AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 mm

1 2 3 4 5

Inches

1.0 1.1 1.25 1.4 1.6 1.8 2.0 2.2 2.5 2.8 3.2 3.6 4.0 4.5 5.0 5.6 6.3 7.1

MANUFACTURED TO AIIM STANDARDS

BY APPLIED IMAGE, INC.

1 of 1

LBL-33573

Can the Measurement of the Cross-Section of Proton-Capture on Beryllium-7 Be Improved?

Chris Bowers

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720, USA

January 1993

This work was supported by the Director, Office of Energy Research Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

The solar neutrino "problem" arises from the discrepancy between the observations of solar neutrinos fluxes in experiments at Homestake and Kamiokande and the solar model predictions of those fluxes. Both experiments, which are sensitive mainly to high-energy neutrinos, observe fewer neutrinos than predicted by solar models. Most of the expected high-energy solar neutrinos come from the beta-decay of ^8B, which is produced in the reaction $^7Be(p,\gamma)^8B$.

A study of all of the measurements to date of the zero-energy S-factor for the reaction $^7Be(p,\gamma)^8B$ [1] concludes that $S_{17}(0) = 0.0224 +- 0.0021$ keV-barn. Although a 10% error in $S_{17}(0)$ alone will not solve the solar neutrino problem, it would still be useful to nail down all of the inputs of the solar models as well as possible. This serves to guard against the possibility that a conspiracy among the errors might be the source of the discrepancy and provides tighter constraints on the "new physics" interpretations of the experimentally measured solar neutrino spectrum. In this paper, we examine several ways of improving this measurement. None appear to offer a significant improvement over past experiments.

Previous measurements with ^7Be targets

All of the previous experiments have relied on very similar methods to measure $S_{17}(0)$, and it might be argued that a radically different approach would provide a good check on the previous measurements and offer an avenue to a more precise measurement. To have impact , however, the new measurement must be reliable enough to stand on its own.

The cross-section falls very rapidly with decreasing energy, as shown in Figure 1, because of the Coulomb barrier. It is convenient to define $S_{17}(E_{cm}) = \sigma_{17}(E_{cm})E_{cm}\exp\left(\left(\frac{E_g}{E_{cm}}\right)^{1/2}\right)$, where $E_g = \frac{(2\pi\alpha Z_1 Z_2)^2 \mu c^2}{2} = 13798.8 keV$ so that $S_{17}(E_{cm})$ varies little with E_{cm}. To measure $S_{17}(0)$, one measures σ_{17} at several different energies, determines $S_{17}(E_{cm})$ for those energies, and

extrapolates to E_{cm}=0 using the theoretical energy dependence of S_{17}. The energy dependence of S_{17} is known to a high degree of certainty only in the energy region below the first resonance at 630 keV, where direct capture dominates. It turns out that the theoretical energy dependence of S_{17} is best normalized to the experimental data from about 100 to 450 keV, where the cross-section is large enough to be measured reliably, but the effects of the resonance are negligible. Once one assumes the energy dependence of S_{17}, cross-section measurements at different energies do not help reduce the uncertainty in the extrapolation. However, they do allow one to evaluate the correctness of the theoretical extrapolation and to have confidence in the experiment itself. For example, Johnson et al. argue that the uncertainty in their theoretical extrapolation is less than 2%[1]. The systematic uncertainties in past measurements of the cross-section as a function of energy far outweigh the uncertainty in the extrapolation of the cross-section to zero energy. Thus, measurements at lower energies will probably not significantly reduce the total error. The best way to reduce the overall uncertainty is to reduce the systematic uncertainty in the measurement of the cross-section. Figure 2 shows all of the measurements of S_{17} to date. There is general agreement on the energy dependence of S_{17}, but the overall normalization is disputable. A measurement utilizing a very different experimental setup might be very useful to resolve this discrepancy.

All previous measurements have used a target of ^{7}Be and a beam of protons. Measuring the gamma-ray from the proton-capture reaction is not feasible since the electron-capture decay of ^{7}Be($\tau_{1/2}$ = 53 days) to an excited state of ^{7}Li results in a 477 keV gamma-ray when that excited state decays to the ground state of ^{7}Li. This chain occurs in 10% of the ^{7}Be decays. The energy of the gamma-ray from the proton-capture reaction will be essentially the Q-value of the reaction (136 keV) plus E_{cm}. At low E_{cm}, the proton-capture gamma-rays will be easily overwhelmed by the gamma-rays in the ^{7}Be electron-capture chain, so it is prudent to detect the ^{8}B.

