Cross section of the capture reaction $^3He(\alpha,\gamma)^7Be$

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The cross sections for the astrophysically significant reactions $^3He(\alpha,\gamma)^7Be$ and $^4He(^3He,\gamma)^7Be$ have been measured near 900 keV in the center of mass by measuring the activity of ^7Be produced in a gas cell. The results imply a zero-energy cross-section factor $S(0)$ of 0.63(4) keV b, consistent with the larger of previous measurements. Extant values of $S(0)$ are reviewed and a recommended value for use in stellar evolution calculations is presented.

[NUCLEAR REACTIONS $^3He(\alpha,\gamma)^7Be$, $^4He(^3He,\gamma)^7Be$, $E_{c.m.}=897$ keV, measured σ, deduced astrophysical capture cross section.]

I. INTRODUCTION

The reaction $^3He(\alpha,\gamma)^7Be$ is a link in the chain of reactions leading to ^8B in the interior of the sun and other hydrogen-burning stars.[1] Since ^8B is responsible for most of the neutrinos observable in the experiment of Davis,[2] there is great interest in the recent experiment of Kräwinkel *et al.*,[3] who reported cross sections for $^3He(\alpha,\gamma)^7Be$ almost a factor of 2 lower than those found in previous work.[4,5] Adopting their value significantly reduces, but does not entirely remove, the discrepancy between the predicted neutrino flux[1] and the experimental result.[2]

It appears that there is no significant disagreement about the energy dependence of the cross section and that it is only the normalization that is in question. In an effort to resolve the discrepancy, we have undertaken a measurement at a single energy (900 keV in the center of mass) using a method well suited to a reliable determination of the absolute cross section. A cell containing ^3He (^4He) is bombarded with ^4He (^3He) for a known integrated flux and the resulting ^7Be is assayed with a detector of known absolute efficiency. The technique is independent of the angular distribution of capture radiation and of its disposition between cascade paths. Furthermore, an accurate determination of the target thickness is easier than it is for windowless gas targets.

II. EXPERIMENT METHOD

Three identical gas cells were used: one was filled with ^3He and bombarded with ^4He; the second was filled with ^4He and bombarded with ^3He; the third was filled with ^4He and bombarded with ^4He. This last cell was used for beam tuning and to check the radiochemical purity of the construction materials. The cells were mounted on a post having rotational and up-down translational freedom in a scattering chamber. The beam entered the chamber through a 4-jaw slit located 56.2 cm from the center of the cell, and was in every irradiation limited to 240 nA ($^3He^+$ or $^4He^+$) in order to avoid damage to the Ni entrance windows of the cells. The beam spot size was set to 0.28 by 0.28 cm at the slit, and care was taken to illuminate the slit aperture uniformly to avoid destructive localized heating of the entrance windows. Figure 1 shows a schematic drawing of the gas cell.

The energy of the beam delivered by the vertical Van de Graaff accelerator at the Los Alamos National Laboratory was determined by magnetic analysis. In a test run immediately prior to the experiments reported herein, the calibration of the analyzing magnet was checked against the 3.046-MeV resonance[6] in $^{16}O(\alpha,\alpha)^{16}O$ and was found to be accurate to within the 10 keV uncertainty of the measurement.

The number of beam particles incident on the target was determined by elastic scattering from a gold foil placed 0.48 cm in front of the entrance window of the cell. Elastically scattered particles were detected in a Si surface barrier detector mounted in an extension tube connected to the vacuum chamber. A tantalum collimator 0.638 cm in diameter defined the solid angle subtended by this detector to be $1.310(5)\times10^{-4}$ sr. The distance from the gold foil

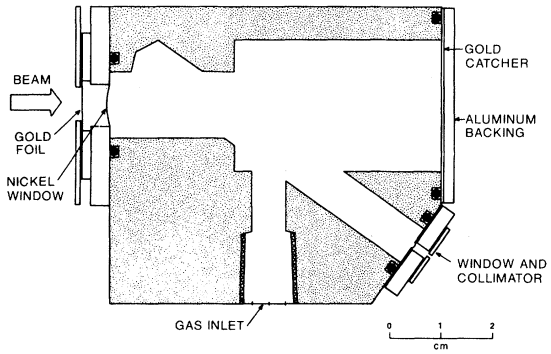

FIG. 1. Cross-sectional view of the gas cells. The cell body, shown stippled, is brass.

to the detector, 49.4 cm, and the scattering angle, 144.4(1) deg, were determined by triangulation. The gold foils were sufficiently thick that the elastic scattering peak was broad and flat-topped, permitting a determination of the number of incident beam particles independent of the foil thickness by using the accurately known stopping power for ^{4}He ions in gold. Beam current was also measured and integrated electrically, but owing to losses of secondary electrons through the chamber pumping port and contamination of the nominally singly-charged beam by ions stripped in the residual gas of the beam line, the electrical method was used only for general monitoring and tuning. When approximate corrections were made for the noted effects, the electrical method and the scattering method agreed within about 5%.

