$, and the rare high-energy neutrinos from ^{8}B decay, $\phi(^8{\rm B})$. The *pp* neutrinos are the most abundant experimentally-accessible solar neutrinos and the ^{8}B neutrinos have the smallest detectable flux, according to the predictions of standard models (Bahcall, 1989).

Let S_{11}, S_{33}, and S_{34} be the low-energy, nuclear cross-section factors (defined in Sec. II A) for the *pp*, $^3{\rm He} + {^3{\rm He}}$, and $^3{\rm He} + {^4{\rm He}}$ reactions and let S_{17} and S_{e^-7} be the cross-section factors for the capture by ^{7}Be of, respectively, protons and electrons. Then (Bahcall 1989)

$$\phi(pp) \propto S_{11}^{0.14}\, S_{33}^{0.03}\, S_{34}^{-0.06}\ , \tag{6a}$$

$$\phi(^7{\rm Be}) \propto S_{11}^{-0.97}\, S_{33}^{-0.43}\, S_{34}^{0.86}\ , \tag{6b}$$

and

$$\phi(^8\mathrm{B}) \propto S_{11}^{-2.6}\, S_{33}^{-0.40}\, S_{34}^{0.81}\, S_{17}^{1.0}\, S_{e^-7}^{-1.0} \; . \tag{6c}$$

Nuclear fusion reactions among light elements both generate solar energy and produce solar neutrinos. Therefore, the observed solar luminosity places a strong constraint on the current rate of solar neutrino generation calculated with standard solar models. In addition, the shape of the neutrino energy spectrum from each neutrino source is unaffected, to experimental accuracy, by the solar environment. A good fit to the results from current solar neutrino experiments is not possible, independent of other, more model-dependent solar issues provided nothing happens to the neutrinos after they are created in the sun (see, e.g., Castellani *et al.* 1997; Heeger and Robertson, 1996; Bahcall, 1996; Hata, Bludman, and Langacker, 1994, and references therein).

But, the ultimate limit of our ability to extract astronomical information and to infer neutrino parameters will be constrained by our knowledge of the spectrum of neutrinos created in the center of the sun. Returning to the example of the ^{8}B neutrinos, the total flux (independent of flavor) of these neutrinos will be measured in the neutral current experiment of SNO, and–using the charged current measurements of SNO and ICARUS–in Super-Kamiokande. This total flux is very sensitive to temperature, $\phi(^8\mathrm{B}) \sim S_{17} T^{24}$ (Bahcall and Ulmer, 1996), where T is the central temperature of the sun. Therefore, our ability to test solar model calculations of the central temperature profile of the sun is limited by our knowledge of S_{17}.

Existing or planned solar neutrino experiments are expected to determine whether the energy spectrum of electron type neutrinos created in the center of the sun is modified by physics beyond standard electroweak theory. Moreover, these experiments have the capability of determining the mechanism, if any, by which new physics is manifested in solar neutrino experiments and thereby determining how the original neutrino spectrum is altered by the new physics. Once we reach this stage, solar neutrino experiments will provide precision tests of solar model predictions for the rates at which nuclear reactions occur in the sun.

After the neutrino physics is understood, neutrino experiments will determine the average ratio in the solar interior of the ^{3}He-^{3}He reaction rate to the rate of the ^{3}He-^{4}He reaction. This solar ratio of reaction rates, R_{33}/R_{34}, can be inferred directly from the measured total flux of ^{7}Be and *pp* neutrinos (Bahcall, 1989). The comparison of the measured and the calculated ratio of R_{33}/R_{34} will constitute a stringent and informative test of the theory of stellar interiors and nuclear energy generation. In order to extract the inherent information about the solar interior from the measured ratio, we must know the nuclear fusion cross sections that determine the branching ratios among the different reactions in the *pp* chain.

B. The origin of this work

This paper originated from our joint efforts to critically assess the state of the nuclear physics important to the solar neutrino problem. There are two motivations for taking on such a task at this time. First, we have entered a period where the sun, and solar models, can be probed with unprecedented precision through neutrino flux measurements and helioseismology. It is therefore important to assess how uncertainties in our understanding of the underlying nuclear physics might affect our interpretation of such precise measurements. Second, as the importance of the solar neutrino problem to particle physics and astrophysics has grown, so has also the size of the community interested in this problem. Many of the interested physicists are unfamiliar with the decades of effort that have been invested in extracting the needed nuclear reaction cross sections, and thus uncertain about the quality of the results. The second goal of this paper is to provide a critical assessment of the current state of solar fusion research, describing what is known while also delineating the possibilities for further reducing nuclear cross-section uncertainties.

In order to achieve these goals, an international collection of experts on nuclear physics and solar fusion—representing every speciality (experimental and theoretical) and every point of view (often conflicting points of view)—met in a workshop on "Solar Fusion Reactions." In particular, the participants included experts on all the major controversial issues discussed in widely circulated preprints or in the published literature. The workshop was held at the Institute for Nuclear Theory, University of Washington, February 17-20, 1997.[1] The goal of the workshop was to initiate critical discussions evaluating all of the existing measurements and calculations relating to solar fusion and to recommend a set of standard parameters and their associated uncertainties on which all of the participants could agree. To achieve this goal, we undertook *ab initio* analyses of each of the important solar fusion reactions; previously cited reviews largely concentrated on incremental improvements on

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[1]The workshop was proposed by John Bahcall, the principal editor of this paper, in a letter submitted to the Advisory Committee of the Institute for Nuclear Theory, August 20, 1996. W. Haxton, P. Parker, and H. Robertson served as joint organizers (with Bahcall) of the workshop and as co-editors of this paper. All of the co-authors participated actively in some stage of the work and/or the writing of this paper. We attempted to be complete in our review of the literature prior to the workshop meeting and have taken account of the most relevant work that has been published prior to the submission of this paper in September, 1997.

earlier work. This paper is our joint work and represents the planned culmination of the workshop activities.

At the workshop, we held plenary sessions on each of the important reactions and also intensive specialized discussions in smaller groups. The discussions were led by the following individuals: extrapolations (K. Langanke), electron screening (S. Koonin), *pp* (M. Kamionkowski), $^{3}\mathrm{He} + ^{3}\mathrm{He}$ (C. Rolfs), $^{3}\mathrm{He} + ^{4}\mathrm{He}$ (P. Parker), $e^{-} + {}^{7}\mathrm{Be}$ (J. Bahcall), $p + {}^{7}\mathrm{Be}$ (E. Adelberger), and CNO (H. Robertson). Initial drafts of each of the sections in this paper were written by the discussion leaders and their close collaborators. Successive iterations of the paper were posted on the Internet so that they could be read and commented on by each member of the collaboration, resulting in an almost infinite number of iterations. Each section of the paper was reviewed extensively and critically by co-authors who did not draft that section, and, in a few cases, vetted by outside experts.

C. Contents

The organization of this paper reflects the organization of our workshop. Section II describes the theoretical justification and the phenomenological situation regarding extrapolations from higher laboratory energies to lower solar energies, as well as the effects of electron screening on laboratory and solar fusion rates. Sections III–IX contain detailed descriptions of the current situation with regard to the most important solar fusion reactions. We do not consider explicitly in this review the reactions $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$, $^{7}\mathrm{Li}(p,\alpha)^{4}\mathrm{He}$, and $^{8}\mathrm{B}(\beta^{+}\nu_{e})^{8}\mathrm{Be}$, which occur in the *pp* chain but whose rates are so fast that the precise cross section or decay time does not affect the energy generation or the neutrino flux calculations. We concentrate our discussion on those reactions that are most important for calculating solar neutrino fluxes or energy production.

In our discussions at the workshop, and in the many iterations that have followed over the subsequent months, we placed as much emphasis on determining reliable error estimates as on specifying the best values. We recognize that, for applications to astronomy and to neutrino physics, it is as important to know the limits of our knowledge as it is to record the preferred cross-section factors. Wherever possible, experimental results are given with 1σ error bars (unless specifically noted otherwise). For a few quantities, we have also quoted estimates of a less precisely defined quantity that we refer to as an "effective 3σ" error (or a maximum likely uncertainty). In order to meet the challenges and opportunities provided by increasingly precise solar neutrino and helioseismological data, we have emphasized in each of the sections on individual reactions the most important measurements and calculations to be made in the future.

The sections on individual reactions, III–IX, answer the questions: "What?", "How Well?", and "What Next?". Table I summarizes the answers to the questions "What?" and "How Well?"; this table gives the best estimates and uncertainties for each of the principal solar fusion reactions that are discussed in greater detail later in this paper. The different answers to the question "What Next?" are given in the individual Secs. II–IX.

II. EXTRAPOLATION AND SCREENING

A. Phenomenological Extrapolation

Nuclear fusion reactions occur via a short-range (less than or comparable to a few fm) strong interaction. However, at the low energies typical of solar fusion reactions (~ 5 keV to 30 keV), the two nuclei must overcome a sizeable barrier provided by the long-range Coulomb repulsion before they can come close enough to fuse. Therefore, the energy dependence of a (nonresonant) fusion cross section is conveniently written in terms of an S-factor which is defined by the following relation:

$$\sigma(E) = \frac{S(E)}{E} \exp\left\{-2\pi\eta(E)\right\}, \tag{7}$$

where

$$\eta(E) = \frac{Z_1 Z_2 e^2}{\hbar v} \tag{8}$$

is the Sommerfeld parameter. Here, E is the center-of-mass energy; $v = (2E/\mu)^{1/2}$ is the relative velocity in the entrance channel; Z_1 and Z_2 are the charge numbers of the colliding nuclei; $\mu = mA_1A_2/(A_1+A_2)$ is the reduced mass of the system; m is the atomic mass unit; and A_1 and A_2 are the masses (in units of m) of the reacting nuclei.

The exponential in Eq. (7) (the Gamow penetration factor) takes into account quantum-mechanical tunneling through the Coulomb barrier; the exponential describes well the rapid decrease of the cross section with decreasing energy. The Gamow penetration factor dominates the energy dependence, derived in the WKB approximation, of the cross section in the low-energy limit. In the low-energy regime in which the WKB approximation is valid, the function $S(E)$ is slowly varying (except for resonances) and may be approximated by

$$S(E) \simeq S(0) + S'(0)E + \frac{1}{2}S''(0)E^2. \tag{9}$$

The coefficients in Eq. (9) can often be determined by fitting a quadratic formula to laboratory measurements or theoretical calculations of the cross section made at energies of order

100 keV to several MeV. The cross section is then extrapolated to energies, $\mathcal{O}(10\,\mathrm{keV})$, typical of solar reactions, through Eq. (7). However, special care has to be exercised for certain reactions like ^{7}Be(p,γ)^{8}B, where the S-factor at very low energies expected from theoretical considerations cannot be seen in available data (cf. discussion in Sec. VIII).

The WKB approximation for the Gamow penetration factor is valid if the argument of the exponential is large, $2\pi\eta \gtrsim 1$. This condition is satisfied for the energies over which laboratory data on solar fusion reactions are usually fitted. Because the WKB approximation becomes increasingly accurate at lower energies, the standard extrapolation to solar-fusion energies is valid.

The most compelling evidence for the validity of the approximations of Eqs. (7)–(9) is empirical: they successfully fit low-energy laboratory data. For example, for the ^{3}He(^{3}He,2p)^{4}He reaction, a quadratic polynomial fit (with only a small linear and even smaller quadratic term) for $S(E)$ provides an excellent fit to the measured cross section over two decades in energy in which the measured cross section varies by over ten orders of magnitude (see discussion in Sec. IV).

The approximation of $S(E)$ by the lowest terms in a Taylor expansion is supported theoretically by explicit calculations for a wide variety of reasonable nuclear potentials, for which $S(E)$ is found to be well approximated by a quadratic energy dependence. The specific form of Eq. (7) describes s-wave tunneling through the Coulomb barrier of two point-like nuclei. Several well-known and thoroughly investigated effects introduce slowly-varying energy dependences that are not included explicitly in the standard definition of the low-energy S-factor. These effects include (see, for example, Barnes, Koonin, and Langanke, 1993; Descouvemont, 1993; Langanke and Barnes, 1996) 1) the finite size of the colliding nuclei, 2) nuclear structure and strong interaction effects, 3) antisymmetrization effects, 4) contributions from other partial waves, 5) screening by atomic electrons, and 6) final-state phase space. These effects introduce energy dependences in the S-factor that, in the absence of near-threshold resonances, are much weaker than the dominant energy dependence represented by the Gamow penetration factor. The standard picture of an S-factor with a weak energy dependence has been found to be valid for the cross-section data of all nuclear reactions important for the solar pp-chains. Theoretical energy dependences that take into account all the effects listed above are available (and have been used) for extrapolating data for all the important reactions in solar hydrogen burning.

One can reduce (*but not eliminate*) the energy dependence of the extrapolated quantity by removing nuclear finite-size effects (item 1) from the data. The resulting modified $\tilde{S}(E)$ factor is still energy dependent (because of items 2–6) and cannot be treated as a constant [as assumed by Dar and Shaviv (1996)].

B. Laboratory Screening

It has generally been believed that the uncertainty in the extrapolated nuclear cross sections is reduced by steadily lowering the energies at which data can be taken in the laboratory. However, this strategy has some complications (Assenbaum, Langanke, and Rolfs, 1987) since at very low energies the experimentally measured cross section does not represent the bare nucleus cross section: the laboratory cross section is increased by the screening effects arising from the electrons present in the target (and in the projectile). The resulting enhancement of the measured cross section, $\sigma_{\rm exp}(E)$, relative to the cross section for bare nuclei, $\sigma(E)$, can be written as

$$f(E) = \frac{\sigma_{\rm exp}(E)}{\sigma(E)} \ . \tag{10}$$

Since the electron screening energy, U_e, is much smaller than the scattering energies, E, currently accessible in experiments, one finds (Assenbaum, Langanke, and Rolfs, 1987)

$$f(E) \approx \exp\left\{\pi\eta(E)\frac{U_e}{E}\right\} \ . \tag{11}$$

In nuclear astrophysics, one starts with the bare nuclei cross sections and corrects them for the screening appropriate for the astrophysical scenario (plasma screening, see Sec. II C). In the laboratory experiments, the electrons are bound to the nucleus, while in the stellar plasma they occupy (mainly) continuum states. Therefore, the physical processes underlying screening effects are different in the laboratory and in the plasma.

The enhancement of laboratory cross sections due to electron screening is well established, with the $^3{\rm He}(d,p)^4{\rm He}$ reaction being the best studied and most convincing example (Engstler *et al.*, 1988; Prati *et al.*, 1994). However, it appeared for some time that the observed enhancement was larger than the one predicted by theory. This discrepancy has recently been removed after improved energy loss data became available for low-energy deuteron projectiles in helium gas. To a good approximation, atomic-target data can be corrected for electron screening effects within the adiabatic limit (Shoppa *et al.*, 1993) in which the screening energy, U_e, is simply given by the difference in electronic binding energy of the united atom and the sum of the projectile and target atoms. It appears now as if the electron screening effects for *atomic targets* can be modeled reasonably well (Langanke *et al.*, 1996; Bang *et al.*, 1996; but see also Junker *et al.* 1998). This conclusion must be demonstrated for *molecular* and *solid* targets. Experimental work on electron screening with molecular and solid targets is discussed in Engstler *et al.* (1992), while the first theoretical approaches are presented in Shoppa *et al.* (1996) (molecular) and in Boudouma, Chami, and Beaumevieille (1997) (solid targets).