The ^{8}B which is created by the proton-capture reaction is normally stopped in the target backing. The ^{8}B decays to a broad excited state of ^{8}Be by emitting a positron with an endpoint energy of about 15 MeV and a half-life of 780 ms. (The branching fraction to the 2.94 MeV excited state is nearly 100% contrary to the erroneous value listed in the Table of Isotopes; see [10]. The excited state of ^{8}Be decays promptly into 2 alphas, each with energies distributed in a broad peak at 1.5 MeV. Although Kavanaugh(1960)[2] measured the reaction by detecting the positrons in this decay chain, Parker(1968)[3] and all subsequent measurements have detected alpha particles in singles with improved signal to noise. Table 1

lists all measurements of S_{17} to date along with the method of detection and the method of measuring the ^{7}Be areal density.

Since it is difficult to make a uniform radioactive target containing microscopic quantities of ^{7}Be with a precisely known areal density, the areal density of ^{7}Be has to be measured in the experiment itself. This proves to the most difficult part of the experiment and two different methods have been used in the past. Most experiments have made use of the fact that ^{7}Be decays into ^{7}Li, which when bombarded with deuterons produces ^{8}Li via ^{7}Li(d,p)^{8}Li. ^{8}Li is the mirror isobar of ^{8}B and decays by the emission of a high energy beta to the first excited state of ^{8}Be which decays into two 1.5 MeV alphas. By making continuous measurements of the yield of ^{8}Li from deuterons using the same target and hopefully the same spatial beam intensity distribution and knowing the absolute cross-section of ^{7}Li(d,p)^{8}Li, one can know the areal density times the geometrical acceptance of the alpha detector. This normalization is performed at the 770 keV resonance of σ_{dp}.

The resonance cross-section for ^{7}Li(d,p)^{8}Li is itself somewhat controversial. After examining all of the measurements of σ_{dp}, Filippone concluded that σ_{dp} = 157 +- 10 mb [16], contributing 6% to the uncertainty in S_{17}. However, Barker has questioned the measurement of the stopping power for protons in lithium upon which all of these measurements are based and advocates a significantly lower σ_{dp}.[17]

A new measurement of σ_{dp} [15] uses a beam of ^{7}Li on a gas jet target of CD_4. Both the protons produced in the (d,p) reaction and the elastically scattered ^{7}Li are detected in a silicon detector at $\theta = 72°$. The Rutherford scattering cross-section for ^{7}Li on ^{12}C is used to normalize the differential cross-section for ^{7}Li(d,p)^{8}Li. The previously measured angular distributions for protons from ^{7}Li(d,p) are then used to determine the total cross-section. The preliminary value is σ_{dp} = 147 +- 10 mb, where a large part of the uncertainty is due to the uncertainty in the stoichiometry of the CD_4 gas, since the gas is recirculated.

An improved measurement of σ_{dp} would definitely reduce the uncertainty in S_{17}. However, the uncertainty in the world average of S_{17}, excluding the uncertainty in σ_{dp}, is already 7%[1], reducing the benefit of improving σ_{dp}. Table 2 is a breakdown of the uncertainties in the experiment of Filippone(1983). No single uncertainty dominates the others. It may be the case that no tremendous effort was made to reduce other uncertainties once it was apparent that the uncertainty in σ_{dp} would contribute 6% to the total uncertainty. None of the other uncertainties seems as fundamentally difficult as the uncertainty in the measurement of the ^{7}Be areal density. If the uncertainty in σ_{dp} were significantly reduced,

one might consider repeating the experiment of Filippone(1983) with the aim of reducing the other uncertainties to the same level.

The other method has been to directly measure the total ^{7}Be activity and its distribution on the target, by measuring the gamma-rays in the ^{7}Be electron-capture chain. In the two experiments that used this method[4,5], the measurement of the total activity carried about 7% uncertainty, while the uneven distribution of ^{7}Be in the target led to a 5% uncertainty in determining the overlap with the beam spot. Filippone(1983)[4] used both the ^{7}Li(d,p)^{8}Li reaction and the gamma-ray activity to measure the ^{7}Be areal density and obtained consistent results.

Possible improvements of the measurements with ^{7}Be targets

The fundamental uncertainty in previous measurements has been the uncertainty in the areal density of the ^{7}Be. Many nuclear physics techniques are commonly used to characterize the composition of materials, but each method has limitations that make it inapplicable to the problem at hand. Calibrating reactions which use ^{7}Be as a target suffer the same difficulties that we face in trying to measure ^{7}Be(p,γ)^{8}B. In fact, the best-measured absolute cross-section of a reaction involving ^{7}Be in the initial state is the one we want to measure. One way around this is to use a reaction that does not have to be measured, but can be calculated very accurately.