The number of beam projectiles N_p incident on a thick foil is related to the number of scattered particles N_s detected per channel by[8]

$$N_p = N_s \frac{[\epsilon(E)]\epsilon(E_1)}{\sigma_R(E)\Omega\delta E_1 \epsilon(KE)} ,$$

where $\sigma_R(E)$ is the Rutherford scattering cross section at laboratory energy E, Ω is the solid angle subtended by the detector, δE_1 is the width of one channel, and $\epsilon(E_1)$ is the atomic stopping power at energy E_1. The quantity $[\epsilon(E)]$ is an effective atomic stopping power given by

$$[\epsilon(E)] = K\epsilon(E) + \epsilon(KE) \,|\cos\theta\,|^{-1} ,$$

where θ is the laboratory scattering angle. The kinematic factor K is the ratio of scattered to incident laboratory energies. In the above expressions, E is the energy at which a scattering takes place while E_1 is the observed laboratory energy of the particle so scattered. These relationships are approximate in the sense that stopping powers are assumed to vary linearly over small intervals, but numerical tests suggest that this assumption is good to 0.1% or better under the conditions of our experiments.

The ^{7}Be recoils resulting from ^{3}He+^{4}He capture were stopped in a catcher consisting of a 0.127-mm gold sheet epoxied to a 1.59-mm thick aluminum backing. In this we were guided by some experimental observations made[7] by Filippone and Davids that gold was "excellent" and tantalum "poor" at retaining ^{7}Be implants. Our experiments used beam currents a hundred times weaker than the tests conducted by Filippone and Davids, for comparable periods of time. Gas pressures were chosen such that ^{7}Be recoils would not stop in the gas. Nevertheless, as a precaution against possible ^{7}Be migration, the cells were filled and sealed by means of a valve external to the chamber. After irradiation, the chamber pressure was raised slightly above that of the cell by admitting argon. Then argon was also admitted to the cell until both chamber and cell were at atmospheric pressure. By means of a valve inside the chamber, the cell, still containing target gas and argon, was sealed off and removed for counting. The complete sealed cells were assayed in this way, and subsequently the catcher was removed so that the catcher and the cell body could be counted separately. It was found that the results were consistent with all the ^{7}Be being trapped in the catcher; however, because the cell interior is complicated in shape and is located, on the average, much further from the detector than the catcher, it is difficult to place a quantitative limit on ^{7}Be located elsewhere than in the catcher. It is possible that as much as 20% of the ^{7}Be could escape detection if it were distributed throughout the volume of the cell. However, we have made the assumption that all the ^{7}Be is located in the catcher, and we note in passing that failure of this assumption would imply larger cross sections than we measure.

The cells were filled with high-purity gases (^{3}He nominally 99.9% isotopically and chemically pure, ^{4}He nominally 99.998% chemically pure). The pressure was measured with an aneroid manometer whose calibration was checked against a precision fused-quartz pressure gauge accurate to 0.02 Torr. The temperature of the (water-cooled) cells was monitored by means of a thermistor. A 35° port on the cells allowed observation of elastic scattering from the target gas. This feature was used to measure the influence of beam heating on the gas in the cell (about a 2% reduction in density) and the growth of air contamination in the gas (about 1% by volume per day). Because the 35° monitor inspects only a limited region of gas about 2 cm behind the window, it is not sensitive to localized heating of the gas caused by the window itself. However, the measurements made by Parker and Kavanagh[4] imply that, for our experiment, an error in target thickness

no more than 2% would result. We have not attempted to include any extra correction for this effect.