Electron screening effects, estimated in the adiabatic limit, are relatively small in the measured cross sections for most solar reactions, including the important $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ and $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reactions (Langanke, 1995). However, both the $^3\mathrm{He}(^3\mathrm{He},2p)^4\mathrm{He}$ and the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ data, which extend to very low energies, are enhanced due to electron screening and have been corrected for these effects (see Sec. IV and IX).

C. Stellar Screening

As shown by Salpeter (1954), the decreased electrostatic repulsion between reacting ions caused by the Debye-Hückel screening leads to an increase in reaction rates. The reaction rate enhancement factor for solar fusion reactions is, to an excellent approximation (Gruzinov and Bahcall, 1998),

$$f = \exp\left(\frac{Z_1 Z_2 e^2}{kTR_D}\right), \tag{12}$$

where R_D is the Debye radius and T is the temperature. The Debye radius is defined by the equation $R_D = (4\pi n e^2 \zeta^2/kT)^{-1/2}$, where n is the baryon number density (ρ/m_{amu}), $\zeta = \left\{\Sigma_i X_i \frac{Z_i^2}{A_i} + \left(\frac{f'}{f}\right)\Sigma_i X_i \frac{Z_i}{A_i}\right\}^{1/2}$, X_i, Z_i, and A_i are, respectively, the mass fraction, the nuclear charge, and the atomic weight of ions of type i. The quantity $f'/f \simeq 0.92$ accounts for electron degeneracy (Salpeter 1954). Equation (12) is valid in the weak-screening limit which is defined by $kTR_D \gg Z_1Z_2e^2$. In the solar case, screening is weak for Z_1Z_2 of the order 10 or less (Gruzinov and Bahcall, 1998). Thus, plasma screening corrections to all important thermonuclear reaction rates are known with uncertainties of the order of a few percent. Although originally derived for thermonuclear reactions, the Salpeter formula also describes screening effects on the ^{7}Be electron capture rate with an accuracy better than 1% (Gruzinov and Bahcall, 1997) (for $^7\mathrm{Be}(e,\nu)^7\mathrm{Li}$, we have $Z_1 = -1$, and $Z_2 = 4$).

Two papers questioning the validity of the Salpeter formula in the weak-screening limit appeared during the last decade, but subsequent work demonstrated that the Salpeter formula was correct. The "3/2" controversy introduced by Shaviv and Shaviv (1996) was resolved by Brüggen and Gough (1997); a "dynamic screening" effect discussed by Carraro, Schäfer, and Koonin (1988) was shown to be not present by Brown and Sawyer (1997a) and Gruzinov (1997).

Corrections of the order of a few percent to the Salpeter formula come from the nonlinearity of the Debye screening and from the electron degeneracy. There are two ways to treat these effects - numerical simulations (Johnson *et al.*, 1992) and illustrative approximations (Dzitko *et al.*, 1995; Turck-Chièze and Lopes, 1993). Fortunately, the asymmetry of fluctuations is not important (Gruzinov and Bahcall, 1997), and numerical simulations of a spherically symmetrical approximation are possible even with nonlinear and degeneracy effects included (Johnson *et al.*, 1992). The discussion of intermediate screening by Graboske *et al.* (1973) is not applicable to solar fusion reactions because Graboske *et al.* assume complete electron degeneracy (cf. Dzitko *et al.*, 1995).

A fully analytical treatment of nonlinear and degeneracy effects is not available, but Brown and Sawyer (1997a) have recently reproduced the Salpeter formula by diagram summations. It would be interesting to evaluate higher order terms (describing deviations from the Salpeter formula) using these or similar methods.

III. THE *pp* AND *pep* REACTIONS

The rates for most stellar nuclear reactions are inferred by extrapolating measurements at higher energies to stellar reaction energies. However, the rate for the fundamental $p+p \to {}^2\mathrm{D}+e^{+}+\nu_e$ reaction is too small to be measured in the laboratory. Instead, the cross section for the *p*-*p* reaction must be calculated from standard weak interaction theory.

The most recent calculation was performed by Kamionkowski and Bahcall (1994), who used improved data on proton-proton scattering and included the effects of vacuum polarization in a self-consistent fashion. They also isolated and evaluated the uncertainties due to experimental errors and theoretical evaluations.

The calculation of the *p*-*p* rate requires the evaluation of three main quantities: (i) the weak-interaction matrix element, (ii) the overlap of the *pp* and deuteron wave functions, and (iii) mesonic exchange-current corrections to the lowest-order axial-vector matrix element.

The best estimate for the logarithmic derivative,

$$S'(0) = (11.2 \pm 0.1)\,\mathrm{MeV}^{-1}, \tag{13}$$

is still that of Bahcall and May (1968). At the Gamow peak for the *pp* reaction in the Sun, this linear term provides only an $\mathcal{O}(1\%)$ correction to the $E = 0$ value. The quadratic correction is several orders of magnitude smaller, and therefore negligible. Furthermore, the 1% uncertainty in Eq. (13) gives rise to an $\mathcal{O}(0.01\%)$ uncertainty in the total reaction rate. This is negligible compared with the uncertainties described below. Therefore, in the following, we focus on the $E = 0$ cross-section factor.

At zero relative energy, the S-factor for the *pp* reaction rate can be written (Bahcall and May, 1968, 1969) ,

$$S(0) = 6\pi^2 m_p c\alpha \ln 2\,\frac{\Lambda^2}{\gamma^3}\left(\frac{G_A}{G_V}\right)^2 \frac{f^R_{pp}}{(ft)_{0^+\to 0^+}}(1+\delta)^2, \tag{14}$$

where α is the fine-structure constant; m_p is the proton mass; G_V and G_A are the usual Fermi and axial-vector weak coupling constants; $\gamma = (2\mu E_d)^{1/2} = 0.23161\ \mathrm{fm}^{-1}$ is the deuteron binding wave number (μ is the proton-neutron reduced mass and E_d is the deuteron binding energy); f^R_{pp} is the phase-space factor for the pp reaction (Bahcall, 1966) with radiative corrections; $(ft)_{0^+\to 0^+}$ is the ft value for superallowed $0^+ \to 0^+$ transitions (Savard *et al.*, 1995); Λ is proportional to the overlap of the pp and deuteron wave functions in the impulse approximation (to be discussed below); and δ takes into account mesonic corrections.

Inserting the current best values, we find

$$S(0) = 4.00 \times 10^{-25}\ \mathrm{MeV\ b} \left(\frac{(ft)_{0^+\to 0^+}}{3073\,\mathrm{sec}}\right)^{-1} \left(\frac{\Lambda^2}{6.92}\right) \left(\frac{G_A/G_V}{1.2654}\right)^2 \left(\frac{f^R_{pp}}{0.144}\right) \left(\frac{1+\delta}{1.01}\right)^2 . \quad (15)$$

We now discuss the best estimates and the uncertainties for each of the factors which appear in Eq. (15).

The quantity Λ^2 is proportional to the overlap of the initial-state pp wave function and the final-state deuteron wave function. The wave functions are determined by integrating the Schrödinger equations for the two-nucleon systems with an assumed nuclear potential. The two-nucleon potentials cannot be determined from first principles, but the parameters in any given functional form for the potentials must fit the experimental data on the two-nucleon system. By trying a variety of dramatically different functional forms, we can evaluate the theoretical uncertainty in the final result due to ignorance of the form of the two-nucleon interaction.

The proton-proton wave function is obtained by solving the Schrödinger equation for two protons that interact via a Coulomb plus nuclear potential. The potential must fit the pp scattering length and effective range determined from low-energy pp scattering. In Kamionkowski and Bahcall (1994), five forms for the nuclear potential were considered: a square well, Gaussian, exponential, Yukawa, and a repulsive-core potential. The uncertainty in Λ^2 from the pp wave function is small because there is only a small contribution to the overlap integral from radii less than a few fm (where the shape of the nuclear potential affects the wave function). At larger radii, the wave function is determined by the measured scattering length and effective range. The experimental errors in the pp scattering length and effective range are negligible compared with the theoretical uncertainties.

Similarly, the deuteron wave function must yield calculated quantities consistent with measurements of the static deuteron parameters, especially the binding energy, effective range, and the asymptotic ratio of D- to S-state deuteron wave functions. In Kamionkowski and Bahcall (1994), seven deuteron wave functions which appear in the literature were considered. The spread in Λ due to the spread in assumed neutron-proton interactions was 0.5%, and the uncertainty due to experimental error in the input parameters was negligible.

Figure 1 shows why the details of the nuclear physics are unimportant. The figure displays the product of the radial pp and deuteron wave functions, $u_{pp}(r)$ and $u_d(r)$. The wavelength of the pp system is more than an order of magnitude larger than the extent of the deuteron wave function, so the shape of the curve shown in Fig. 1 is independent of pp energy. Most of the contribution to the overlap integral between the pp wave function and the deuteron wave function comes from relatively large radii where experimental measurements constrain the wave function most strongly. The assumed shape of the nuclear potential produces visible differences in the wave function only for $r \lesssim 5$ fm, and these differences are small. Furthermore, only $\sim 40\%$ of the integrand comes from $r \lesssim 5$ fm and $\sim 2\%$ of the integrand comes from $r \lesssim 2$ fm.

Including the effects of vacuum polarization and the best available experimental parameters for the deuteron and low-energy pp scattering, one finds (Kamionkowski and Bahcall, 1994)

$$\Lambda^2 = 6.92 \times (1 \pm 0.002^{+0.014}_{-0.009}), \tag{16}$$

where the first uncertainty is due to experimental errors, and the second is due to theoretical uncertainties in the form of the nuclear potential.

An anomalously high value of $\Lambda^2 = 7.39$ was obtained by Gould and Guessoum (1990), who did not make clear what values for the pp scattering length and effective range they used. Even by surveying a wide variety of nuclear potentials that fit the observed low-energy pp data, Kamionkowski and Bahcall (1994) never found a value of Λ^2 greater than 7.00. We therefore conclude that the large value of Λ^2 reported by Gould-Guessoum is caused by either a numerical error or by using input data that contradict the existing pp scattering data.

The calculation of Λ^2 includes the overlap only of the s-wave (i.e., orbital angular momentum $l = 0$) part of the pp wave function and the S state of the deuteron. Because the matrix element is evaluated in the usual allowed approximation, $D-$state components in the deuteron wave function do not contribute to the transition.

We use $(ft)_{0^+ \to 0^+} = (3073.1 \pm 3.1)$, which is the ft value for superallowed $0^+ \to 0^+$ transitions that is determined from experimental rates corrected for radiative and Coulomb effects (Savard *et al.*, 1995). This value is obtained from a comprehensive analysis of data on numerous $0^+ \to 0^+$ superallowed decays. After radiative corrections, the ft values for all such decays are found to be consistent within the quoted error.

Barnett *et al.* (1996) recommend a value $G_A/G_V = 1.2601 \pm 0.0025$, which is a weighted average over several experiments that determine this quantity from the neutron decay asymmetry. However, a recent experiment (Abele *et al.*, 1997) has obtained a slightly higher value. We estimate that if we add this new result to the compilation of Barnett *et al.* (1996), the weighted average will be $G_A/G_V = 1.2626 \pm 0.0033$. Alternatively, G_A/G_V may be obtained from $(ft)_{0^+ \to 0^+}$ and the neutron ft-value from

$$\left(\frac{G_A}{G_V}\right)^2 = \frac{1}{3}\left[\frac{2(ft)_{0^+ \to 0^+}}{(ft)_n} - 1\right] . \tag{17}$$

For the neutron lifetime, we use $t_n = (888 \pm 3)$ sec. The range spanned by this central value and the 1σ uncertainty covers the ranges given by the recommended value and uncertainty (887 ± 2.0) of Barnett *et al.* (1996) and the value and uncertainty (889.2 ± 2.2), obtained if the results of Mampe (1993)—which have been called into question by Ignatovich (1995)—are left out of the compilation. We use the neutron phase-space factor, $f_n = 1.71465$ (including radiative corrections), obtained in Wilkinson (1982). Inserting the ft values into Eq. (17), we find $G_A/G_V = 1.2681 \pm 0.0033$, which is slightly larger (by 0.0055 or 0.4%) than the value obtained from neutron decay distributions. To be conservative, we take $G_A/G_V = 1.2654 \pm 0.0042$.

Considerable work has been done on corrections to the nuclear matrix element for the exchange of π and ρ mesons (Gari and Huffman, 1972; Dautry, Rho, and Riska, 1976), which arise from nonconservation of the axial-vector current. By fitting an effective interaction Lagrangian to data from tritium decay, one can show phenomenologically that the mesonic corrections to the *pp* reaction rate should be small (of order a few percent) (Blin-Stoyle and Papageorgiou, 1965). Heuristically, this is because most of the overlap integral comes from proton-proton separations that are large compared with the typical ($\sim$ 1 fm) range of the strong interactions. In tritium decay, most of the overlap of the initial and final wave functions comes from a much smaller radius. If mesonic effects are to be taken into account properly, they must be included self-consistently in the nuclear potentials inferred from data and in the calculation of the overlap integral described above. Here, we advocate following the conservative recommendation of Bahcall and Pinsonneault (1992) in adopting $\delta = 0.01^{+0.02}_{-0.01}$. The central value is consistent with the best estimates from two recent calculations which take into account ρ as well as π exchange (Bargholtz, 1979; Carlson *et al.*, 1991) .

The quoted error range for δ could probably be reduced by further investigations. The primary uncertainty is not in the evaluation of exchange current matrix elements, since the deuteron wave function is well determined from microscopic calculations, but in the meson-nucleon-delta couplings that govern the strongest exchange currents. The coupling constant combinations appearing in the present case are similar to those contributing to tritium beta-decay, another system for which accurate microscopic calculations can be made. Thus the measured ^{3}H lifetime places an important constraint on the exchange current contribution to the *pp* reaction. In the absence of a detailed analysis of this point, the error adopted above, which spans the range of recently published calculations, remains appropriate. But we point out that the ^{3}H lifetime should be exploited to reduce this uncertainty.

For the phase-space factor f^R_{pp}, we have taken the value without radiative corrections, $f_{pp} = 0.142$ (Bahcall and May, 1969) and increased it by 1.4% to take into account radiative corrections to the cross section. Although first-principle radiative corrections for this reaction have not been performed, our best *ansatz* (Bahcall and May, 1968) is that they should be comparable in magnitude to those for neutron decay (Wilkinson, 1982). To obtain the magnitude of the correction for neutron decay, we simply compare the result $f^R = 1.71465$ with radiative corrections obtained in Wilkinson (1982) to that obtained without radiative corrections in Bahcall (1966). We estimate that the total theoretical uncertainty in this approximation for the *pp* phase-space factor is 0.5%. Therefore, we adopt $f^R_{pp} = 0.144 \times (1 \pm 0.005)$, where the error is a total theoretical uncertainty (see Bahcall, 1989). It would be useful to have a first-principles calculation of the radiative corrections for the *pp* interaction.