Rutherford back-scattering (RBS) has the potential to provide a very precise measurement of the ^{7}Be areal density, because it can be calculated very accurately, relying only on the charge and mass of the nucleus. The elastic scattering cross-section for protons on ^{7}Be should simply be the Rutherford cross-section, since at E_{cm}=100 keV the classical distance of closest approach is about 60 fm while the interaction radius is about 5 fm. The elastic scattering cross-section should roughly obey the Rutherford law up to about E_{cm}= 1000 keV. However, since there is a resonance in the proton-capture cross-section at E_p=630 keV, there will be anomalies in the elastic scattering cross-section near that energy.. It is thus necessary to use as low a beam energy as possible to minimize the effect of such anomalies. A study of the angular and energy dependence of elastic scattering at low energies can be used to estimate the extent to which the elastic scattering cross-section deviates from the Rutherford cross-section. Assuming reasonable uncertainties in the angular acceptance to detect elastically scattered protons, one can obtain a 3% uncertainty in the areal density of ^{7}Be. [12]

Several practical difficulties arise when one actually tries to use RBS to measure the areal density of ^{7}Be. The ^{7}Be must rest on some backing,

and the protons will back-scatter from that backing as well as from the ^{7}Be. One can distinguish the protons which back-scattered from ^{7}Be from those which scattered off of a nucleus of another mass, by the energy of the proton. Any conventional target backing material will have a mass greater than 7, corresponding to back-scattered protons of higher energy. Very thin backings are typically made of carbon. Protons back scattering off of ^{7}Be will have 0.56 the initial energy of the proton, while those scattering off of ^{12}C will have 0.716 the initial energy. A proton that back-scatters from the carbon backing will have lost energy by electronic collisions on its way in and out of the backing, producing a spread below what would otherwise be a sharp mass 12 energy peak. The thinnest self-supporting carbon backing is about 5 $\mu g/cm^2$. A 200 keV proton passing through this thickness of C twice will lose about 5 keV. Using a detector with an energy resolution of better than 5%, the mass-7 peak should be readily distinguished from the mass-12 plateau. However, it would be very difficult to deposit the ^{7}Be on such a thin carbon backing. If a much thicker target backing were used, the background of protons elastically scattered and slowed by the carbon would have to be subtracted from the signal of protons scattered by ^{7}Be. This background is twice the size of the ^{7}Be signal.

The gamma-rays from the ^{7}Be decay could also make it difficult to detect protons of low energy with a solid state detector. For a 100 mCi ^{7}Be target with a 1 μA current of protons at 200 keV, there will be 10^3 times as many gamma-rays as elastically back-scattered protons. However, only one out of every 10^4 477 keV gamma-ray will scatter in a silicon detector with a 10 μm active thickness. If the gamma-ray background still presents a problem, one could use a magnetic spectrometer to detect the protons with energy resolution of 0.1% and angular resolution of 0.3°.[11]

Another problem with this method arises from the fact that the kinematics of elastic scattering is sensitive only to the nuclear mass and not the nuclear charge, so it is impossible to distinguish between a proton that has been back-scattered by ^{7}Be or by ^{7}Li. The ^{7}Li either produced in the decay of ^{7}Be or remaining from the production of ^{7}Be will interfere with the determination of the ^{7}Be areal density by RBS. The production mechanism used to create ^{7}Be in past experiments has been $^{7}Li(p,n)^{7}Be$, and the ^{7}Li has been chemically separated from the ^{7}Be. If one could know the efficiency of the chemical separation process to two percent, then uncertainty due to the subtraction of the ^{7}Li contribution would be tolerable. Or if one used a production reaction that did not involve ^{7}Li, for example $^{6}Li(p,\gamma)^{7}Be$ or $^{6}Li(d,n)^{7}Be$, then there would be no initial interference of ^{7}Li with the RBS determination of ^{7}Be.

By measuring the beam current and using the fact that the Rutherford cross-section is proportional to the target nucleus charge

squared, one could hope to observe a decrease in the elastic scattering rate at a fixed current as ^{7}Be decays into ^{7}Li, and thus extrapolate the initial concentration of ^{7}Be. This would require measurements spanning several ^{7}Be half-lives of 53 days. Although this could be facilitated by the admixture of a heavier element with the same spatial distribution as the ^{7}Be to provide a benchmark RBS signal which will not change over time, it would be very difficult to make precise measurements over such a long period of time. Given the many difficulties involved, RBS determination of the areal density of a ^{7}Be target does not seem very promising.

