Abstract

We discuss results and future plans for low-energy reactions that play an important role in current nuclear astrophysics research and that happen to concentrate around the region of $A=7$. The $^{7}\text{Be}(p,\gamma)^{8}\text{B}$ and the $^{3}\text{He}(^{4}\text{He},\gamma)^{7}\text{Be}$ reactions are crucial for understanding the solar-neutrino oscillations phenomenon and the latter one plays a central role in the issue of cosmic $^{7}\text{Li}$ abundance and Big-Bang Nucleosynthesis. We also present results regarding the host dependence of the half life of the electron-capture $^{7}\text{Be}$ radio-nuclide.

1 SOLAR FUSION REACTIONS, SOLAR-NEUTRINOS and BIG-BANG NUCLEOSYNTHESIS

1.1 The cross section of the $^{7}\text{Be}(p,\gamma)^{8}\text{B}$ reaction

Our planet is bombarded every second with a large number of charge-less, mass-less neutrinos, originating in the nuclear fusion reactions that power the energy production in the Sun. A major, long-lasting research effort, focusing on the apparent shortfall of detected solar neutrinos as compared to theoretical predictions, culminated recently with the results of the Sudbury Neutrino Observatory (SNO) experiment [1], affirming the notion of neutrino oscillations (and hence neutrino mass). The SNO experiment, as well as the preceding Homestake [2] and Super-Kamiokande [3] experiments are sensitive only to a small fraction of the solar neutrino spectrum, to the high-energy neutrinos that are emitted as a result of the fusion of protons with the nucleus $^{7}\text{Be}$ and the subsequent beta decay of the $^{8}\text{B}$ product nucleus.

The cross section of this reaction has been measured in the laboratory several times. However, mostly due to difficulties with the preparation and homogeneity of the radioactive $^{7}\text{Be}$ target, large discrepancies still persist in the extracted cross section values. The present experiment uses in a novel way a 2 mm diameter target of the $^{7}\text{Be}$ radioactive nuclei (with a halflife of 53 days), prepared by direct implantation at the ISOLDE (CERN) laboratory and brought to the Van de Graaff accelerator of the Weizmann Institute, Israel, for the measurement of the reaction. The results of these experiments have been published in detail in several previous papers [4, 28, 6, 7, 8]. Fig. 1 presents a brief summary of the results.

With the present determination of the $p+^{7}\text{Be}$ cross section at solar energies to an accuracy of better than 4%, this important nuclear physics quantity ceases to be the largest source of error in the Standard Solar Model [9] estimates of the $^{8}\text{B}$ neutrino flux.
Figure 1: The astrophysical $S_{17}$ factor (the cross section of the reaction, with the penetrability through the Coulomb barrier factored out) from the present measurement. The extrapolation to $E=0$ yields $S_{17}(0)=21.5 (7)$ eV.b. Depicted in the figure are the regions of the M1 resonance and those above and below it.

1.2 The cross section of the $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$ reaction

The $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$ reaction is another major source of uncertainty in determining the solar neutrino flux that is proportional approximately [9] to the astrophysical $S$ factor of this reaction, $S_{34}(0)^{0.8}$. A compilation of previous data, together with the latest measurement by the authors, is presented by Hilgemeier et al. in Ref.[10], from which a significant scatter in $S_{34}(0)$ can be seen, resulting in a considerable uncertainty on the adopted $S_{34}(0)$. It is therefore highly important to provide a more precise value than the presently recommended value of $S_{34}(0) = 0.51\pm0.02$ keV-b [10]. We have recently initiated a new precision measurement of this cross section at energies around $E_{\text{c.m.}} = 500 - 950$ keV to serve as a normalization to the $S_{34}(E)$ curve, using a $^3\text{He}$ beam and a $^4\text{He}$ gas cell and determining the cross section by measuring the ensuing $^7\text{Be}$ activity. Since the energy dependence among various theoretical approaches and experimental determinations agrees quite well [11, 12], the normalized curves will then be compared with $S(E)$ values from our ongoing experiment to obtain $S_{34}(0)$. We note here also our earlier attempt towards a new determination of $S_{34}(0)$ by using the accelerator mass spectrometry technique [?].