Amalgamating all these results, we find that the current best estimate for the *pp* cross-section factor, taking account of the most recent experimental and theoretical data, is

$$S(0) = 4.00 \times 10^{-25}\,(1 \pm 0.007^{+0.020}_{-0.011})\,\mathrm{MeV\ b}, \tag{18}$$

where the first uncertainty is a 1σ experimental error, and the second uncertainty is one-third the estimated *total* theoretical uncertainty.

Ivanov *et al.* (1997) have recently calculated the *pp* reaction rate using a relativistic field theoretic model for the deuteron. Their calculation is invalidated by, among other things, the fact that they used a zero-range effective interaction for the protons, in conflict with low-energy *pp* scattering experiments (see Bahcall and Kamionkowski, 1997).

The rate for the $p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$ reaction is proportional to that for the *pp* reaction. Bahcall and May (1969) found that the *pep* rate could be written,

$$R_{pep} \simeq 5.51 \times 10^{-5} \rho (1 + X) T_6^{-1/2} (1 + 0.02 T_6) R_{pp}, \tag{19}$$

where ρ is the density in g cm^{-3}, X is the mass fraction of hydrogen, T_6 is the temperature in units of 10^6 K, and R_{pp} is the *pp* reaction rate. This approximation is accurate to approximately 1% for the temperature range, $10 < T_6 < 16$, relevant for solar-neutrino production. Therefore, the largest uncertainty in the *pep* rate comes from the uncertainty in the *pp* rate.

IV. THE ^{3}He(^{3}He, $2p$)^{4}He REACTION

The solar Gamow energy of the $^3\mathrm{He}(^3\mathrm{He}, 2p)^4\mathrm{He}$ reaction is at $E_0 = 21.4$ keV (see Eq. 2). As early as 1972, there were desperate proposals (Fetisov and Kopysov, 1972; Fowler, 1972) to solve the solar neutrino problem[2] that suggested a narrow resonance may exist in this reaction at low energies. Such a resonance would enhance the $^3\mathrm{He} + {}^3\mathrm{He}$ rate at the expense of the $^3\mathrm{He}+{}^4\mathrm{He}$ chain, with important repercussions for production of ^{7}Be and ^{8}B neutrinos. Many experimental investigations [see Rolfs and Rodney (1988) for a list of references] have searched for, but not found, an excited state in ^{6}Be at $E_x \approx 11.6$ MeV that would correspond to a low-energy resonance in $^3\mathrm{He} + {}^3\mathrm{He}$. Microscopic theoretical models (Descouvemont, 1994; Csótó, 1994) have also shown no sign of such a resonance.

Microscopic calculations of the ^{3}He(^{3}He,2p)^{4}He reaction (Vasilevskii and Rybkin, 1989; Typel *et al.*, 1991) view this reaction as a two-step process: After formation of the compound nucleus, the system decays into an α-particle and a 2-proton cluster. The latter, being energetically unbound, finally decays into two protons. This, however, is expected to occur outside the range of the nuclear forces. In Typel *et al.* (1991), the model space was spanned by ^{4}He+$2p$ and ^{3}He+^{3}He cluster functions as well as configurations involving ^{3}He pseudostates. The calculation reproduces the measured S-factors for $E \leq 300$ keV reasonably well and predicts $S(0) \approx 5.3$ MeV b, in agreement with the measurements discussed later in this section. Further confidence in the calculated energy dependence of the low-energy ^{3}He(^{3}He,2p)^{4}He cross sections is gained from a simultaneous microscopic calculation of the analog $^3\mathrm{H}(^3\mathrm{H}, 2n)^4\mathrm{He}$ reaction, which again reproduces well the measured energy dependence of the ^{3}H+^{3}H fusion cross sections (Typel *et al.*, 1991). Recently, Descouvemont (1994) and Csótó (1997b, 1998) have extended the microscopic calculations to include $^5\mathrm{Li} + p$ configurations. Their calculated energy dependences, however, are in slight disagreement with the data, possibly indicating the need for a genuine 3-body treatment of the final continuum states.

The relevant cross sections for the $^3\mathrm{He}(^3\mathrm{He}, 2p)^4\mathrm{He}$ reaction have recently been measured at the energies covering the Gamow peak. The data have to be corrected for laboratory electron screening effects. Note that the extrapolation given by Krauss *et al.* (1987) and used in Dar and Shaviv (1996) ($S(0) = 5.6$ MeV b) is too high, because it is based on low-energy data that were not corrected for electron screening.

The reaction data show that at energies below 1 MeV the reaction proceeds predomi-

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[2] In 1972, the "solar neutrino problem" consisted entirely of the discrepancy between the predicted and measured rates in the Homestake experiment (see Bahcall and Davis, 1976).

nately via a direct mechanism and that the angular distributions approach isotropy with decreasing energy. The energy dependence of $\sigma(E)$—or equivalently of the cross-section factor $S(E)$—observed by various groups (Bacher and Tombrello, 1965; Wang *et al.*, 1966; Dwarakanath and Winkler, 1971; Dwarakanath, 1974; Krauss, Becker, Trautvetter, and Rolfs, 1987; Greife *et al.*, 1994; Arpesella *et al.*, 1996; Junker *et al.*, 1998) presents a consistent picture. The only exception is the experiment of Good, Kunz, and Moak (1951), for which the discrepancy is most likely caused by target problems (^{3}He trapped in an Al foil).

The absolute $S(E)$ values of Dwarakanath and Winkler (1971), Krauss, Becker, Trautvetter, and Rolfs (1987), Greife *et al.* (1994), Arpesella *et al.* (1996), and Junker *et al.* (1998) are in reasonable agreement, although they are perhaps more consistent with a systematic uncertainty of 0.5 MeV b. The data of Wang *et al.* (1966) and Dwarakanath (1974) are lower by about 25%, suggesting a renormalization of their absolute scales. However, in view of the relatively few data points reported in Wang *et al.* (1966) and Dwarakanath (1974), and their relatively large uncertainties—in comparison to other data sets—we suggest that the data of Wang *el al.* (1966) and Dwarakanath (1974) can be omitted without significant loss of information.

Figure 2 is adapted from Fig. 9 of Junker *et al.* (1998). The data shown are from Dwarakanath and Winkler (1971), Krauss, Becker, Trautvetter, and Rolfs (1987), Arpesella *et al.* (1996), and Junker *et al.* (1998) . The data provide no evidence for a hypothetical low-energy resonance over the entire energy range that has been investigated experimentally.

Because of the effects of laboratory atomic electron screening (Assenbaum, Langanke, and Rolfs, 1987), the low-energy $^3\mathrm{He}(^3\mathrm{He}, 2p)^4\mathrm{He}$ measurements must be corrected in order to determine the "bare" nuclear S-factor. Assume, for specificity, a constant laboratory screening energy of $U_e = 240$ eV, corresponding to the adiabatic limit for a neutral ^{3}He beam incident on the atomic ^{3}He target. If we assume that the projectiles are singly ionized, the adiabatic screening energy increases only slightly to $U_e \approx 250$ eV. TDHF calculations for atomic screening of low-Z targets (Shoppa *et al.*, 1993; Shoppa *et al.*, 1996) have shown that the adiabatic limit is expected to hold well at the low energies where screening is important. Junker *et al.* (1998) have converted published laboratory measurements $S_{\rm lab}(E)$ to bare nuclear S-factors $S(E)$ using the relation $S(E) = S_{\rm lab}(E)\exp(-\pi\eta(E)U_e/E)$, with $U_e = 240$ eV [cf. Eq. (10) and Eq. (11)].

The resulting bare S-factors were fit to Eq. (9). Junker *et al.* (1998) find $S(0) = 5.40 \pm 0.05$ MeV b, $S'(0) = -4.1 \pm 0.5$ b, and $S''(0) = 4.6 \pm 1.0$ b/MeV, but important systematic uncertainties must also be included as in Eq. (20) below. An effective 3σ uncertainty of about ± 0.30 MeV b due to lack of understanding of electron screening in the laboratory experiments should be included in the error budget for $S(0)$ (cf. Junker *et al.*, 1998).

The cross-section factor at solar energies is relatively well known by direct measurements (see Fig.2). Junker *et al.* (1998) give

$$S(\mathrm{E}_0) = 5.3 \pm 0.05(\mathrm{stat}) \pm 0.30(\mathrm{syst}) \pm 0.30(\mathrm{U_e}) \text{ MeV b}, \tag{20}$$

where the first two quoted 1σ errors are from statistical and systematic experimental uncertainties and the last error represents a maximum likely error (or effective 3σ error) due to the lack of complete understanding of laboratory electron screening. The data seem to suggest that the effective value of U_e may be larger than the adiabatic limit.

Future experimental efforts should extend the $S(E)$ data to energies at the low-energy tail of the solar Gamow peak, i.e. at least as low as 15 keV. Furthermore, improved data should be obtained at energies from E = 25 keV to 60 keV to confirm or reject the possibility of a relatively large systematic error in the $S(E)$ data near these energies. On the theoretical side, an improved microscopic treatment is highly desirable.

V. THE ^{3}He$(\alpha,\gamma)^7$Be REACTION

The relative rates of the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ and $^3\mathrm{He}(^3\mathrm{He},2p)^4\mathrm{He}$ reactions determine what fractions of *pp*-chain terminations result in ^{7}Be or ^{8}B neutrinos.

Since the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction at low energies is essentially an external direct-capture process (Christy and Duck, 1961), it is not surprising that direct-capture model calculations of different sophistication yield nearly identical energy dependences of the low-energy S-factor. Both the microscopic cluster model (Kajino and Arima, 1984) and the microscopic potential model (Langanke, 1986) correctly predicted the energy dependence of the low-energy $^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$ cross section (the isospin mirror of $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$) before it was precisely measured by Brune, Kavanagh, and Rolfs (1994). The absolute value of the cross section was also predicted to an accuracy of better than 10% from potential model calculations by Langanke (1986) and Mohr *et al.* (1993).

Separate evaluations of this energy dependence based on the Resonating Group Method (Kajino, Toki, and Austin, 1987) and on a direct-capture cluster model (Tombrello and Parker, l963) agree to within $\pm 1.25\%$ and are also in good agreement with the measured energy dependence (see also Igamov, Tursunmuratov, and Yarmukhamedov, 1997). This confluence of experiments and theory is illustrated in Fig. 3. Even more detailed calculations are now possible (cf. Csótó, 1997a).

Thus the energy dependence of the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction seems to be well determined. The only free parameter in the extrapolation to thermal energies is the normalization of the energy dependence of the cross sections to the measured data sets. While the energy dependence predicted by the existing theoretical models is in good agreement with the energy dependence of the measured cross sections, it would be useful to explore how robust this energy dependence is for a wider range of models. Extrapolations based on physical models should be used; such extrapolations are more credible than those based only on the extension of multiparameter mathematical fits (e.g., those of Castellani *et al.*, 1997).

There are six sets of measurements of the cross section for the ^{3}He$(\alpha,\gamma)^7$Be reaction that are based on detecting the capture gamma rays (Table II). The weighted average of the six prompt γ-ray experiments yields a value of $S_{34}(0) = (0.507 \pm .016)$ keV b, based on extrapolations made using the calculated energy dependence for this direct-capture reaction. In computing this weighted average, we have used the renormalization of the Kräwinkel *et al.* (1982) result by Hilgemeier *et al.* (1988).

There are also three sets of cross sections for this reaction that are based on measurements of the activity of the synthesized ^{7}Be (Table II). These decay measurements have the advantage of determining the *total* cross section directly, but have the disadvantage that (since the source of the residual activity can not be uniquely identified) there is always the possibility that some of the ^{7}Be may have been produced in a contaminant reaction that evaded background tests. The three activity measurements (when extrapolated in the same way as the direct-capture gamma ray measurements) yield a value of $S_{34}(0) = (0.572 \pm 0.026)$ keV b, which differs by about 2.5σ with the value based on the direct-capture gamma rays.

It has been suggested that the systematic discrepancy between these two data sets might arise from a small monopole (E0) contribution to which the prompt measurements would be much less sensitive and whose contribution could have been overlooked. However, estimates of the E0 contribution are consistently found to be exceedingly small in realistic models of this reaction; they are of order α^2, whereas the leading contribution is of order α (the fine structure constant). The importance of any E0 contributions would be further suppressed by the fact that they would have to come from the p-wave incident channel, in contrast to the s-wave incident channel which is responsible for the dominant E1 contributions. (See Fig. 4.)

When the nine experiments are combined, the weighted mean is $S_{34}(0) = (0.533 \pm 0.013)$ keV b, with $\chi^2 = 13.4$ for 8 degrees of freedom. The probability of such a distribution arising by chance is 10%, and that, together with the apparent grouping of the results according to whether they have been obtained from activation or prompt-gamma yields, suggests the possible presence of a systematic error in one or both of the techniques. An approach that gives a somewhat more conservative evaluation of the uncertainty is to form the weighted means within each of the two groups of data (the data show no indication of non-statistical behavior within the groups), and then determine the weighted mean of those two results. In the absence of information about the source and magnitude of the excess systematic error, if any, an arbitrary but standard prescription can be adopted in which the uncertainties of the means of the two groups (and hence the overall mean) are increased by a common factor of 3.7 (in this case) to make $\chi^2 = 0.46$ for 1 degree of freedom, equivalent to making the estimator of the weighted population variance equal to the weighted sample variance. The uncertainty in the extrapolation is common to all the experiments, although it is likely to be only a relatively minor contribution to the overall uncertainty. The result is our recommended value for an overall weighted mean:

$$S_{34}(0) = 0.53 \pm 0.05 \text{ keV b}. \tag{21}$$

The slope, $S'(0)$, is well determined within the accuracy of the theoretical calculations (e.g., Parker and Rolfs, 1991):

$$S'(0) = -0.00030 \text{ b}. \tag{22}$$

Neither the theoretical calculations nor the experimental data are sufficiently accurate to determine a second derivative.

Dar and Shaviv (1996) quote a value of $S_{34}(0) = 0.45$ keV b, about 1.5σ lower than our best estimate. The difference between their value and our value can be traced to the fact that Dar and Shaviv fit the entire world set of data points as a single group to obtain one $S_{34}(0)$ intercept, rather than fitting independently each of the nine independent experiments and then combining their intercepts to determine a weighted average for $S_{34}(0)$. The Dar and Shaviv method thereby overweights the experiments of Kräwinkel *et al.* (1982) and Parker and Kavanagh (1963) because they have by far the largest number of data points (39 and 40, respectively) and underweights those experiments which have only 1 or 2 data points (e.g., the activity measurements). Systematic uncertainties, such as normalization errors, common to all the points in one data set make it impossible to treat the common points as statistically independent and uncorrelated, and thus the Dar and Shaviv method distorts the average.

VI. THE ^{3}He$(p, e^+ + \nu_e)^4$He REACTION

The *hep* reaction,

$$^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e, \tag{23}$$

produces neutrinos with an endpoint energy of 18.8 MeV, the highest energy expected for solar neutrinos. The region between 15 MeV and 19 MeV, above the endpoint energy for

^{8}B neutrinos and below the endpoint energy for *hep* neutrinos, is potentially useful for solar neutrino studies since the background in electronic detectors is expected to be small in this energy range. For a given solar model, the flux of *hep* neutrinos can be calculated accurately once the $S-$factor for reaction (23) is specified. The rate of the *hep* reaction is so slow that it does not affect the solar structure calculations. The calculated *hep* flux is very small ($\sim 10^3$ cm^{-2}s^{-1}, Bahcall and Pinsonneault, 1992), but the interaction cross section is so large that the *hep* neutrinos are potentially detectable in sensitive detectors like SNO and Superkamiokande (Bahcall, 1989).