Although the independent measurement of a calibrating reaction involving ^{7}Be in the initial state would face many of the same difficulties as the measurement of the proton-capture cross-section itself, the measurement of a reaction involving ^{7}Be in the final state might be easier to carry out. The cross-section for the inverse reaction involving ^{7}Be in the initial state could then be inferred. However, no obvious candidates present themselves.

Particle induced X-ray emission (PIXE) is sensitive to the chemistry of a sample, relying on the Z-dependence of atomic transitions, and thus has the potential to distinguish between ^{7}Li and ^{7}Be . PIXE is generally accurate to 5% and precise to 2%.[6] However, the PIXE is usually limited to identifying elements with Z>13. K-shell X-rays from Li and Be have energies of 54 eV and 108 eV respectively, which would be difficult to measure accurately above the large X-ray background from a target backing of higher Z.

^{7}Be beams

No experiment has yet employed a ^{7}Be beam on a target of protons. This would have several advantages over using a beam of protons and a target of ^{7}Be. One can obtain an isotopically and isobarically pure beam of ^{7}Be by utilizing the +4 charge state of ^{7}Be. The completely stripped ^{7}Be nucleus would not even decay since its only mode of decay is through electron-capture. The experimental setup envisioned is a beam of completely stripped ^{7}Be incident on a hydrogen gas jet target. A gas jet is necessary to provide a thin but localized target, so that the elastic scattering angle is very well defined. The ^{8}B produced in the gas target continues in the beam direction until it is stopped along with the ^{7}Be in the beam in a catcher, where the alphas from its decay are detected. The elastically scattered ^{7}Be or the recoil protons from the target could then be used to normalize the absolute proton-capture cross-section. This arrangement is much more conducive to measuring elastic scattering and elastic recoil products. The absence of a target backing in a gas jet eliminates

interference from other nuclei in the elastic scattering signal. The larger laboratory energy of ^{7}Be required to achieve a given center of momentum energy results in more energetic daughters which are easier to measure. The gamma-rays from ^{7}Be decay would not be a problem since the amount of ^{7}Be in region of the target at any given time is very small. If uncertainties in the calculated elastic scattering cross-section of ^{7}Be on protons are too great due to resonant behavior, one can use CH_4.gas as the target. The elastic scattering of ^{7}Be on ^{12}C can then be used to normalize the proton-capture cross-section, since the Rutherford cross-section should be quite accurate at these energies for nuclear charges of four and six..

Previous experiments have had about 4% uncertainty in the number of ^{8}B produced due to the background from the large flux of 477 keV gammas in the alpha detectors from the ^{7}Be present in the target. This has not been a serious problem in the past since the experiments were dominated by other uncertainties. This problem would have to be addressed in a higher precision experiment, however. The ^{8}B produced by proton-capture has essentially the same momentum as the ^{7}Be which produced it, coming out of the target collimated within 1° of the beam axis. One can choose a catcher thickness such that the ^{8}B stops in the middle of the catcher. Then both of the alphas can escape from the catcher, back-to-back. Using alpha detectors on either side of the catcher and requiring two alphas in coincidence and cutting on their sum energy will remove the uncertainty due to gamma-ray background. This can be accomplished with a single catcher at low COM energies where the ^{8}B produced has a much shorter range than the 1.2 MeV alphas in its decay chain. For higher energies, a series of foils would be necessary to slow the ^{8}B before ultimately stopping it in a foil thin enough for both alphas to escape. Alternatively, one can separate the ^{8}B beam from the ^{7}Be beam using an ExB velocity selector to cut down on the background from ^{7}Be gammas.

A disposable ^{7}Be beam

Radioactive beams facilities have so far collected and separated primary beam-produced nuclear fragments which are then accelerated into a target. However, the beam currents from these facilities are presently too low to be of any use to measure a cross-section on the order of nanobarns. A proposal has been made to measure σ_{17} with ^{7}Be produced in the reaction ^{9}Be(p,t)^{7}Be. [18] The ^{7}Be produced in an initial target of ^{9}Be are focused onto a target of protons with a superconducting magnet, where the ^{7}Be capture protons to produce ^{8}B. The expected flux of ^{7}Be is 10^{7}/s, while the expected ^{7}Be energy spread is 20%. A "beam" of such poor quality might be able to make a measurement of σ_{17} at or above the