Following the bombardments, the cells were counted with a large Ge(Li) detector whose nominal efficiency at 1333 keV was 22% that of a 7.6-cm diameter by 7.6-cm deep NaI(Tl) detector at 25 cm, and whose resolution was 1.3 keV at 478 keV. The detector was surrounded by 5 cm of copper and 10 cm of lead. Background rates of 2 counts per hour per keV resulted in peak-height-to-background ratios in the range of 3 to 5. Figure 2 shows the 478-keV line from the cell containing ^3He.

The absolute photopeak efficiency of the detector for 478-keV photons at various distances both on and off the detector axis was determined by measuring the activity of a ^7Be source with the aid of an intensity standard provided by the National Bureau of Standards (NBS). That source, containing ^{125}Sb, ^{154}Eu, and ^{155}Eu, emitted lines in the 100- to 1300-keV range whose absolute intensities were known to 0.6—0.8 %. The efficiencies measured were checked with a ^{60}Co standard prepared by the Radiochemical Centre, Amersham, England, and found to agree within 1%. The ^7Be source, prepared via the $^6Li(d,n)$ reaction at 2 MeV, was standardized at a distance (10 cm) sufficient to ensure that true coincidence summing between photons from the NBS source was negligible.

Standard electronics was used to record data both during irradiation and counting. Precision pulsers provided dead-time correction and gain stabilization.

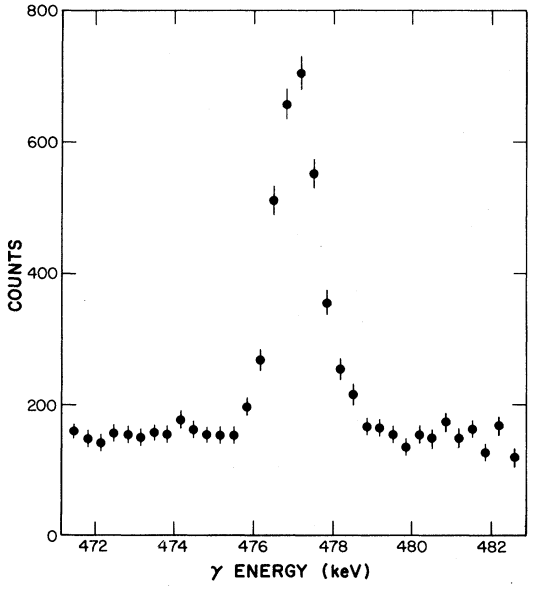

FIG. 2. Portion of γ-ray spectrum showing 478-keV line from ^7Be decay.

TABLE I. Typical parameters for the irradiations.

Beam	Target	Pressure (Torr)	Temperature (K)	Run duration (h)
2.66-MeV ^4He	^3He	135	285	48
2.15-MeV ^3He	^4He	61	285	24

III. RESULTS

During the irradiation of each cell, data on the number of scattered particles, pressure, temperature, and time were recorded at intervals of approximately 1 h. The number of ^7Be nuclei produced in each interval was calculated per unit capture cross section and corrected to a fixed reference time. Typical run parameters are listed in Table I. In calculating the number of ^7Be nuclei we considered several small effects and the uncertainties therein. The length of the cell, 63.80(25) mm, includes a correction for the bowing of the entrance window, about 0.25 mm. The cell pressure, known to 0.5 Torr, was corrected by the beam-heating factor 0.980(15), and for air contamination (a time-dependent correction contributing uncertainties of 0.3% for the ^3He filling and 0.5% for the ^4He filling). The average width of one channel in the 144° monitor spectrum was 4184(14) eV. The stopping power for ^4He in Au, taken from the work of Ziegler,[9] is believed to be accurate to about 2%. It has been assumed that ^3He ions lose energy at the same rate as ^4He ions of the same velocity. Finally, a small correction was made for loss of beam particles due to Rutherford scattering in the entrance window of the cell; this factor was calculated to be 0.995(2) for the ^4He beam and 0.990(2) for the ^3He beam.