The thermal neutron cross section on ^{3}He has been measured accurately in two separate experiments (Wolfs *et al.*, 1989; Wervelman, *et al.*, 1991). The results are in good agreement with each other.

Unfortunately, there is a complicated relation between the measured thermal-neutron cross section and the low-energy cross-section factor for the production of *hep* neutrinos. The most recent detailed calculation (Schiavilla, *et al.*, 1992) that includes Δ-isobar degrees of freedom yields low-energy cross-section factors calculated, with specific assumptions, in the range $S(0) = 1.4 \times 10^{-20}$ keV b to $S(0) = 3.2 \times 10^{-20}$ keV b . Less sophisticated calculations yield very different answers (see Wolfs *et al.*, 1989; Wervelman *et al.*, 1991; see also the detailed calculation by Carlson *et al.*, 1991).

There are significant cancellations among the various matrix elements of the one- and two-body parts of the axial current operator. The inferred S-factor is particularly sensitive to the model for the axial exchange-current operator. The uncertainties in the various components of the exchange-current operator and the uncertainty in the weak coupling constant $g_{\beta N\Delta}$ introduce a substantial uncertainty in $S(0)$. Schiavilla *et al.* use different input parameters that reflect these uncertainties, and provide a range of calculated $S(0)$.

We adopt as a best estimate low-energy cross-section factor a value in the middle of the range calculated by Schiavilla *et al.* (1992),

$$S(0) \ = \ 2.3 \times 10^{-20}\,\mathrm{keV\ b}. \tag{24}$$

There is no satisfactory way of determining a rigorous error to be associated with this best estimate.

Theoretical studies that could predict the cross-section factor for reaction (23) with greater accuracy would be important since the *hep* neutrino flux contains significant information about both solar fusion and neutrino properties.

VII. ^{7}Be ELECTRON CAPTURE

The ^{7}Be electron capture rate under solar conditions has been calculated using an explicit picture of continuum-state and bound-state electrons and independently using a density matrix formulation that does not make assumptions about the nature of the quantum states. The two calculations are in excellent agreement within a calculational accuracy of about 1%.

The fluxes of both ^{7}Be and ^{8}B solar neutrinos are proportional to the ambient density of ^{7}Be ions. The flux of ^{7}Be neutrinos, $\phi(^7\mathrm{Be})$, depends upon the rate of electron capture, $R(e)$, and the rate of proton capture, $R(p)$, only through the ratio

$$\phi(^7\mathrm{Be}) \ \propto \ \frac{R(e)}{R(e)+R(p)}. \tag{25}$$

With standard parameters, solar models yield $R(p) \approx 10^{-3} R(e)$. Therefore, Equation (25) shows that the flux of ^{7}Be neutrinos is actually independent of the local rates of both the electron capture and the proton capture reactions to an accuracy of better than 1% . The ^{7}Be flux depends most strongly on the branching between the ^{3}He-^{3}He and the ^{3}He-^{4}He reactions. The ^{8}B neutrino flux is proportional to $R(p)/[R(e)+R(p)]$ and therefore the ^{8}B flux is inversely proportional to the electron-capture rate.

The first detailed calculation of the ^{7}Be electron capture rate from continuum states under stellar conditions was by Bahcall (1962), who considered the thermal distribution of the electrons, the electron-nucleus Coulomb effect, relativistic and nuclear size corrections, and a numerical self-consistent Hartree wave function needed for evaluating the electron density at the nucleus in laboratory decay (for comparison with the electron density in stars). Iben, Kalata, and Schwartz (1967) made the first explicit calculation of the effect of bound electron capture. They included the effects of the stellar plasma in the Debye-Hückel approximation and demonstrated that electron screening decreases significantly the bound rate compared to the case where screening is neglected.

Applying the same Debye-Hückel screening picture to continuum states, Bahcall and Moeller (1969) showed that plasma effects on the continuum capture rate were small. Bahcall and Moeller (1969) also formulated the total capture rate in a convenient analytic form, which is in general use today (Bahcall, 1989), and averaged the capture rates over three different solar models. Let $R \equiv R(e)$ be the total capture rate and C be the rate of capture from the continuum only. Bahcall and Moeller (1969) found that the ratio of total rate to continuum rate averaged over the solar models was $< R/C > \ \simeq \ < C/R >^{-1} \ = 1.205 \pm 0.005$.

Watson and Salpeter (1973) first drew attention to the small number (~ 3) of ions per Debye sphere in the solar interior; they emphasized the possible importance of thermal plasma fluctuations on the bound-state electron-capture rate. Johnson *et al.* (1992) performed a series of detailed calculations, especially for the bound state capture rate, using a form of self-consistent Hartree theory. They derived a correction to the usual total rate of about 1.4%.

Using the previously-calculated electron capture rate as a function of temperature, density, and composition, Bahcall (1994) calculated the fraction of decays from bound states and found that the ratio of total to continuum captures was $R/C = 1.217 \pm 0.002$ for three modern solar models, which is about 1% larger than the results of Bahcall and Moeller (1969) cited earlier. Using this slightly higher bound-state fraction, we find

$$R(^7\mathrm{Be} + e^-) \;=\; 5.60 \times 10^{-9} (\rho/\mu_e) T_6^{-1/2} [1 \;+\; 0.004(T_6 \;-\; 16)] \mathrm{s}^{-1} \;, \tag{26}$$

where μ_e is the electron mean molecular weight. In most recent discussions (Bahcall and Moeller, 1969; Bahcall, 1989), the numerical coefficient in Eq. (26) was 5.54 instead of 5.60. The slightly higher value given here reflects the newer determination of the bound fraction (Bahcall, 1994).

Most recently, Gruzinov and Bahcall (1997) abandoned the standard picture of bound and continuum states in the solar plasma and have instead calculated the total electron capture rate directly from the equation for the density matrix (Feynman, 1990) of the plasma. Their numerical results agree to within 1% with the standard result obtained with an explicit picture of bound and continuum electron states. They also show that a simple heuristic argument, derivable from the density matrix formulation, gives an analytic form for the effect of the solar plasma that is of the familiar Salpeter (1954) form and agrees to within 1% with the numerical calculations.[3] An explicit Monte Carlo calculation of the effects of fluctuations, not required to be spherically symmetric, shows that the net effect of fluctuations is less than 1% of the total capture rate. This result is surprising given the small number of ions in the Debye sphere (Watson and Salpeter, 1973). However, the fact that fluctuations are unimportant can be understood (or at least made plausible) using second-order perturbation theory in the density-matrix formulation. The effect of fluctuations is indeed shown (Gruzinov and Bahcall, 1997) to depend upon an inverse power ($-5/3$) of the

[3]Even more recently, Brown and Sawyer (1997b) have re-investigated the electron capture problem using multi-particle field-theory methods. Their technique automatically gives the correct weighting with Fermi statistics (a small correction) including an account of bound states which obviates the need for "Saha-like" reasoning. They derive analytic sum rules which confirm the Gruzinov and Bahcall (1997) result that the Salpeter (1954) correction holds to good accuracy in the electron capture process.

number of ions in the Debye sphere. But, the dimensionless coefficient is tiny (2×10^{-4}). The net result of the calculations performed with the density-matrix formalism is to confirm to high accuracy the standard ^{7}Be electron-capture rate given here in Eq. (26).

How accurate is the present theoretical capture rate, R? The excellent agreement between the numerical results obtained using different physical pictures (models for bound and continuum states and the density matrix formulation) suggests that the theoretical capture rate is relatively accurate. Moreover, a simple physical argument shows (Gruzinov and Bahcall, 1997) that the effects of electron screening on the total capture rate can be expressed by a Salpeter factor (Salpeter, 1954) that yields the same numerical results as the detailed calculations. The simplicity of this physical argument provides supporting evidence that the calculated electron capture rate is robust.

The largest recognized uncertainty arises from possible inadequacies of the Debye screening theory. Johnson *et al.* (1992) have performed a careful self-consistent quantum mechanical calculation of the effects on the ^{7}Be electron capture rate of departures from the Debye screening. They conclude that Debye screening describes the electron capture rates to within 2%. Combining the results of Gruzinov and Bahcall (1997) and of Johnson *et al.* (1992), we conclude that the total fractional uncertainty, $\delta R/R$, is small and that (at about the 1σ level)

$$\frac{\delta R\,(^{7}\mathrm{Be} + e^{-})}{R\,(^{7}\mathrm{Be} + e^{-})} \leq \; 0.02. \tag{27}$$

VIII. THE ^{7}Be(p,γ) ^{8}B REACTION

A. Introduction

The neutrino event rate in all existing solar neutrino detectors, except for those based on the ^{71}Ga(ν, e) reaction, is either dominated by (in the case of the Homestake Mine ^{37}Cl detector), or almost entirely due to (in the cases of the Kamiokande, Super-Kamiokande, and SNO detectors), the high-energy neutrinos produced in ^{8}B decay. It is therefore important to assess critically the information needed to predict the solar production of ^{8}B.[4] The most

[4]The shape of the energy spectrum from ^{8}B decay is the same (Bahcall, 1991), to one part in 10^{5}, as the shape determined by laboratory experiments and is relatively well known (see Bahcall *et al.*, 1996).

poorly known quantity in the entire nucleosynthetic chain that leads to ^{8}B is the rate of the final step, the ^{7}Be$(p,\gamma)^8$B reaction which has a Q-value of 137.5 ± 1.2 keV (Audi and Wapstra, 1993).

The ^{7}Be$(p,\gamma)^8$B rate is conventionally given in terms of the zero-energy S-factor $S_{17}(0)$. This quantity is deduced by extrapolating the measured absolute cross sections, which have been studied to energies as low as $E_p = 134$ keV, to the astrophysically relevant regime.

Due to the small binding energy of ^{8}B, the ^{7}Be$(p,\gamma)^8$B reaction at low energies is an external, direct-capture process (Christy and Duck, 1961). Consequently the energy dependence of the S-factor for $E \leq 300$ keV is almost model-independent (Williams and Koonin, 1981; Csótó, 1997a; Timofeyuk, Baye, and Descouvemont, 1997) and is given by the predicted ratio of E1 capture from ^{7}Be$+p$ s-waves and d-waves into the ^{8}B ground state (Robertson, 1973; Barker, 1980). The S-factor is expected to exhibit a modest rise at solar energies due to the energy dependences of the Whittaker asymptotics of the ground state, the regular Coulomb functions describing the ^{7}Be $+ p$ scattering states, and the E_γ^3 dipole phase-space factor. Because this expected rise of the S-factor towards solar energies cannot be seen at the energies at which capture data is currently available, extrapolations that do not incorporate the correct physics of the low-energy ^{7}Be$(p,\gamma)^8$B reaction, for example, the extrapolation presented by Dar and Shaviv (1996), are not correct.

We have fitted Johnson *et al.'s* (1992) microscopic calculations of $S(E)$ to quadratic functions between 20 keV and 300 keV. The overall normalization was allowed to float and only the energy dependence was fitted. The results were practically the same for the Minnesota force (Chwieroth *et al.*, 1973) and the Hasegawa-Nagata force (Furutani *et al.*, 1980). A combined fit, weighting the results from both force laws equally, yields $S'(0)/S(0) = -0.7 \pm 0.2$ MeV^{-1} and $S''(0)/2S(0) = 1.9 \pm 0.3$ MeV^{-2}, which are our recommended values. The quadratic formulae given above reproduce the detailed microscopic calculations to an accuracy of ± 0.3 eV b in the energy range 0 to 300 keV.

At moderate energies, say $E \geq 400$ keV, the ^{7}Be$(p,\gamma)^8$B S-factor becomes model-dependent (e.g., Csótó, 1997a), because at these energies the capture process probes the internal ^{8}B wave function and becomes sensitive to nuclear structure. The argument of Nunes, Crespo, and Thompson (1997) that the energy dependence of S_{17} is sensitive to core polarization effects has been found to be invalid and the paper has been withdrawn by the authors. At the present time, statistical and systematic errors in the experimental data dominate the uncertainty in the low-energy cross-section factor (see also Turck-Chièze *et al.*, 1993). A measurement of the cross section below 300 keV with an uncertainty significantly better than 5% would make a major contribution to our knowledge of this reaction. A measurement of the ^{7}Be quadrupole moment would also help distinguish between different nuclear models for the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction (see Csótó *et al.*, 1995).

We begin by reviewing the history of direct measurements of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ cross section. Then we discuss recent indirect attempts to determine the cross section. Finally we make recommendations for $S_{17}(0)$.

B. Direct $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ measurements

The first experimental study of $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ was made by Kavanagh (1960) who detected the $^8\mathrm{B}$ β^+ activity. This pioneering measurement was followed by an experiment by Parker (1966, 1968), who improved the signal-to-background by detecting the β-delayed α's, a strategy followed in all subsequent works. Subsequently, extensive measurements were reported by Kavanagh *et al.* (1969) in the energy region $E_p = 0.165$ to 10 MeV, and by Vaughn *et al.* (1970) at 20 proton energies between 0.953 and 3.281 MeV. The most recent published works are a single point at $E_p = 360$ keV by Wiezorek *et al.* (1977) and a very comprehensive and careful experiment by Filippone *et al.* (1983a,b), who measured the cross section at 25 points at center-of-mass energies between 0.117 and 1.23 MeV. The cross section displays a strong $J^\pi = 1^+$ resonance at $E_p = 0.72$ MeV, but this has almost no effect at solar energies where the cross section is essentially due to direct $E1$ capture.

Direct $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ experiments require radioactive targets. It has not been practical to use the conventional geometry with large-area, thin targets, and "pencil" beams; instead the experimenters were forced to use comparable beam and target sizes. As a result the absolute normalization of the cross sections has posed severe experimental problems.

In the experiments to date, the mean areal density of $^7\mathrm{Be}$ atoms seen by the proton beam has been determined in one of two ways:

1. counting the number of $^7\mathrm{Be}$ atoms by detecting the 478 keV photons emitted in $^7\mathrm{Be}$ decay and measuring the target spot size (Wiezorek *et al.*, 1977; Filippone *et al.*, 1983a,b).

2. measuring the yield of the $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ reaction on the daughter $^7\mathrm{Li}$ atoms that build up in the targets as the $^7\mathrm{Be}$ decays (Kavanagh, 1960; Parker, 1966, 1968; Kavanagh *et al.*, 1969; Vaughn *et al.*, 1970; Filippone *et al.*, 1982). These measurements are made on the peak of a broad ($\Gamma \approx 0.2$ MeV) resonance at $E_d = 0.78$ MeV.

The first method has the advantage of being direct. The second method has the advantage that the $^8\mathrm{B}$ produced in the (p,γ) reaction and the $^8\mathrm{Li}$ produced in the (d,p) calibration reaction can both be detected by counting the beta-delayed alphas, so that detection efficiency uncertainties largely cancel out. However the second method requires an absolute measurement of the total ^{7}Li$(d,p)^8$Li cross section which has turned out to be rather difficult to measure correctly.