A schematic diagram of our experimental setup is shown in Fig. 2. The $^3\text{He}$ beam from the 3 MV Van de Graaff accelerator at the Weizmann Institute of Science enters the $^4\text{He}$ gas cell through a nickel (Ni) window of either 0.5 or 1 $\mu$m and is raster-scanned in order to avoid excessive localized heating of the Ni window. The beam direction is defined by an upstream slit at 2 meters from the center of the cell and two Ta collimators of 3 mm, one at the entrance and the other at the exit of the chamber. An
aperture operated at -400 V, placed before the Ni window, serves as a secondary electron suppressor. The gas cell is insulated from the beam line and the entire chamber, including the Cu stopper that is in electric contact with the chamber, serves as Faraday cup to determine the number of impinging \(^3\)He particles. \(^7\)Be nuclei produced by fusion of \(^3\)He on \(^4\)He in the cell move forward in the laboratory system and are implanted in the Cu catcher at depths of few microns. The catcher is kept at distances of 10.3 or 13.9 cm from the Ni foil and the \(^4\)He gas pressure inside the cell is accordingly adjusted to obtain \(\sim120\,\text{g/cm}^2\) thickness of gas. This corresponds to an energy width of the target of \(\sim200\,\text{keV}\) at \(E_{\text{cm}} = 1.1\,\text{MeV}\). The gas pressure was monitored and maintained at a constant pressure. In addition, we monitor on-line the elastically scattered \(^3\)He from the Ni window, using a Si surface barrier detector placed at 44.68\(^\circ\) with respect to the beam direction. This provides a crosscheck of the beam current measurement.

Table 1: Preliminary results from the present experiment at \(E_{\text{c.m.}} = 952\,\text{keV}\). The cross section and S-factor values are quoted in arbitrary units for both current integration (CI) and elastic scattering (Rut.) beam-particle normalizations as described in the text. The total number \(N(7\text{Be}, t=0)\) of \(^7\)Be nuclei is normalized to correspond to the end of the implantation.

| \(E_{\text{c.m.}}\) | \(N(7\text{Be}, t=0)\) | \(\sigma_{\text{CI}}\) | \(\sigma_{\text{Rut}}\) | \(S(E)\) | \(S_{\text{Rut}}(E)\) |
|-----------------|-----------------|------------------|------------------|--------|--------|
| 952             | 6.64 \(10^6\) (3.5%) | 1000             | 1000             | 0.400  | 0.400  |
| 952             | 8.61 \(10^6\) (3.0%) | 911              | 893              | 0.364  | 0.357  |
| 952             | 6.89 \(10^6\) (4.1%) | 1024             | 1089             | 0.409  | 0.434  |
| 952             | 5.86 \(10^6\) (4.5%) | 952              | 1012             | 0.380  | 0.405  |
| 951             | 10.4 \(10^6\) (3.6%) | 1006             | 940              | 0.402  | 0.377  |

Figure 2: A schematic drawing of the chamber. The various items described above, such as the gas foil, electron suppression, the Si detector and the Cu stopper, are depicted.

The \(^7\)Be nucleus decays by a 478 keV \(\gamma\)-ray transition from the first excited state in \(^7\)Li with a lifetime of \(T_{1/2} = 53.29 \pm 0.07\) d and a branching ratio of 10.45 \(\pm 0.04\)% [see, e.g., Refs. 7,8, and references therein]. The number of \(^7\)Be nuclei produced in the reaction is obtained by measuring the
478 keV γ-activity at the NRC-Soreq laboratory, using a large-volume Ge detector, placed in a specially shielded environment for low count rate measurements. A similar setup was used previously by our group to determine with high accuracy the number of 7Be atoms in our implanted 7Be target for the determination of $S_{17}(0)$ [6, 7]. A typical γ-ray spectrum is shown in Fig. 3. The results from our recent experiment [13] are shown in Table I and in Fig. 4.

![Graphical representation](image)

Figure 3: A typical spectrum from the decay of 6-106 atoms of 7Be, corresponding to one of the measurements presented in Table I. The 478 keV α-peak can be seen prominently with very small background.

The value of the S factor we obtain is $S_{34}(0) = 0.53(2)(1)$ keV.b, in excellent agreement with earlier compilation but with a much reduced error. Our present result is also in excellent agreement with a recent experiments of the Luna collaboration ([14]).

## 2 HOST-DEPENDENCE of the 7Be HALF LIFE

The decay rate of radioactive nuclei that undergo orbital Electron Capture (EC) depends on the properties of the atomic electron cloud around the nucleus. Hence, EC may exhibit varying decay rates if the nucleus is implanted into host materials with different properties of their corresponding electron clouds. The first suggestion of this effect in 7Be, which is the lightest nucleus that decays by EC, and reports of experiments trying to investigate this phenomenon, have been presented by Segrè et al. [15, 16, 17]. This effect has been qualitatively attributed in the past to the influence of the electron affinities of neighboring host atoms [18]. The electron density of the 7Be atom in a high-electron affinity material such as gold is decreased via the interaction of its 2s electrons with the host atoms, resulting in a lower decay rate (longer half-life). Recently, the life-time modification has been suggested to stem from differences of the Coulomb screening potential [31] between conductors and insulators (see below).