Figure 3 shows the monitor spectrum observed

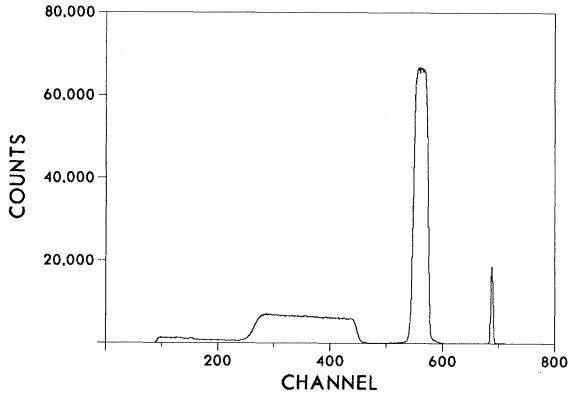

FIG. 3. Spectrum of α particles scattered at 144° from the gas cell entrance window. The prominent features from right to left are the pulser, the Au peak, and the plateau from the Ni window.

with the 2.66-MeV ^{4}He beam. From the width of the gold peak it was concluded that the thickness of the foil used for the first cell was 165 μg cm^{-2} and for the second, 187 μg cm^{-2}. These figures compare well with the results of direct weighing, 163 and 190 μg cm^{-2}, reassuring us that there are no substantial errors in the Ziegler stopping powers. Below the gold peak in the monitor spectrum is the long plateau due to the nickel window, the lower edge of which can be used to determine the energy at which particles entered the target gas. The energy lost in the gas was deduced from the tabulation of Ziegler.[9] Because the capture cross section varies slowly with energy in this range, our results are relatively insensitive to errors in this tabulation. The thicknesses of the nickel windows were 549 and 698 μg cm^{-2} for the ^{3}He and ^{4}He filled cells, respectively. These values, determined from the 144° monitor spectrum, were checked independently with an "α gauge." The mean energies of the capture reactions in the center of mass were 898 keV for ^{3}He(α,γ)^{7}Be and 896 keV for ^{4}He(^{3}He,γ)^{7}Be. The corresponding energy losses in the targets were 142 and 88 keV, respectively. In deriving the mean energies, we have assumed that the capture cross section varies linearly over the small energy losses involved. The uncertainty in the mean energy, 6 keV, corresponds to a 1.5% cross-section uncertainty.

The activities of ^{7}Be resulting from each irradiation were determined with the calibrated Ge(Li) detector. The branching ratio to the 478-keV state[10] is 10.37(12)%. Peak areas were extracted under the assumptions of linear backgrounds, backgrounds with step discontinuities at the peak center, and the reference peak method. The reference peak shape was taken from the ^{7}Be source spectrum, and a linear background was assumed. All methods gave consistent results, and the reference peak method was adopted. Standardization of the ^{7}Be calibration source could be carried out with an uncertainty of 2%, and geometrical uncertainty in the location of the catchers contributed additional 3% effects. The radial distribution of ^{7}Be in the catchers, although poorly known, contributes only a 1% uncertainty by virtue of the second-order dependence of detector efficiency on radial displacement. Interaction of gammas in the catchers reduced the photopeak area by a factor of 0.914(10). Statistical uncertainties in the yields amounted to 2.7% for the ^{3}He(α,γ)^{7}Be and 5.9% for the ^{4}He(^{3}He,γ)^{7}Be experiments. The activity in the catcher alone from the ^{3}He cell agreed with that measured for the total cell within the combined uncertainties, 4.3%.

We conclude from the ^{3}He(α,γ)^{7}Be experiment that the capture cross section at $E_{\text{c.m.}}=898$ keV is

$$\sigma=1.76(11)\ \mu\text{b}\ ,$$

and, from the ^{4}He(^{3}He,γ)^{7}Be experiment, that the cross section at $E_{\text{c.m.}}=896$ keV is

$$\sigma=1.93(15)\ \mu\text{b}\ .$$

Given the insignificant difference in $E_{\text{c.m.}}$, we can form a suitable average (taking into account the correlations introduced by those uncertainties which are common to the two experiments),

$$\bar{\sigma}=1.81(10)\ \mu\text{b}\ .$$

The "S factor"[4] at 0.897 MeV corresponding to this average cross section is 0.39(2) keV b. The uncertainties that influence the above results are compiled in Table II.

IV. DISCUSSION AND CONCLUSIONS

The cross section for ^{3}He(α,γ)^{7}Be at the energy of interest in the sun is so low that there is little prospect for its direct measurement. Consequently one must rely on a theoretical extrapolation from laboratory energies. Naturally, the lower the laboratory energy at which measurements can be made, the less subject the extrapolation is to details of the theory. Nevertheless, some extrapolation is required, and the accuracy of our knowledge of the astrophysical cross section thus contains two distinct components, (a) accuracy of the laboratory cross section, and (b) accuracy of the theoretical extrapolation. We consider these aspects independently by extrapolating each measurement to zero energy using one arbitrarily selected theoretical prescription (that of Tombrello and Parker[11]), and then examining the sensitivity of the extrapolation of each data set to alternative theoretical analyses.