The absolute ^{7}Be$(p,\gamma)^8$B cross sections originally quoted from these experiments were not consistent with each other, although the shapes of the cross sections as functions of bombarding energy were in agreement. Furthermore, the quoted ^{7}Li$(d,p)^8$Li normalization cross sections also differed by much more than the quoted uncertainties (values differing by up to a factor of two were quoted). However, as pointed out by Barker and Spear (1986), even after all the ^{7}Be$(p,\gamma)^8$B cross sections are renormalized to a common value of the ^{7}Li$(d,p)^8$Li cross section, the results are not consistent.

Because poorly understood systematic errors dominated the actual uncertainties in the results, we adopt the following guidelines for evaluating the existing data to arrive at a recommended value for $S_{17}(0)$.

1. We consider only those experiments that were described in sufficient detail that we can assess the reliability of the error assignments.

2. We review experiments that pass the above cuts and make our own assessment of the systematic errors, using information given in the original paper plus more recent information (such as improved values for the ^{7}Li$(d,p)^8$Li cross section) when available.

The only low-energy ^{7}Be$(p,\gamma)^8$B measurement that meets these criteria is the experiment of Filippone *et al.* (1983a,b) at Argonne. Filippone *et al.* (1983a,b) obtained the areal density of their target by counting the 478 keV radiation from ^{7}Be decay and also by detecting the (d,p) reaction on the ^{7}Li produced in the target by ^{7}Be decay. The Argonne experimenters made two independent measurements of the ^{7}Li$(d,p)^8$Li cross section [Elwyn *et al.* (1982) and Filippone *et al.* (1982)]. These two determinations were consistent. In addition, Filippone *et al.*'s (1982) gamma-ray counting and (d,p) normalization techniques gave results in excellent agreement.

C. The ^{7}Li$(d,p)^8$Li cross section on the $E = 0.6$ MeV resonance

Strieder *et al.* (1996) give a complete listing of existing ^{7}Li$(d,p)^8$Li cross-section measurements. The results scatter from a maximum value of (211 ± 15) mb (Parker, 1966) to a minimum of (110 ± 22) mb (Haight, Matthews, and Bauer, 1985). We obtain a recommended value for the ^{7}Li$(d,p)^8$Li cross section by applying the same criteria used above in evaluating the ^{7}Be$(p,\gamma)^8$B data. The experiments that pass our selection criteria are listed in Table III. The absolute cross sections given in the first three rows of Table III are based on target areal densities determined from the energy loss of protons (McClenahan and Segal, 1975) or deuterons (Elwyn *et al.*, 1982 and Filippone *et al.*, 1982) in the targets. These results therefore share a common systematic uncertainty in the stopping powers. Filippone *et al.* (1982) cite evidence that the tabulated stopping powers were accurate to 5%, but quote an overall target thickness uncertainty of 7%. Elywn *et al.* (1982) quote a ≈7.5% uncertainty in the stopping power. McClenahan and Segal (1975) quote a target thickness uncertainty of 10%.

The last two entries in Table III differ from those given by the authors. The next-to-last row was obtained by combining Filippone *et al.*'s (1982) two independent, but concordant, normalizations of their target thickness. The normalization based on counting the 478 keV photon activity from ^{7}Be decay implies a corresponding areal density of ^{7}Li in the target, and hence can be used to give an independent absolute normalization to their $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ cross section. We obtained the next-to-last value in Table III by requiring that Filippone *et al.*'s (1982) measured $^7\mathrm{Li}+d$ yield corresponded exactly to their measured ^{7}Li areal density inferred by counting the 478 keV photons. Finally, the errors on the $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ cross section quoted by Strieder *et al.* (1996) are unrealistic. Strieder *et al.* (1996) used a ^{7}Li beam on a D_2 gas target. They normalized their target density and geometry factor to the $^7\mathrm{Li}+d$ elastic scattering cross section, which they assumed had reached the Rutherford value at their lowest measured energy $E = 0.1$ MeV. However, their data (see their Fig. 5) do not show that the $^7\mathrm{Li}(d,p)$ cross section divided by the Rutherford cross section had become constant at this energy. Therefore, in the last row in Table III, we replace Strieder *et al.*'s (1996) quoted 5% error in the elastic scattering cross section with an 11% uncertainty which is the quadratic sum of the 10% uncertainty in the absolute $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ cross section quoted by Ford (1964) [Ford's absolute normalization agrees very well with that of Filippone *et al.* (1982)] and a 5% uncertainty in relative normalization of Strieder *et al.*'s (1996) data to those of Ford.

We obtain our recommended value for the $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ cross section by the following somewhat arbitrary procedure necessitated by the fact that McClenahan and Segal (1975) do not give enough information to do otherwise. We assume that each of the first three entries in Table III had assigned a 7% uncertainty to the stopping power and subtract this error in quadrature from the quoted uncertainties. We then combine the resulting values as if they were completely independent and then add back a conservative 7% common-mode error. This value is then combined with those of the last two rows in Table III which are treated as completely independent results.

D. Indirect experiments

Two indirect techniques have been proposed that may eventually provide useful quantitative information on the low-energy ^{7}Be$(p,\gamma)^8$B reaction: dissociation of ^{8}B's in the Coulomb field of heavy nuclei (Motobayashi *et al.*, 1994), and measurement of the $^8\mathrm{B} \rightarrow {}^7\mathrm{Be} + p$ nuclear vertex constant using single-nucleon transfer reactions (Xu *et al.*, 1994). Motobayashi *et al.* (1994) quote a "very preliminary value" of $S_{17}(0) = (16.7 \pm 3.2)$ eV b. Measurements at low bombarding energies may also provide a constraint of S_{17} (Schwarzenberg *et al.*, 1996; Shyam and Thompson, 1997).

At this point it would be premature to use information from these techniques when deriving a recommended value of $S_{17}(0)$ because the quantitative validity of the techniques has yet to be demonstrated.

What would constitute a suitable demonstration? In the case of the Coulomb dissociation studies, we need a measurement of a dissociation reaction in which radiative capture can also be studied directly; the ideal test case will have many features in common with ^{7}Be$(p,\gamma)^8$B, i.e., a low Q-value, a non-resonant $E1$ cross section, and similar Coulomb acceleration of the reaction products. However, the dissociation cross section has a very different dependence on the multipolarity than does the radiative capture process. Although ^{16}O(p,γ)^{17}F, ^{3}H$(\alpha,\gamma)^7$Li, and ^{12}C$(p,\gamma)^{13}$N each has some of the desired properties, a suitable test case in which the dominant capture multipolarity is E1 and the nuclear structure is sufficiently simple has not yet been identified. On the other hand, a measurement of the $^{17}\mathrm{F} \rightarrow {}^{16}\mathrm{O} + p$ vertex constant and the prediction, using the measured vertex constant, of the ^{16}O$(p,\gamma)^{17}$F capture reaction at low energies will provide a good test of the vertex-constant technique.

To be useful as tests, the indirect calibration reaction and the comparison direct reaction must both be measured with an accuracy of 10% or better. Otherwise, one cannot have confidence in the method to the accuracy required for the cross section of the ^{7}Be$(p,\gamma)^8$B reaction.

E. Recommendations and conclusions

We recommend the value

$$S_{17}(0) = 19^{+4}_{-2} \text{ eV b} , \tag{28}$$

where the 1σ error contains our best estimate of the systematic as well as statistical errors. The recommended value is based entirely on the ^{7}Be$(p,\gamma)^8$B data of Filippone *et al.* (1983a,b) and is 15% smaller than the previous, widely-used value of 22.4 eV b (Johnson *et* *al.*, 1992) that was based upon a weighted average of all of the available experiments. The cross sections were obtained by combining Filippone *et al.*'s (1982) two independent determinations of the target areal density [for the ^{7}Li$(d,p)^8$Li method we used the recommended cross section in Table III], and extrapolated these to solar energies using the calculation of Johnson *et al.* (1992). It is important to note that in the region around $E_p = 1$ MeV where the two data sets overlap, Filippone *et al.*'s (1983a,b) cross sections agree well with those of Vaughn *et al.* (1970). [We renormalized the Vaughn *et al.* (1970) data to our recommended ^{7}Li$(d,p)^8$Li cross section.]

Because history has shown that the uncertainties in determining this cross-section factor are dominated by systematic effects, it is difficult to produce a 3σ confidence interval from a single acceptable measurement. Instead, we quote a "prudent conservative range," outside of which it is unlikely that the "true" $S_{17}(0)$ lies

$$S_{17}(0) = 19^{+8}_{-4} \text{ eV b} . \tag{29}$$

Past experience with measurements of the ^{7}Be$(p,\gamma)^8$B cross section demonstrates the unsatisfactory nature of the existing situation in which the recommended value for $S(0)$ depends on a single measurement. It is essential to have additional ^{7}Be$(p,\gamma)^8$B measurements, to establish a secure basis for assessing the best estimate and the systematic errors for $S_{17}(0)$.

Experiments with ^{7}Be ion beams would be valuable. Such experiments would avoid many of the systematic uncertainties that are important in interpreting measurements of proton capture on a ^{7}Be target. For example, experiments performed with a radioactive beam can measure the beam-target luminosity by observing the recoil protons and Rutherford scattering. But the ^{7}Be-beam experiments will have their own set of systematic uncertainties that must be understood. Fortunately, experiments with ^{7}Be beams are being initiated at several laboratories and results from the first of these measurements may be available within a year or two.

Various theoretical calculations of the ratio of the S-value at 300 keV and at 20 keV differ by several percent. Since these differences will be difficult to measure, yet will contribute to the systematic uncertainty in future precise determinations of the solar S-value, a careful theoretical study should be made to try to understand the origins of the differences in the extrapolations.

F. Late Breaking News

In a recent experiment Hammache *et al.* (1998) measured the cross section at 14 energy points between 0.35 and 1.4 MeV (in the center-of-mass system), excluding the 1^+ resonance energy range. In this experiment two different targets were used with different activities but similar results. Hammache *et al.* determined the ^{7}Be areal density using the two methods employed by Filippone *et al.* (1983a,b) and find consistent results. The measured cross section values are in excellent agreement with those of Filippone *et al.* over the wide energy range where both experiments overlap.

Weissman *et al.* (1998) report a new measurement of the $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ cross section, 155$\pm$8 mb . The authors also draw attention to the importance of the possible loss of product nuclei from the target in cross section measurements performed with high-Z backings. The net result of including this new measurement of the $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ cross section together with the values given in Table III, combined with estimates of the effect of loss of product nuclei on the previously computed values of S_{17}, is a cross-section factor for ^{8}B production that is very close to the best-estimate given in Eq. (29).

IX. NUCLEAR REACTION RATES IN THE CNO CYCLE

The CNO reactions in the Sun form a polycycle of reactions, among which the main CNO-I cycle accounts for 99% of CNO energy production. The contribution of the CNO cycles to the total solar energy output is believed to be small, and, in standard solar models, CNO neutrinos account for about 2% of the total neutrino flux. CNO reactions have been studied much less extensively than the *pp* reactions and therefore, in some important cases, we are unable to determine reliable error limits for the low-energy cross-section factors.

Network calculations show that three reactions primarily determine the reaction rates of the CNO cycles. The three reactions, $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$, $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$, and $^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$, are considered in some detail in this review. With a nuclear reaction rate almost 100 times slower than the other CNO-I reactions, the reaction $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ determines, at solar temperatures, the rate of the main CNO cycle. The ^{13}N and ^{15}O neutrinos have energies and fluxes ($E_\nu \leq 1.8$ MeV, $\phi_\nu(\mathrm{CNO})/\phi_\nu(^7\mathrm{Be}) \approx 0.2$) comparable to the ^{7}Be neutrinos. The production of ^{17}F neutrinos, with a flux two orders of magnitude smaller, is determined by the reaction $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$ in the second cycle, while $^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$ closes the second branch of the CNO cycle.

Figure 5 shows the most important CNO reactions.

A. $^{14}N(p,\gamma)^{15}O$

1. Current Status and Results

A number of measurements of the $^{14}N(p,\gamma)^{15}O$ cross section have been carried out over the past 45 years. Most recently, Schröder *et al.* (1987), measured the prompt capture γ radiations from this reaction at energies as low as $E_p = 205$ keV; the 1957 measurements of the residual β^+-activity of ^{15}O carried out by Lamb and Hester (1957) between $E_p = 100$ and 135 keV remain the lowest proton bombarding energies to be reached in this reaction. The solar Gamow peak is at $E_0 = 26$ keV. Three other experiments are available: Hebbard and Bailey (1963), Pixley (1957), and Duncan and Perry (1951).

Table IV summarizes the measurements and the S-values determined in previous publications, as well as our recommendations.

As emphasized by Schröder *et al.* (1987), the relative contributions to the reaction mechanism are not fully understood. While Hebbard and Bailey (1963) analyze the data in terms of hard-sphere direct-capture mechanisms to the ground, 6.16 MeV, and 6.79 MeV states of ^{15}O, Schröder *et al.* (1987) find a significant contribution to the ground-state capture from the subthreshold resonance at $E_R = -504$ keV, which corresponds to the 6.79-MeV state. The agreement of the S-values recommended by Schröder (1987) and by Hebbard and Bailey (1963) seems therefore accidental. The unexplained 40% correction to the γ-ray detection efficiency of Schardt, Fowler, and Lauritsen (1952) [an experiment on $^{15}N(p,\alpha)^{12}C$ used as a cross-section normalization by Hebbard and Bailey (1963)] and the anomalous energy dependence of the cross sections in Hebbard and Bailey's (1963) analysis argue against inclusion of their results in a modern evaluation of S(0). The lack of a refereed publication describing the work of Pixley (1957), and the use of Geiger-counter technology in the pioneering experiment of Duncan and Perry (1951), are responsible for our excluding these data from the final evaluation.

2. Stopping Power Corrections

The $^{14}N(p,\gamma)^{15}O$ cross sections of Lamb and Hester (1957) are important for our understanding of the CNO-I cycle, since the data were obtained over an energy range significantly closer to the solar Gamow peak (about 30 keV) than other studies of this reaction (see Table IV). Lamb and Hester concluded that the S-factor for this reaction was essentially constant over the range of proton beam energies from 100 to 135 keV with a value $S = (2.7 \pm 0.2)$ keV b. Their measurements were carried out using thick TiN targets and hence measured yields were integrated over energy as the beam slowed down in the target. They assumed a constant stopping power of 2.35×10^{-20} MeV cm^2/atom, a good approximation at these energies—a recent tabulation (Ziegler, Biersack, and Littmark, 1985) gives values of 2.30×10^{-20} MeV cm^2/atom at 100 keV and 2.22×10^{-20} MeV cm^2/atom at 135 keV. In view of the intense proton beams used by Lamb and Hester, there may have been significant hydrogen content in their targets, which would increase the molecular stopping power by 10% (for TiNH instead of TiN).