resonance at E_{cm} = 720 keV, where the cross-section is sufficiently large. However, at E_{cm}= 1 MeV, there would be only four ^8B produced per day, requiring a lengthy experiment even with very low backgrounds. In Figure 2, one sees that most measurements agree on the form of $S_{17}(E)$, but disagree on the overall normalization of the cross-section. One might argue that a very good measurement of σ_{17} at 1 MeV or at the resonance could establish an accurate normalization for previous experiments, allowing one to extrapolate to E_{cm}= 0. However, it would be very difficult to convince oneself of the accuracy of the measurement when the cross-section is measured at only one energy and with such a low quality beam. The novelty of a ^7Be beam does not necessarily justify its use.

The most straight-forward way to obtain a high quality ^7Be beam with a range from about 800 keV to at least 3 MeV is to attach an ECR ion source to a Van de Graff or small RF linear accelerator, with an analyzing magnet. The ECR source can be fed with ^7Be produced by $^7Li(p,n)^7Be$ at the same or another accelerator.

In evaluating the feasibility of making improved measurements of S_{17}, I try to keep all of the errors down to the 1 or 2% level, so that the combined error will be around 3 or 4%. I also make the simplifying assumption that if one can measure the cross-section at E_{cm}=117 keV (Filippone's lowest energy measurement) to a few percent. The rest of the points would then be easy to measure. The lowest energy point is the most difficult to measure for several reasons. The cross-section is the lowest, the energy dependence of the cross-section is the highest, and the beam energy spread due to energy lost in the target must be smallest in absolute terms.

The maximum target thickness is determined by the maximum allowable uncertainty in the beam energy. As the beam particle traverses the target it loses energy. Since one doesn't know if the ^7Be captured a proton at the front of the target or the back of the target, there is an uncertainty in the energy at which the reaction took place. One can attempt to calculate the energy distribution at which the interactions take place, but this can probably be trusted only to about 10%, especially at low energies. At E_{cm}=120 keV, a 0.25% uncertainty in the energy corresponds to a 1% uncertainty in the cross-section, since the cross-section is such a rapidly falling function of energy. So in order to get 1% systematic error on the lowest energy point, the energy lost by the beam in the target can only be 0.25% of the beam energy. However, since we can estimate the energy distribution of the ^7Be in the target within 10%, we can afford to lose 2.5% of the beam energy in the target. Assuming 18000 keV/(mg/cm^2) is lost by ^7Be at 960 keV in a H_2 target, then in order to lose only 24 keV,

the target can only be 1.32 $\mu g/cm^2 = 8 \times 10^{17}$ protons/cm^2. This target density is readily achievable with a gas jet target. [13]

The cross-section for proton-capture by ^7Be at 120keV is only $3nb = 3 \times 10^{-33}$ cm^2, so in order to create a single nucleus of ^8B, one needs 4×10^{14} ^7Be to pass through the target. However, for ^7Be, $1Ci = 2.6 \times 10^{17}$ nuclei. So one needs 1.6 mCi for each ^7Be count. One percent statistics requires 10^4 counts, so one needs a total of 16 Ci of ^7Be. This does not take into account the efficiency with which the $^7Be^{4+}$ is produced by the ion source. This efficiency cannot be expected to be any better than 1% for such a high charge state. Thus one would require at least 1.6 kCi. Not only does this present serious contamination problems, but it is difficult to produce so much ^7Be. Filippone[4] needed 5000 μA-h of 3 MeV protons on ^7Li to produce 120 mCi. One might imagine reusing the ^7Be after it has been accelerated and caught, but it would be a very hot and messy process.

Storage Rings

Since it seems impractical to use a disposable beam of ^7Be, storing the ^7Be in a ring and passing it through an internal gas jet target might be a viable alternative. One would have to figure out how to extract the ^8B produced from the ring lattice efficiently, but the main problem with this scheme lies in the fact that a colliding ion and atom have a very large probability of exchanging an electron. Charge exchange cross-sections are generally of the order of 10^{-16} cm^2 for ions with energies around 100keV/A . A storage ring can store only one charge state of a given isotope at a time, so any ^7Be that loses or gains an electron will be lost from the ring. If we use a hydrogen gas target, for every ^8B we produce with a cross-section of 10^{-33} cm^2, we lose 10^{17} ^7Be from the ring. Thus every ^8B produced requires 0.4 Ci of ^7Be, or for 1% statistics we need 4kCi to be lost from the ring.