Several experimental and theoretical investigations were conducted during recent years to study the host material effect on the decay rate of 7Be [18, 20, 21, 22, 23, 24], with a somewhat confusing scattering of experimental results. It was found that the half-life of 7Be encapsulated in a fullerene
Figure 4: Present data together with that of previous results and representative theoretical fits, yielding $S_{34}(0) = 0.533 \pm 0.020(7)$ keV·b.

$C_{60}$ cage and $^7$Be in Be metal is $52.68(5)$ and $53.12(5)$ days, respectively, amounting to a difference of $0.83(13)\%$ [23]. A smaller effect of $\approx 0.2\%$ was measured for the half-life $53.64(22)$ d of $^7$Be in $C_{60}$ and $53.60(19)$ d of $^7$Be in Au [24]. A recent theoretical evaluation shows that short and long half-lives $52.927(56)$ d and $53.520(50)$ d were measured for $^7$Be in Al$_2$O$_3$ and $^7$Be in (average of BeO, BeF$_2$ and Be(C$_5$H$_5$)$_2$), respectively [18]. These results yield the magnitude of the effect to be as large as $1.1\%$. Another experimental investigation has shown that the half-life increases by $0.38\%$ from $^7$Be in graphite, $53.107(22)$ d, to $^7$Be in Au, $53.311(42)$ [21], while a very recent investigation [32] has seen no effect to within $0.4\%$. The great interest in this phenomenon for $^7$Be arises also from the need to explore the possible contribution of the half-life of $^7$Be to the measurement of the cross section of the two fusion reactions, $^7$Be($p,\gamma$)$^8$B and $^3$He($^4$He,$\gamma$)$^7$Be, that play an important role in determining the solar neutrino flux [6, 13].

The present work has been undertaken in order to probe this phenomenon yet again in an experimental approach that takes full advantage of the experience gained in measuring implanted $^7$Be activity in a controlled and precise manner for cross section determinations of the solar fusion reactions mentioned above [6, 13]. As a demonstration of the quality of the $\gamma$-activity measurement, we cite the results of [6, 7] where two independent determinations of the absolute activity of $^7$Be, at the Soreq laboratory and at Texas A&M University, were in excellent agreement to within $0.7\%$. The same setup has also been used for determining the $^7$Be activity ensuing from the $^3$He($^4$He,$\gamma$)$^7$Be reaction [13]. We report the measurement of the half-life of $^7$Be implanted in four host materials: copper, aluminum, aluminum oxide (sapphire - Al$_2$O$_3$) and PVC (polyvinyl chloride - [C$_2$H$_3$Cl]$_n$).

The primary source of $^7$Be for implantation was a graphite target, from the Paul Scherrer Institute (PSI), used routinely for the production of $\pi$ mesons [26]. Many spallation products are accumulated in the target, including $^7$Be. Graphite material from the PSI meson production target was placed in an ion-source canister and was brought to ISOLDE (CERN); $^7$Be was extracted at ISOLDE by selective ionization using a resonance laser ion source. Direct implantation of $^7$Be at 60 keV in the host material was subsequently followed. A detailed description of the extraction and implantation of $^7$Be at ISOLDE is provided in detail in Refs. [7, 27]. This procedure facilitated a precision measurement of the cross
section of the reaction $^7$Be(p,$\gamma$)$^8$B. The implantation spot was defined by a 2 mm collimator positioned at close proximity to the target for the Cu sample and a 5 mm collimator for the other samples. This small change in the ensuing counting geometry has been well investigated for the measurement of $^7$Be activity [13] and does not affect the results in any significant manner. The implantation process provided full control of the spot composition ($^7$Be, $^7$Li) as well as a radial and depth profiles. For earlier implantations, at a density of $^7$Be in Cu far exceeding that of the present experiment, the spot was found to be robust and the $^7$Be inventory in the spot was stable [7, 28], excluding naturally radioactive decay. The copper, aluminum and PVC host material targets consisted of disks of 12 mm diameter and 1.5 mm thickness, while the sapphire target was a square of 10.2 mm x 10.2 mm. The median implantation depth of $^7$Be into these materials has been estimated using the SRIM code [29] and found to be 12, 24, 470 and 37 $\mu$m, respectively, i.e. all implantation depths were well below the surface.

A typical decay curve is presented in Fig. 5 and the results of the four host materials, Al and Cu (conductors) and PVC and Al$_2$O$_3$ are presented in Fig. 6. Even though the statistical test of the present data supports a null effect within $\pm 1\sigma$, the results of Fig. 5 may indicate a slight positive trend of the half-life versus the electron affinity, where a host material with high-electron affinity such as copper (conductor), exhibits a longer half-life, compared to a lower electron affinity material such as aluminum oxide (insulator).