Another point which should be stressed is that the excitation functions which have been obtained presumably contain, in addition to point-to-point uncertainties, an overall normalization uncertainty which is not always easy to discover from published reports. This normalization plays a fundamental role because it is now apparent that all modern measurements of the excitation function essentially agree in the energy dependence of the cross section and disagree mainly in normalization.

In the seminal work of Parker and Kavanagh[4] good agreement with the Tombrello-Parker calculation[11] was obtained over the range 180 to 2500 keV (center of mass energy) leading to a zero-energy S factor $S(0)$ of 0.47(5) keV b. Subsequently, Nagatani, Dwarakanath, and Ashery,[5] using very different experimental apparatus, obtained data between 164 and 245 keV. Finding that the Tombrello-Parker theory could not simultaneously fit both their data and the previous data in a completely satisfactory way, they considered also a poly-

TABLE II. Sources and magnitudes of uncertainty.

Source	$^3He(\alpha,\gamma)^7Be$	$^4He(^3He,\gamma)^7Be$	Common
Monitor solid angle			0.4%
Monitor angle			0.1%
Cell length			0.4%
Air contamination	0.3%	0.5%	
δE_1			0.3%
Stopping power in Au			2.0%
Beam heating			1.5%
Scattering out			0.2%
Cell pressure			0.3–0.8%
Mean energy			1.5%
^7Be branching ratio			1.2%
^7Be source standardization			2.0%
Counting geometry	3.0%	3.0%	
Radial distribution			1.0%
γ absorption			1.1%
Counting statistics	2.7%	5.9%	
Total	4.0%	6.6%	4.2%

nomial fit. However, since the two data sets do not overlap significantly, it is also possible to reconcile them simultaneously with the Tombrello-Parker curve by assuming that there is a small normalization error in one or both data sets. Not only does this seem to be the most reasonable assumption in view of the experimental situation as discussed below, but also the polynomial fit has no basis in theory. Normalizing the Tombrello-Parker curve to the Nagatani *et al.* data set alone leads to $S(0)=0.58$ keV b. Nagatani *et al.* do not give detailed information on the uncertainty, but contributions to the overall normalization uncertainty of about 8% can be identified, quite apart from statistical uncertainties. We adopt 10% (the value they give for an extrapolation incorporating both their own data and those of Parker and Kavanagh), without significantly prejudicing the final result.

As Nagatani *et al.* noted, close inspection of the Parker-Kavanagh data reveals lack of exact agreement with the shape of the Tombrello-Parker curve. The cross section measured falls off slightly less quickly than predicted as the energy is lowered. The fact that recent experiments[3,12] do not show this effect suggests that there is an error in the data rather than in the theory. In this circumstance, one is not sure over what energy range the theory should be normalized to the data. If the problem clearly lies with theory, normalizing to the lower energy part of the Parker-Kavanagh data would be preferred in order to reduce the dependence on theory. However, to adopt this course when the effect is probably experimental would be to bias the conclusion, and we therefore retain the Parker-Kavanagh extrapolated value (0.47 keV b) with the caveat that it may contain a small systematic error.

While the previous two data sets are, at worst, only slightly in disagreement, there is a dramatic discrepancy with the recent data of Kräwinkel *et al.*,[3] which cover the range 107 to 1266 keV (center of mass). When normalized to these data, the Tombrello-Parker theory yields $S(0)=0.31(3)$ keV b.

Finally, new data have been taken by Osborne *et al.*[12] between 165 and 1170 keV with two different experimental approaches. A windowless gas target was used to obtain extensive excitation-function data, and a conventional gas cell was used in an activation experiment similar to ours to obtain points at 950 and 1250 keV. The windowless cell data lead to $S(0)=0.51(3)$ keV b, and the two activation measurements correspond to $S(0)=0.56(3)$ keV b.