One could hope to improve this miserable situation somewhat by using a thick target of hydrogen so that an equilibrium among the ^7Be charge states is reached. This is an improvement because the thicker the target, the greater the probability that the +3 and other charge states produced lose electrons and return to the +4 charge state. Unfortunately, at the velocities of interest, only 2% of the ^7Be remains in the +4 charge state at equilibrium.[19] Thus one could recycle at most 2% of the beam after each pass through the target, effectively making this a more expensive equivalent to the disposable ^7Be beam discussed above.

The cross-section we are trying to measure is seventeen orders of magnitude smaller than that of the dominant loss process, charge exchange. This process must be eliminated if we hope to significantly reduce the

amount of ^{7}Be needed. If the target atoms were bare protons and the stored ^{7}Be were in the +4 charge state, then no charge exchange could occur, since there would be no electrons to exchange. The dominant process for loss of ^{7}Be from the ring would be the ^{7}Be scattered at large angles, out of the acceptance of the ring. Storage ring acceptance are generally on the order of a few mrad while the maximum angle of deflection for ^{7}Be on a proton is 140 mrad. The cross-section for large angle deflections at E_{cm}=100 keV is on the order of 10^{-24} cm^2/sr. So for every ^{8}B produced, only 10^9 ^{7}Be or 4 nCi would be lost from the ring. So we would need only 40 μCi for 1% statistics.

However, this isn't feasible unless we can store enough free protons to have a high enough rate of proton-capture. Storage rings typically contain 10^{10} ions per fill. For ^{7}Be at 960 keV, that corresponds to a particle current of 10^{15}/s. Typical storage lifetimes are of the order of minutes. Obtaining a high density of protons without electrons is very difficult. The Brillouin limit for magnetically confined particles is $n=B^2/(8\pi mc^2)=10^{10}/cm^3$ for protons and a maximum B-field of 10^4 Gauss. Even if we achieved this maximum density and assuming that the target is 1cm^3 in order to accurately measure the elastic recoil protons at a particular angle, we would only expect 10^{-8} proton-captures/s. This is not at all practical, especially considering the storage lifetimes.

Free electrons can compensate the space-charge repulsion of the protons, allowing a higher density of free protons. The cross-section for the capture of free electrons by a free ^{7}Be nucleus is of the order of 10^{-22} cm^2 for energies of interest.[7] Therefore, $^7Be^{4+}$ passing through a dense, high temperature, well-dissociated plasma of electrons and protons would pick up fewer electrons and change charge state less readily. However, the density of neutral hydrogen atoms would still have to be very low.

The maximum ion charge density attainable with a gap diode is $n=V/(9\pi qd^2) = 10^{14}/cm^2$ for V=3x10^6 V and d=0.1 cm[8], which would give 10^{-4} interactions/second at the 'typical' storage ring current. This is rate is still not practical. However, by creating a dense plasma of electrons and protons and shooting it into a magnetic mirror, charge densities of the order of 10^{18} can be attained[8], providing an amply thick target. This would be throwing out the baby with the bath water, however. Such high density plasmas can only be achieved for short periods of time, and it is not clear what is the density of neutral atoms in the plasma. The presence of a large magnetic field to provide the magnetic mirror would certainly affect both the stored beam and the ability to measure the elastic recoil protons or elastically scattered ^{7}Be, which are used to normalize the relative cross-section for proton-capture.

Finally, it would seem that the estimate of 10^{10} ions/fill is overly optimistic for low energy ions in a storage ring. In order to achieve high

ion current densities in a storage ring, some mechanism must be used to lower the phase space density of the injected ions. Stochastic, laser, or electron cooling are typically used. Laser cooling would not work with $^7Be^{4+}$ since there are no bound electrons for the laser to excite. Electron cooling has been applied at CRYRING. The characteristic electron cooling time, $\tau \propto A/(q^2v^2)$ [9] , favors high charge states and fast ions. ^7Be at 800 keV are rather slow. For CRYRING, realistic values for ions at 100keV/A seem to be $5x10^5$ ions/fill [9]. Thus, the prospects for success using a stored beam of ^7Be and a target of protons are not good, given that serious technological obstacles need to be overcome both to store an intense beam and to create a high density ionized target.