3. Screening Corrections

Low-energy laboratory fusion cross sections are enhanced by electron screening [see Sec. II B and Assenbaum, Langanke, and Rolfs (1987)]. Screening is a significant effect at the low energies at which Lamb and Hester (1957) explored the ^{14}N$(p,\gamma)^{15}$O reaction. Rolfs and Barnes (1990) show that screening effects become negligible for energy ratios $E/U_e > 1000$, where U_e describes the screening potential. This condition is not satisfied for the data of Lamb and Hester (1957). Within the adiabatic approximation (Shoppa *et al.*, 1993), the screening enhancement can be estimated as $f(E) \approx \exp\left\{59.6E^{-3/2}\right\}$, with the scattering energy E in keV. (This estimate has only been verified for atomic targets.) Screening, and the change in the half-life of ^{15}O from 120 to 122.2 seconds, are treated as corrections, while the considerations related to stopping power are viewed as included in the uncertainties quoted by Lamb and Hester. The screening and lifetime corrections reduce by 8% the $S(0)$ value that otherwise would be inferred from the Lamb and Hester results.

4. Width of the 6.79 MeV State

Schröder *et al.* (1987) made detailed studies of the radiative capture to the bound states of ^{15}O, finding in one case, the ground-state transition, marked evidence for the influence of a subthreshold state, the 6.79-MeV level. They were able to observe the capture to this state directly, and could thus obtain a proton reduced width. The gamma width, however, is not known. Schröder *et al.* (1987) extracted the gamma width as a fit parameter, finding an on-shell width of 6.3 eV. Including the subthreshold state substantially improves the fit to the data at energies as high as $E_p = 2.5$ MeV. However, at the lowest energies for which the ground-state transition was measured, the cross section (on the wings of the 278-keV resonance) is not well described by the published fitting function. Since gamma-width of the 6.79 MeV state is not well constrained, the S-factor for the ground-state transition might in principle increase even more rapidly at low energies than found by Schröder *et al.* (1987), if the data at the lowest measured energies were more heavily weighted in the fitting.

Fortunately, however, there exists a precise measurement of the gamma width of the 7.30-MeV analog state in ^{15}N. Moreh, Sellyey, and Vodhanel (1981) find for that state that $\Gamma_\gamma = 1.08(8)$ eV, which would imply for the 6.79-MeV state a width of 0.87 eV if analog symmetry were perfect. An example is known, however, of a case ($A = 13$) of an isovector E1 transition that shows considerable departure (more than a factor of two) from analog symmetry, but a factor of seven would be surprising. It appears probable, therefore, that the width of the 6.79-MeV state is not significantly larger than that found by Schröder *et al.* (1987). A direct measurement of the gamma width of the 6.79 MeV state would be valuable.

5. Conclusions and Recommended S-Factor for $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$

The experiments of Schröder *et al.* (1987) and Lamb and Hester (1957) can be used to estimate $S(0)$ and its energy derivative. Schröder *et al.* (1987) provide the only detailed data on the reaction mechanism, finding that S rises at lower energies as a result of the subthreshold resonance at $E_R = -504$ keV, while Lamb and Hester (1957) constrain the total cross section at the lowest energies. The extent to which the subthreshold resonances affect the extrapolation to astrophysical energies is, however, limited by the known width of the analog state at 7.30 MeV in ^{15}N, and, to a degree, by the total cross section from Lamb and Hester (1957). The value quoted by Schröder *et al.* (1987) is therefore likely to represent the maximum contribution from a subthreshold state, and cross sections could possibly range down to the values found in the absence of the subthreshold resonance. There is an uncertainty in the normalization of the two experiments as well, and the overall normalization uncertainty is derived as the quadrature of the individual uncertainties.

The recommended value,

$$S(0) = 3.5^{+0.4}_{-1.6} \text{ keV b}, \tag{30}$$

has been obtained by adopting the energy dependences given by Schröder *et al.* (1987) in the presence and the absence of the subthreshold resonance. The energy dependence is parameterized in terms of the intercept $S(0)$ and $S'(0)$

$$S'(0) = -0.008[S(0) - 1.9] \text{ b}. \tag{31}$$

The available data are insufficient to determine S''.

At the mean energy of 120 keV, the data of Lamb and Hester (1957), for which the statistical and normalization uncertainty is 12%, have been corrected as described to give $S(120) = 2.48 \pm 0.31$ keV b. For each choice of energy dependence, those data have been converted to zero energy and a weighted average formed with the data of Schröder *et al.* (1987), for which the statistical and normalization uncertainty is 17%. The n-sigma upper limits on the average are a quadrature of $3.7 + n(0.45)$ and $3.2 + n(0.54)$ keV b; the lower limits are a quadrature of $2.5 - n(0.30)$ and $1.9 - n(0.31)$ keV b. This prescription, while arbitrary, reflects our view that the resonance and no-resonance extrapolations represent a total theoretical uncertainty. Hence the recommended "three-sigma" range is

$$S(0) = 3.5^{+1.0}_{-2.0} \text{ keV b}. \tag{32}$$

Figure 6, adapted from Schröder *et al.* (1987), shows the extant data; the extrapolations shown represent the likely range of theoretical uncertainty. Additional uncertainty from normalization is not shown in the figure.

The uncertainty in the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ reaction rate is much larger than previously assumed, and produces comparable uncertainties in the calculated CNO neutrino fluxes. On the other hand, the most important calculated solar neutrino fluxes from the *p-p* cycle are affected by at most 1% for a 50% change in the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ reaction rate, as can be seen using the logarithmic partial derivatives given by Bahcall (1989).

New experiments are necessary to improve the understanding of the capture mechanism and the cross sections in $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$.

B. $^{16}\mathbf{O}(p,\gamma)^{17}\mathbf{F}$

The rate of $^{17}\mathrm{F}$ neutrino production in the Sun is determined primarily (see Bahcall and Ulrich, 1988) by the rate of the $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$ reaction. A number of measurements of the $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$ reaction were made between 1949 and the early 70's, and the data are all in relatively good agreement. Tanner's (1959) work is consistent with Hester, Pixley and Lamb's (1958) lower-energy measurement. Rolfs' (1973) higher-precision work yields the value

$$S(0) = 9.4 \pm 1.7 \text{ keV b}\ . \tag{33}$$

No resonance occurs below $E_p = 2.5$ MeV and a direct capture model describes well the data over the entire energy range studied. Since all of the experimental results are consistent with each other, Rolfs' (1973) value is adopted. For the latest work on this reaction, see Morlock *et al.* (1997).

C. $^{17}\mathbf{O}(p,\alpha)^{14}\mathbf{N}$

The ^{17}O$(p,\alpha)^{14}$N reaction closes the CNO-II branch of the CNO cycles. The S-factor for this reaction has been particularly difficult to measure or predict at solar energies, because of the large number of resonances and the difficulty of detecting low-energy alphas. Rolfs and Rodney (1975) suggested that a 66 keV resonance may introduce complications arising from the interference of the 5604 and 5668 keV energy levels of ^{17}O. In 1995, an experiment at Triangle Universities Nuclear Laboratory (Blackmon *et al.*, 1995) disclosed a resonance located between 65 and 75 keV in a comparison of the alpha yields from ^{17}O and ^{16}O targets. Experiments done by the Bochum group (Berheide *et al.*, 1992), on the other hand, do not show evidence for the resonance, and exclude a resonance of the size seen by Blackmon *et al.* (1995), but only on the basis of a smoothly varying background. The proton partial width of Blackmon *et al.* (1995) is $\Gamma_p = 22^{+5}_{-4}$ neV while Berheide *et al.* (1992) find $\Gamma_p \leq 3$ neV. The Bochum group have recently reanalyzed their data, finding that a different energy calibration procedure and choice of background would change their upper limit to 75 neV (Trautvetter, 1997). They also have new radiative capture data that indicate an upper limit of 38 neV. Landre *et al.* (1989) measured the proton reduced width in ^{17}O$(^3\mathrm{He},d)^{18}$F, but, because the state is weak in proton stripping, uncertainties in the reaction mechanism (multi-step and compound nucleus processes) are reflected in the uncertainty; $\Gamma_p = 71^{+40}_{-57}$ neV. We recommend using the proton width measured by Blackmon *et al.* (1995), but caution the reader that contradictory data have not been revised in the published literature.

Table V summarizes the numerical results. The presence of a near-threshold resonance has a significant, but incompletely quantified, effect on the ^{17}O$(p,\alpha)^{14}$N cross section at solar energies.

D. Other CNO Reactions

We have recomputed the cross-section factors for the ^{12}C$(p,\gamma)^{13}$N reaction, combining the data of Rolfs and Azuma (1974) and Hebbard and Vogl (1960). We find $S(0) = (1.34 \pm 0.21)$ keV b, $S'(0) = 2.6 \times 10^{-3}$ b, and $S''(0) = 8.3 \times 10^{-5}$ b/keV. For the reaction ^{13}C$(p,\gamma)^{14}$N, we recommend the most recent determination of the S-value reported in Table VI, i.e., the values given by King *et al.* (1994).

For the ^{15}N$(p,\alpha_0)^{12}$C reaction, we have computed the weighted average cross-section factor using the results of Redder *et al.* (1982) and of Zyskind and Parker (1979) [including the more accurate measurement by Redder *et al.* of the cross section at the peak of the resonance]. We find a weighted average of $S(0) = (67.5 \pm 4) \times 10^3$ keV b. The cross-section derivatives are $S'(0) = 310$ b and $S''(0) = 12$ b/keV.

For the reaction $^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$, only an approximate S-value is given since $S(E)$ cannot be described by the usual Taylor series and the original analysis by Lorenz-Wirzba *et al.* (1979) determined directly the stellar reaction rates. Wiescher and Kettner (1982) suggest a modification of the rate. Very recently, Spyrou *et al.* (1997) have measured cross sections for the $^{19}\mathrm{F}(p,\alpha)^{16}\mathrm{O}$ reaction, but the S-factor was not determined at energies of interest in solar fusion.

E. Summary of CNO Reactions

Table VI summarizes the most recently published S-values and derivatives for reactions in the solar CNO-cycle. Since the reaction $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ is the most important for calculations of stellar energy generation and solar neutrino fluxes, it is treated in detail in Table IV and the recommended values for the cross-section factor and its uncertainties are presented in Sec. IX A 5. Other CNO reactions are discussed in Sec. IX B, Sec. IX C, and Sec. IX D.

F. Recommended New Experiments and Calculations

Further experimental and theoretical work on the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ reaction is required in order to reach the level of accuracy ($\sim 10\%$) for the low-energy cross-section factor that is needed in stellar evolution calculations.

1. Low-energy Cross Section

The cross-section factor for capture directly to the ground state is expected to increase steeply at energies below the resonance energy of 278 keV; direct experimental proof of this increase is not yet available. Experiments at the Gran Sasso underground laboratory (LNGS) using a 1 kg low-level Ge-detector have shown (Balysh *et al.*, 1994) no background events in the energy region near $E_\gamma = 7.5$ MeV over several days of running. A Ge-detector arrangement coupled with a 200-kV high-current accelerator at LNGS [LUNA phase II; Greife *et al.*, 1994; Fiorentini, Kavanagh, and Rolfs, 1995; LUNA-Collaboration (Arpesella *et al.*, 1996)] would allow measurements down to proton energies of 82 keV (corresponding to 1 event per day) and could thus confirm or reject the predicted steep increase in $S(E)$ for direct captures to the ground state. Still lower energies might be reached by detecting the ^{15}O residual nuclides via their β^+-decay ($T_{\frac{1}{2}} = 122$ s).

2. R-matrix Fits and Estimates of the $^{14}N(p,\gamma)^{15}O$ Cross Section

Though not fully described, the fit to the ground-state transition in Schröder *et al.* (1987) seems to be based on single Breit-Wigner R-matrix resonances and a direct-capture (DC) model added according to a simple prescription not entirely consistent with R-matrix theory. An alternative approach would be to fit the groundstate transition including direct-capture and resonant amplitudes following, for example, the description of Barker and Kajino (1991). Proper account should be taken of the target thickness. Elastic scattering data of protons on ^{14}N should be included in the analysis.

3. Gamma Width Measurement of the 6.79 MeV State

Schröder *et al.* (1987) suggest a large contribution of the sub-threshold state at 6.79 MeV in ^{15}O to the ^{14}N$(p,\gamma)^{15}$O capture data, and find that the gamma width of that state is 6.3 eV. Other experiments yield only an upper limit of 28 fs ($\Gamma_\gamma \geq 0.024$ eV, Ajzenberg-Selove, 1991) for the lifetime of the 6.79-MeV state. Depending upon the actual width, the Variant Doppler Shift Attenuation Method (Warburton, Olness, and Lister, 1979; Catford *et al.*, 1983), or Coulomb excitation of a ^{15}O radioactive beam, might yield an independent measurement of this width. Data on the Coulomb dissociation of ^{15}O could also shed light on the partial cross sections to the ground state (but not on the total cross section, which includes important contributions from capture transitions into ^{15}O excited states).

X. DISCUSSION AND CONCLUSIONS

Table I summarizes our best estimates, and the associated uncertainties, for the low-energy cross sections of the most important solar fusion reactions. The considerations that led to the tabulated values are discussed in detail in the sections devoted to each reaction.

Our review of solar fusion reactions has raised a number of questions, some of which we have resolved and others of which remain open and must be addressed by future measurements and calculations. The reader is referred to the specialized sections for a discussion of the most important additional research that is required for each of the reactions we discuss.

Our overall conclusion is that the knowledge of nuclear fusion reactions under solar conditions is, in general, detailed and accurate and is sufficient for making relatively precise predictions of solar neutrino fluxes from solar model calculations. However, a number of important steps still must be taken in order that the full potential of solar neutrino experiments can be utilized for astronomical purposes and for investigating possible physics beyond the minimal standard electroweak model.

We highlight here four of the most important reactions for which further work is required.

• The only major reaction that has so far been studied in the region of the Gamow energy peak is the ^{3}He(^{3}He, 2p)^{4}He reaction. A more detailed study of this reaction at low energies is required, with special attention to the region between 15 keV and 60 keV.

• The six measurements of the ^{3}He(α,γ)^{7}Be reaction made by direct capture differ by about 2.5σ from the measurements made using activity measurements. Additional precision experiments that could clarify the origin of this apparent difference would be very valuable. It would also be important to make measurements of the cross section for the ^{3}He(α,γ)^{7}Be reaction at energies closer to the Gamow peak.

• The most important nuclear fusion reaction for interpreting solar neutrino experiments is the ^{7}Be(p,γ)^{8}B reaction. Unfortunately, among all of the major solar fusion reactions, the ^{7}Be(p,γ)^{8}B reaction is the least well known experimentally. Additional precise measurements, particularly at energies below 300 keV, are required in order to understand fully the implications of the new set of solar neutrino experiments, Super-Kamiokande, SNO, and ICARUS, that will determine the solar ^{8}B neutrino flux with high statistical significance.

• The ^{14}N(p,γ)^{15}O reaction plays the dominant role in determining the rate of energy generation of the CNO cycle, but the rate of this reaction is not well known. The most important uncertainties concern the size of the contribution to the total rate of a subthreshold state and the absolute normalization of the low-energy cross-section data. New measurements with modern techniques are required.

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TABLE I. Best estimate low-energy nuclear reaction cross-section factors and their estimated 1σ errors.