A possible interpretation of the life-time results follows a recent observation by Wang et al. [30] of an approximately 1% increase in the lifetime of $^7$Be in metallic vs. insulator environments at low temperature. This change is consistent with the Debye screening model [31] that has been successfully used to explain the screening potential for nuclear reactions at very low beam energies. The average life times for the two insulators (PVC and Al$_2$O$_3$) and the two metals (Cu and Al) are 53.180(31) d and 53.299(33) d, respectively, a difference of 0.22%. Indeed, the trend of the present data is in basic agreement with the temperature dependence of the screening model, as well as with the results of [32]. A further investigation of such a small trend and its detailed temperature dependence is clearly called for.

Figure 5: Top (left axis, diamonds): The decay curve of the 477.6 keV line of $^7$Be imbedded in the Al$_2$O$_3$ sample. The straight line was fitted by a weighted linear regression. Bottom (right axis, squares): The deviation between the measured and the fitted count rates, divided by the corresponding uncertainty, for the 10 measurements of the Al$_2$O$_3$ sample (see text).
Figure 6: The half life of $^7$Be in 4 host materials. The solid line represents the weighted average and the broken lines correspond to a ±1σ interval. Also shown is the adopted value in the literature [?]

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References

[1] SNO collaboration, Phys. Rev. Lett. 87, 0713101 (2001); Phys. Rev. Lett. 89, 011301 (2002).

[2] B.T. Cleveland et al., J. Exp. Theor. Phys. 496, 505 (1998).

[3] S. Fukuda et al., Phys. Rev. Lett. 86, 5651 (2001).

[4] L. Weissman, C. Broude, G. Goldring, R. Hadar, M. Hass, F. Schwamm and M. Shaanan, Nucl. Phys. A630, 678 (1998).

[5] M. Hass, C. Broude, V. Fedoseev, G. Goldring, G. Huber, J. Lettry, V. Mishin, H.J. Ravn, V. Sebastian and L. Weissman, Phys. Lett. B462, 237 (1999).

[6] L.T. Baby, C. Bordeanu, G. Goldring, M. Hass, V. Fedoseev, U. Koester, L. Weissman, Y. Nir-El, G. Haquin, H. W. Gaggeler, R. Weinreich and the ISOLDE collaboration Phys. Rev Lett. 90, 22501 (2003).

[7] L.T. Baby, C. Bordeanu, G. Goldring, M. Hass, V. Fedoseev, U. Koester, L. Weissman, Y. Nir-El, G. Haquin, H. W. Gaggeler, R. Weinreich and the ISOLDE collaboration, Phys. Rev. C67, 065805 (2003).

[8] L.T. Baby, C. Bordeanu, G. Goldring, M. Hass, V. Fedoseev, U. Koester, L. Weissman, Y. Nir-El, G. Haquin, H. W. Gaggeler, R. Weinreich and the ISOLDE collaboration, Nucl. Phys. A718, 477c (2003).

[9] See, e.g., J.N. Bahcall, M. Pinsonneault and S. Basu, Astrophys. J. 555, 990 (2001), and references therein.
[10] M. Hilgemeier et al., Z. Phys. A329, 243 (1988).
[11] T.A. Tombrello et al., Phys. Rev. 131, 2582 (1963).
[12] R.D. Williams et al., Phys. Rev. C23, 2773 (1981).
[13] B.S. Nara Singh et al., Phys. Rev. Lett. 93, 262503 (2004)
[14] D. Bemmerer et al., Phys. Rev. Lett. 97, 122502 (2006).
[15] E. Segrè, Phys. Rev. 71, 274 (1947).
[16] E. Segrè and C. E. Wiegand, Phys. Rev. 75, 39 (1949).
[17] R.F. Leininger et al., Phys. Rev. 76, 897 (1949).
[18] P. Das and A. Ray, Phys. Rev. C71, 025801 (2005).
[19] K.U. Kettner et al., J. Phys. G 32, 489 (2006); and references therein.
[20] A. Ray et al., Phys. Lett. B455, 69 (1999).
[21] E.B. Norman et al., Phys. Lett. B519, 15 (2001).
[22] A. Ray et al., Phys. Lett. B531, 187 (2002).
[23] T. Ohtsuki et al., Phys. Rev. Lett. 93, 112501 (2004).
[24] A. Ray et al., Phys. Rev. C73, 034323 (2006).
[25] B.N. Limata et al., Eur. Phys. J. A27, s01, 193-196 (2006).
[26] G. Heidenreich et al., Proc. AIP 642, 122 (2002).
[27] U. Köster et al., Nuc. Inst. Meth. B204, 343 (2003).
[28] M. Hass et al., Phys. Lett. B462, 237 (1999).
[29] SRIM package from www.srim.org
[30] B. Wang et al., Eur. Phys. J. A28, 375-377; and references therein (2006).
[31] K.U. Kettner et al., J. Phys. G 32, 489 (2006); and references therein.
[32] B.N. Limata et al., Eur. Phys. J. A27, s01, 193-196 (2006).