Merged beams

One could obtain a brighter beam of ^7Be by storing it at higher energies, e.g. several MeV. The necessary lower center of momentum energy can be obtained by merging the ^7Be beam with a proton beam of the same velocity at a small angle in the lab frame. Assuming that this energy allows more effective electron cooling to permit 10^{10} ^7Be ions/fill, and assuming a 500 keV proton beam at a (very optimistic) particle current of 1 A intersecting the ^7Be beam over $1cm^3$, the luminosity is only $2x10^{25}cm^{-2}s^{-1}$, due to the low particle density in a swift beam. This luminosity gives the impractical rate of $6x10^{-8}$ proton-captures/s. Bunching of beams and tighter focusing of the beams might be able to increase the luminosity, but not the 5 or 6 orders of magnitude needed to perform the experiment.

Conclusion

Although the zero-energy S-factor for the reaction $^7Be(p,\gamma)^8B$ is known to only 10%, it would be very difficult to significantly improve on previous measurements. The areal density of a ^7Be target proves very difficult to measure. The radioactivity of ^7Be limits the amount which can be practically used in a beam of ^7Be. The attempt to reuse the ^7Be by storing it in a ring is spoiled by the large charge exchange cross-sections between ^7Be in the ring and the target hydrogen. A last-ditch effort keep the target free of bound electrons fails because it is too difficult to achieve high densities of free protons.

References

[1] C.W. Johnson, E. Kolbe, S.E. Koonin, K,Langake, ApJ , 392(1992)320.
[2] R.W. Kavanaugh, Nucl. Phys., 15(1960)411.
[3] P.D. Parker, Phys. Rev., ApJ, 15(1968)L85.
[4] B.W. Filippone, A.J. Elwyn, C.N. Davids, D.D. Koetke, Phys. Rev. C, 28(1983)2222.
[5] C. Wiezorek, H. Kräwinkel, R. Santo, K. Wallek, Z. Phys. A, 282(1977)121.
[6] Cahill, Ann. Rev. Nucl. Part. Sci, 30(1980)211.
[7] M.Stobbe,Ann. Phys. 7(1930)661.
[8] F. Winterberg, Phys. Rev. Lett., 37(1976)713.
[9] A.Barany, C.J. Herrlander, in:Atomic Processes in Electron-Ion and Ion-Ion Collisions, ed., F. Brouillard (Plenum, New York, 1986).
[10] E.K.Wharburton, Phys. Rev. C, 33(1986)303.
[11] A.B.Brown, C.W. Snyder, W.A. Fowler, C.C. Lauritsen, Phys.Rev., 82(1951)159.
[12] H.W. Becker, et al., Z. Phys. A, 305(1982)319.
[13] R.M. Kremer, et al., Phys. Rev. Lett., 60(1988)1475.
[14] B.W. Filippone, A.J. Elwyn, W. Ray, Jr., D.D. Koetke, Phys. Rev. C, 25(1982)2174.
[15] M.S. Smith, et al., Bull. Am. Phys. Soc., 36(1991)2129.
[16] B.W.Filippone, Ann. Rev. Nucl. Part. Sci., 36(1986)717.
[17] F.C.Barker and R.H.Spear, ApJ, 307(1986)847.
[18] R. Boyd, private communication (1992).
[19] J.B. Marion and F.C. Young, Nuclear Reaction Analysis,(North Holland Publishing Company, Amsterdam,1968)