Reaction	$S(0)$ (keV b)	$S'(0)$ (b)
$^1\mathrm{H}\,(p, e^+\nu_e)\,^2\mathrm{H}$	$4.00\left(1 \pm 0.007^{+0.020}_{-0.011}\right)\mathrm{E}-22$	$4.48\mathrm{E}-24$
$^1\mathrm{H}\,(pe^-, \nu_e)\,^2\mathrm{H}$	Eq. (19)	
$^3\mathrm{He}\,(^3\mathrm{He}, 2p)\,^4\mathrm{He}$	$(5.4 \pm 0.4)\,\mathrm{E}+3$[a]	
$^3\mathrm{He}\,(\alpha, \gamma)\,^7\mathrm{Be}$	0.53 ± 0.05	$-3.0\mathrm{E}-4$
$^3\mathrm{He}\,(p, e^+\nu_e)\,^4\mathrm{He}$	$2.3\mathrm{E}-20$	
$^7\mathrm{Be}\,(e^-, \nu_e)\,^7\mathrm{Li}$	Eq. (26)	
$^7\mathrm{Be}\,(p, \gamma)\,^8\mathrm{B}$	$0.019^{+0.004}_{-0.002}$	See Sec. VIII A
$^{14}\mathrm{N}\,(p, \gamma)\,^{15}\mathrm{O}$	$3.5^{+0.4}_{-1.6}$	See Sec. IX A 5

[a]Value at the Gamow peak, no derivative required. See text for $S(0), S'(0)$.

TABLE II. Measured values of $S_{34}(0)$.

$S_{34}(0)$ (keV b)	Reference
Measurement of capture γ-rays:	
0.47 ± 0.05	Parker and Kavanagh (1963)
0.58 ± 0.07	Nagatani, Dwarakanath, and Ashery (1969) [a]
0.45 ± 0.06	Kräwinkel *et al.* (1982)[b]
0.52 ± 0.03	Osborne *et al.* (1982, 1984)
0.47 ± 0.04	Alexander *et al.* (1984)
0.53 ± 0.03	Hilgemeier *et al.* (1988)
Weighted Mean = $0.507 \pm .016$	
Measurement of ^{7}Be activity:	
0.535 ± 0.04	Osborne *et al.* (1982, 1984)
0.63 ± 0.04	Robertson *et al.* (1983)
0.56 ± 0.03	Volk *et al.* (1983)
Weighted Mean = $0.572 \pm .026$	

[a]As extrapolated using the direct-capture model of Tombrello and Parker (1963).
[b]As renormalized by Hilgemeier, *et al.* (1988).

TABLE III. ^{7}Li$(d,p)^{8}$Li cross section (σ) at the peak of the 0.6 MeV resonance[a]

Reference	σ (mb)
McClenahan and Segal (1975)	138 ± 20
Elywn *et al.* (1982)	146 ± 13
Filippone *et al.* (1982)	148 ± 12
Filippone *et al.* (1982) (Our evaluation, see text)	146 ± 19
Strieder *et al.* (1996) (Our evaluation, see text)	144 ± 15
Recommended value	147 ± 11

[a]see also the discussion of Weissman *et al.* (1998) in Sec. VIII F

TABLE IV. Cross-section factor, $S(0)$, for the reaction ^{14}N$(p,\gamma)^{15}$O. The proton energies, E_p, at which measurements were made are indicated.

$S(0)$ keV b	E_p MeV	Reference
3.20 ± 0.54	0.2-3.6	Schröder *et al.* (1987)
3.32 ± 0.12		Bahcall *et al.* (1982)[a]
3.32		Fowler, Caughlan, and Zimmerman (1975)[a]
2.75	0.2-1.1	Hebbard and Bailey (1963)
3.12		Caughlan and Fowler (1962)[a]
2.70	0.100-0.135	Lamb and Hester (1957)
$3.5^{+0.4}_{-1.6}$		Present recommended value

[a]Compilation and evaluation: no original experimental data.

TABLE V. Near threshold resonance widths for ^{17}O$(p,\alpha)^{14}$N

^{18}F levels (keV)	5603.4	5604.9	5673	Reference
Γ_α (eV)	43	60	130	Mak *et al.* (1980), Silverstein *et al.* (1961)
Γ_γ (eV)	0.5	0.9	1.4	Mak *et al.* (1980), Silverstein *et al.* (1961)
Γ_p (neV)			71^{+40}_{-57}	Landre *at al.* (1989)
			≤ 3, ≤ 75	Berheide *et al.* (1992)
			22^{+5}_{-4}	Blackmon *et al.* (1995)

TABLE VI. Summary of published S-values and derivatives for CNO reactions. See text for details and discussion. When more than one S-value is given, the recommended value is indicated in the table.

Reaction	Cycle	$S(0)$ keV b	$S'(0)$ b	$S''(0)$ b keV^{-1}	Reference
$^{12}C(p,\gamma)^{13}N$	I	1.34 ± 0.21	2.6E−3	8.3E−5	Recommended; this paper
		1.43			Rolfs and Azuma (1974)
		1.24 ± 0.15			Hebbard and Vogl (1960)
$^{13}C(p,\gamma)^{14}N$	I	7.6 ± 1	−7.8E−3	7.3E−4	Recommended; King *et al.* (1994)
		10.6 ± 0.15			Hester and Lamb (1961)
		5.7 ± 0.8			Hebbard and Vogl (1960)
		8.2			Woodbury and Fowler (1952)
$^{14}N(p,\gamma)^{15}O$	I	$3.5^{+0.4}_{-1.6}$	see text		see Table IV
$^{15}N(p,\alpha_0)^{12}C$	I	(6.75 ± 0.4)E+4	310	12	Recommended; this paper
		(6.5 ± 0.4)E+4			Redder *et al.* (1982)
		(7.5 ± 0.7)E+4	351	11	Zyskind and Parker (1979)
		5.7E+4			Schardt, Fowler, and Lauritsen (1952)
$^{15}N(p,\alpha_1)^{12}C$	I	0.1			Rolfs (1977)
$^{15}N(p,\gamma)^{16}O$	II	64 ± 6	2.1E−2	4.1E−3	Rolfs and Rodney (1974)
$^{16}O(p,\gamma)^{17}F$	II	9.4 ± 1.7	−2.4E−2	5.7E−5	Rolfs (1973)
$^{17}O(p,\alpha)^{14}N$	II				Brown (1962) (see Table V)
					Kieser, Azuma, and Jackson (1979)
$^{17}O(p,\gamma)^{18}F$	III	12 ± 2			Rolfs (1973)
$^{18}O(p,\alpha)^{15}N$	III	$\sim$ 4E+4			Lorenz-Wirzba *et al.* (1979)
$^{18}O(p,\gamma)^{19}F$	IV	15.7 ± 2.1	3.4E−4	−2.4E−6	Wiescher *et al.* (1980)

FIG. 1. The figure shows the integrand, $u_{pp}(r) \times u_d(r)$, of the nuclear matrix element Λ versus radius (fm). The ordinate is given in units of $(\mathrm{fm})^{-1/2}$. Here $u_{pp}(r)$ and $u_d(r)$ are, respectively, the radial wave functions of the p-p initial state and the deuteron final state. The figure (taken from Kamionkowski and Bahcall, 1994) displays the integrand calculated assuming five very different p-p potentials. In (a) we show the overlap out to a radius of 50 fm, while in (b) we magnify the first 5 fm. Even drastic changes in the p-p potential result in relatively small changes of the integrand.

FIG. 2. This figure is adapted from Fig. 9 of Junker *et al.* (1998), a recent paper by the LUNA Collaboration. The measured cross-section factor $S(E)$ for the $^3\mathrm{He}(^3\mathrm{He}, 2p)^4\mathrm{He}$ reaction is shown and a fit with a screening potential U_e is illustrated. The Gamow peak at the solar central temperature is shown in arbitrary units. The data shown here correspond to a bare nucleus value at zero energy of $S(0) = 5.4$ MeV b and a value at the Gamow peak of $S(\mathrm{Gamow\ Peak}) = 5.3$ MeV b.

FIG. 3. Comparison of the energy dependence of the direct-capture model calculation (Tombrello and Parker, 1963) with the energy dependence of each of the four $S_{34}(E)$ data sets which cover a significant energy range. The data sets have been shifted arbitrarily in order to show the comparison of the calculation with *each* data set.

[Hi88]: (Hilgemeier *et al.*, 1988)

[Kr82]: (Kräwinkel *et al.*, 1982)

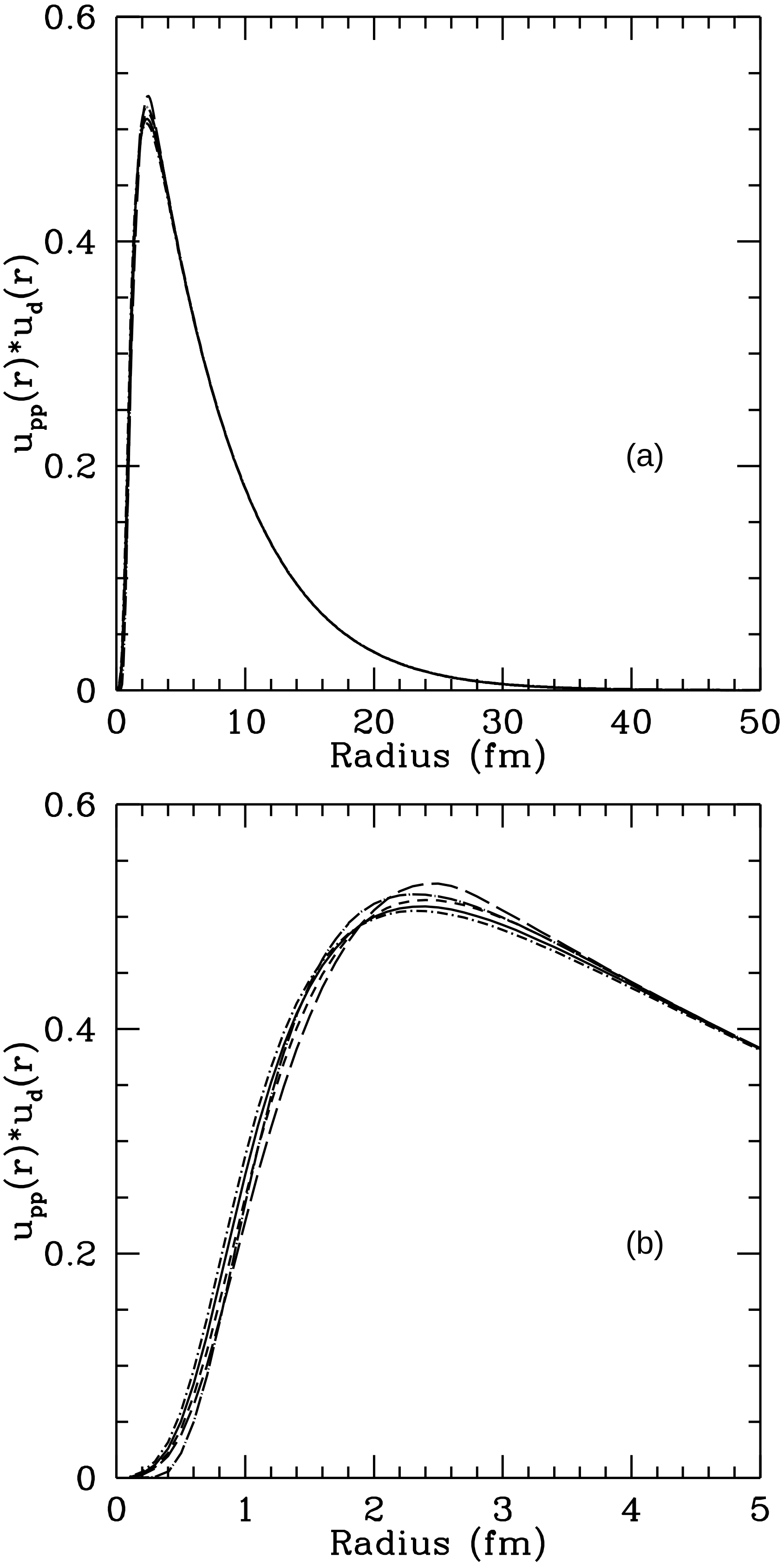
[Os82]: (Osborne *et al.*, 1982)

[Pa63]: (Parker and Kavanagh, 1963)

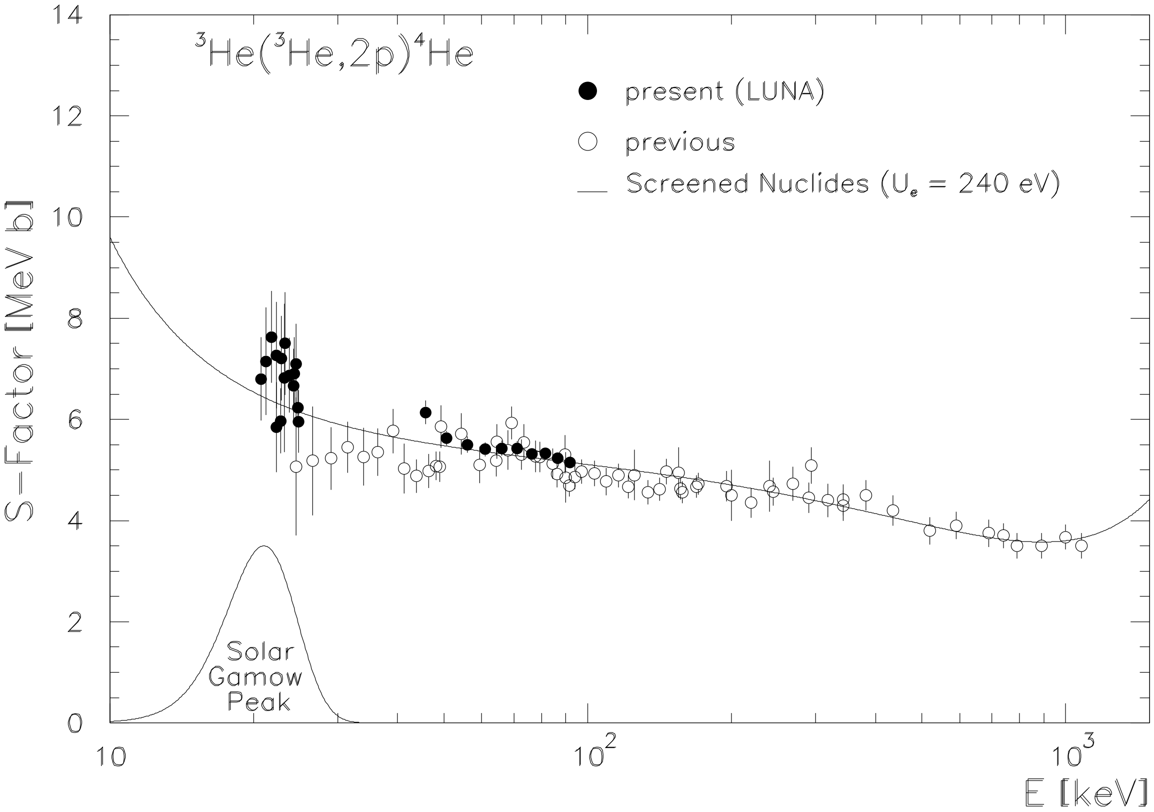
FIG. 4. Model calculations (Tombrello and Parker, 1963) of the fractional contributions of various partial waves and multipolarities to the total (ground state plus first excited state) $^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$ direct-capture cross section factor.