Our results, when extrapolated to zero energy via the Tombrello-Parker calculation, give $S(0)=0.63(4)$ keV b, a value somewhat higher than all previous measurements. The present status of the experiments is summarized graphically in Fig. 4. There is some indication that the recent result of Kräwinkel *et al.* may be systematically low, but even if that result is rejected there is little cause for celebration in the consistency of the remaining experiments. The fact that the three most recent investigations, presumably carried out with considerable care in view of their possible impact, agree so poorly is quite puzzling. As we have remarked,

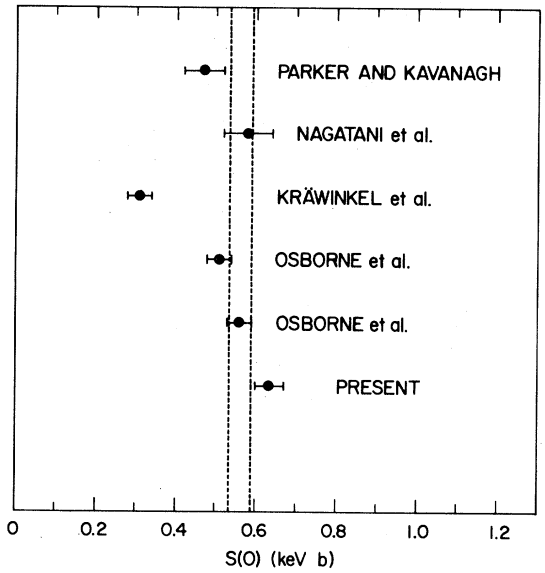

FIG. 4. Graphical representation of $S(0)$ from various experiments. Reference numbers from top to bottom are 4, 5, 3, 12, and 12. The band represents 1-σ limits from the recommended value. As discussed in the text, further uncertainty is contributed by the choice of theoretical extrapolation. The data in this figure have all been reduced to zero energy with the aid of the Tombrello-Parker theory (Ref. 11).

there may be evidence for a small systematic error in the Parker-Kavanagh data, and if one excludes both those data and the data of Kräwinkel *et al.*, the remainder form a reasonably consistent set with an average $S(0)=0.56(3)$ keV b, which we would recommend as an interim value pending further experimentation.

Three recent theoretical papers have been published which, together with the Tombrello-Parker work, allow us some insight into possible theoretical uncertainties. One cannot, of course, rule out the possibility that all the calculations are very much in error owing to some overlooked aspect of the theory, but this seems most unlikely, and the scatter in the extrapolations is a reasonable estimator of the uncertainty. Liu, Kanada, and Tang[13] have calculated the radiative capture cross section in the framework of a resonating-group model. At laboratory energies, their results agree well with measurements of the energy dependence of the cross section (and also very well with our value for the normalization), but at astrophysical energies their calculation has an unusually small first derivative. Williams and Koonin[14] have shown, however, that the S factor for $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ rises as the energy approaches zero, and that it must vary smoothly and monotonically far below the Coulomb barrier. This suggests that there is a minor error in the low-energy dependence calculated by Liu, Kanada, and Tang.[13] Kim, Izumoto, and Nagatani[15] have considered the capture reaction from three different theoretical viewpoints. In the first approach, they used a hard-core potential and Whittaker functions for the bound state wave function, a model essentially identical to that of Tombrello and Parker,[11] whose results Kim *et al.* closely reproduced. In the two more refined calculations, a phenomenological optical potential and the orthogonality-condition model potential were used.

There are, therefore, five calculations to be considered, all of which are in rather close accord despite the different methods used. We have estimated the effect of normalizing each of the theoretical curves to each of the experimental data sets by fixing the normalization energy at values between 205 and 950 keV which are roughly appropriate to measurements of Nagatani *et al.*, Kräwinkel *et al.*, the present work, and Osborne *et al.* At the lowest energy $S(0)$ ranges from 1.6% above to 10% below the value obtained with the Tombrello-Parker prescription, while at the highest energy it ranges from 9% above to 10% below. These spreads (or perhaps some fraction thereof) are an indication of the theoretical uncertainties possibly present in the extraction of the astrophysical cross section from the data sets.

We conclude that our present results are inconsistent with those of Kräwinkel *et al.*,[3] marginally inconsistent with those of Parker and Kavanagh,[4] and consistent with those of Nagatani *et al.*[5] and Osborne *et al.*[12] The value we recommend for the zero-energy cross-section factor, 0.56 keV b, lies slightly above the value chosen by Bahcall *et al.*,[1] 0.52 keV b. A reasonable one-standard-deviation experimental uncertainty for the zero-energy cross section factor is approximately 0.03 keV b, or 0.07 keV b, if one includes uncertainties in the theoretical extrapolation. Our recommended value raises the expected neutrino event rate[1] in $^{37}\mathrm{Cl}$ by 6%, exacerbating the solar neutrino "problem."

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