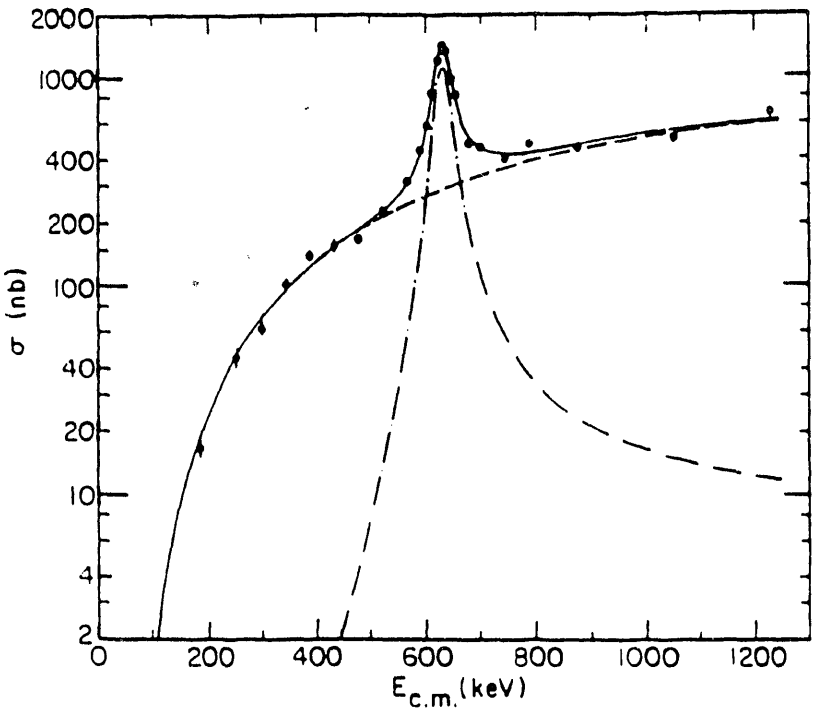

Figure 1. The measurement of σ_{17} as a function of energy from [4]. The dashed curve is the nonresonant direct capture contribution . while the dashed-dotted curve is the resonant cross-section. The solid curve is the sum of the two.

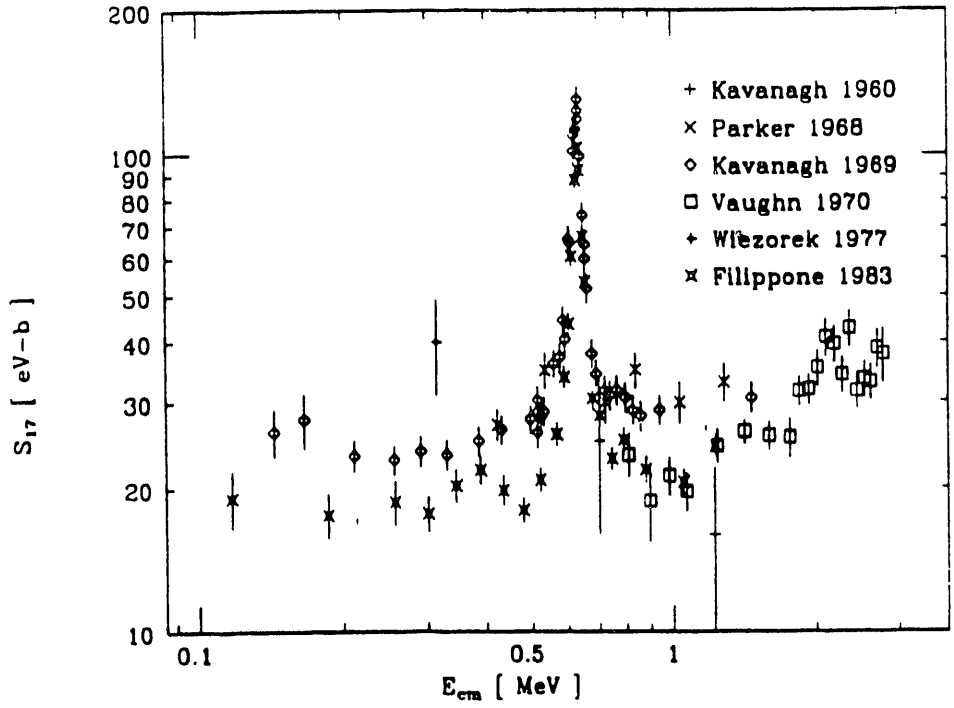

Figure 2. Measurements to date of S_{17} as a function of energy from [1].

Experiment	Detection Method	Calibration Method	$S_{17}(0)$, eV-b	Uncertainty in $S_{17}(0)$
Kav 60	beta	$^{7}Li(d,p)^{8}Li$	15	40%
Par 68	alpha	$^{7}Li(d,p)^{8}Li$	27	15%
Kav 69	alpha	$^{7}Li(d,p)^{8}Li$	25.2	10%
Vau 70	alpha	$^{7}Li(d,p)^{8}Li$	19.4	14%
Wie 77	alpha	^{7}Be activity	41.5	22%
Fil 83	alpha	Both	20.2	11%

Table 1. A summary of measurements of $S_{17}(0)$, adapted from [1]. The extrapolation of $S_{17}(0)$ are those calculated in [1] using the latest value of σ_{dp}.

Source of uncertainty	Uncertainty
Common errors	
Alpha energy cut	4%
S_{17} dependence on E_{cm}	3%—11%
Current integration	2%
Counting statistics	3%—13%
^{7}Li(d,p)^{8}Li calibration	7%
^{7}Be activity calibration	
Total activity	7%
Inhomogeneity over beam spot	<=5%
Diameter of beam spot	3%
Solid angle of alpha detection	1.5%

Table 2. The experimental uncertainties in the measurement of ^{7}Be(p,g)^{8}B by Filippone(1983) as extracted from [4]. The uncertainty in current integration is assumed to be the same as [14].

DATE
FILMED
8/18/93

END