FIG. 5. CNO reactions summarized in schematic form. The widths of the arrows illustrate the significance of the reactions in determining the nuclear fusion rates in the solar CNO cycle. Certain "Hot CNO" processes are indicated by dotted lines.

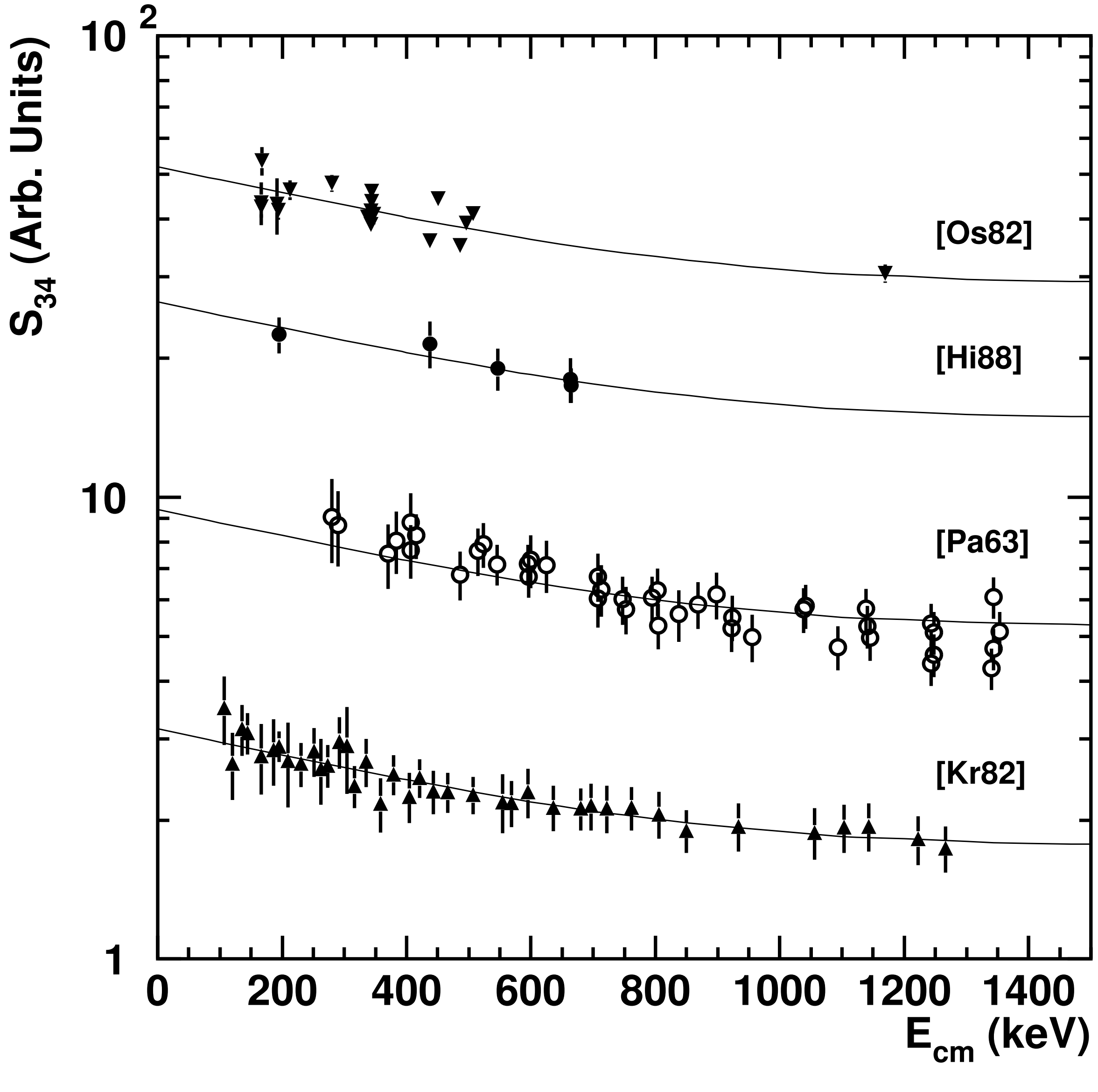
FIG. 6. Cross sections for $^{14}\mathrm{N}\,(p,\gamma)\,^{15}\mathrm{O}$, expressed as $S(E)$, from extant experimental data. The data of Lamb and Hester have been corrected as described in the text. The curves represent the low-energy extrapolations that would be obtained under the two assumptions of no subthreshold resonance (dotted) at $E_R = -504$ keV, and a resonance of the strength considered by Schröder *et al.* (dashed).



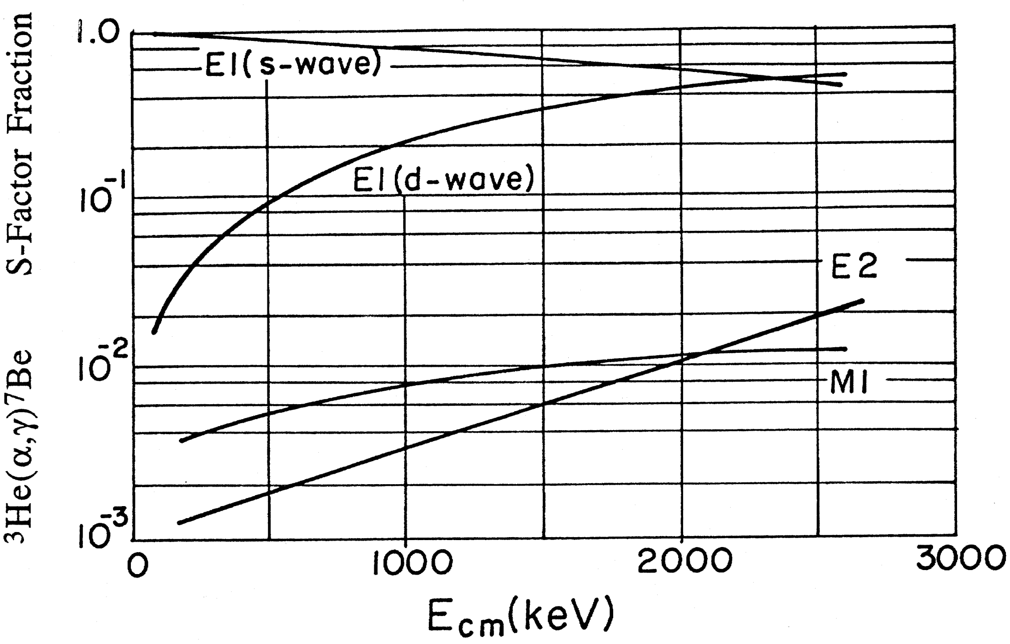
0.6
0.4
0.2
0
0
10
20
30
40
50
Radius (fm)
u_pp(r)*u_d(r)
(a)
0.6
0.4
0.2
0
0
1
2
3
4
5
Radius (fm)
u_pp(r)*u_d(r)
(b)



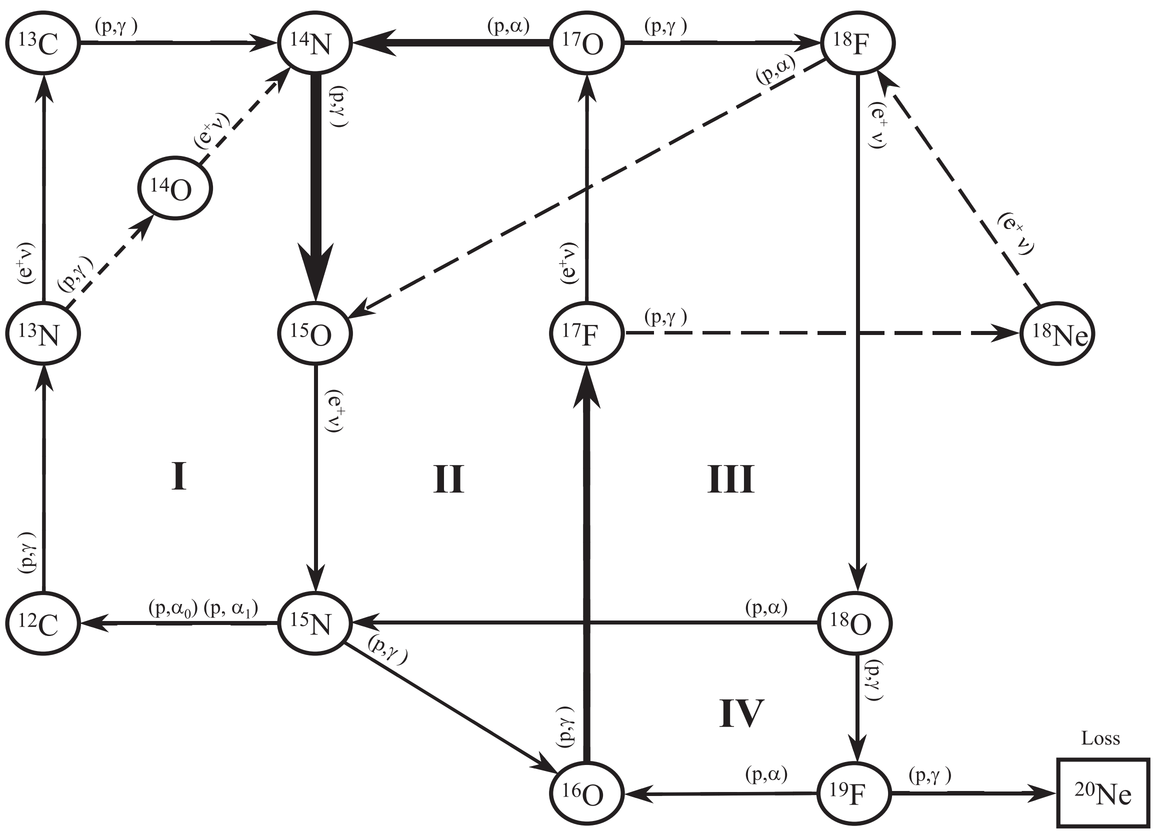
$^3He(^3He,2p)^4He$
present (LUNA)
previous
Screened Nuclides (U_e = 240 eV)
Solar
Gamow
Peak
S-Factor [MeV b]
E [keV]
0
2
4
6
8
10
12
14
10
10^2
10^3



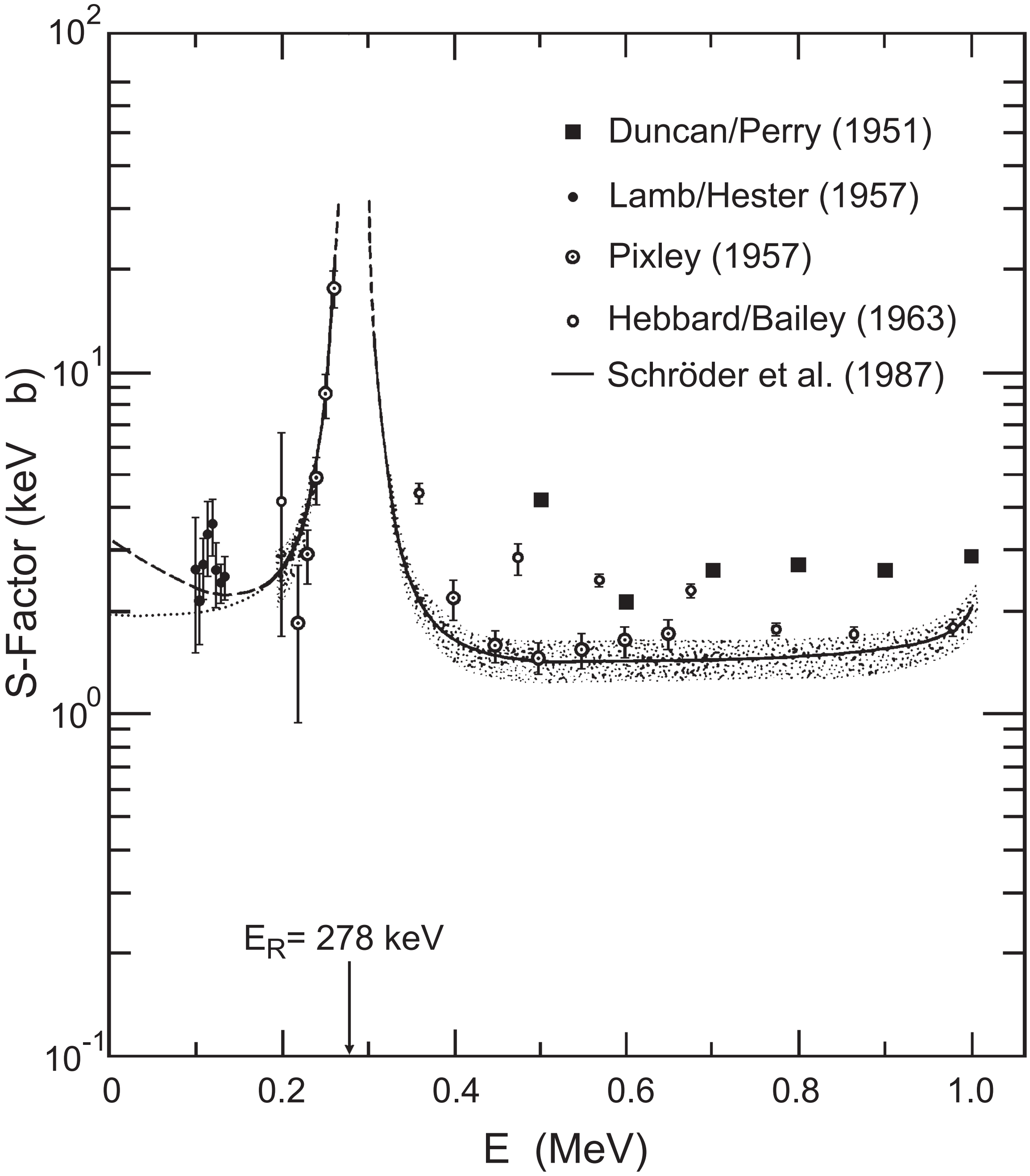
S_{34} (Arb. Units)
10 2
10
1
[Os82]
[Hi88]
[Pa63]
[Kr82]
0
200
400
600
800
1000
1200
1400
E_{cm} (keV)



1.0
E1(s-wave)
E1(d-wave)
E2
M1
10^{-1}
10^{-2}
10^{-3}
0
1000
2000
3000
E_{cm}(keV)
^{3}He(α,γ)^{7}Be S-Factor Fraction



13C
14N
17O
18F
14O
13N
15O
17F
18Ne
12C
15N
18O
16O
19F
20Ne
Loss
I
II
III
IV
(p,γ)
(p,α)
(e+ν)
(p,α0) (p, α1)


Duncan/Perry (1951)
Lamb/Hester (1957)
Pixley (1957)
Hebbard/Bailey (1963)
Schröder et al. (1987)
S-Factor (keV b)
E (MeV)
E_R= 278 keV
10^2
10^1
10^0
10^-1
0
0.2
0.4
0.6
0.8
1.0