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Study of the $^7Be(p,\gamma)^8B$ Reaction, With Very Low Energy ^7Be Beams

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Abstract

We propose to develop and use low energy ^7Be beams at ISOLDE to study the $^7Be(p,\gamma)^8B$ reaction, a major source of uncertainty in the Standard Solar Model and crucial for understanding the ^8B solar neutrino flux. The ^7Be beam is essential for a high precision measurement with systematic uncertainty differing from all other currently active experiments. Moreover, measurements at low energies are important for testing extrapolation procedures. We concentrate on one measurement at ISOLDE at $E_{^7Be}$ in the range of 1.2 MeV (E_{cm} = 150 keV). After completion of this stage and with significant improvements in setup and beam intenstity, we intend to continue to measure at lower energies E_{cm} < 150 keV so as to test extrapolation procedures.

We draw on the expertise of the present investigators in the various aspects of the propsed experiment and the unique instrumentation available and proposed for ISOLDE. These include the ISOLDE production and acceleration of the most intense ^{7}Be beam thus far (IS366), the ISOLDE High Charge breeding (most likely the proposed ECR source), the HV platform (IS303) and the measuring setup (UConn and Louvain-La-Neuve). In addition, the coupling of a High Voltage platform to a High Charge breeding would place ISOLDE in the unique situation of providing intense Radioactive Beams with energies in the range of 100 keV/u presently NOT available at any facility in the world and much needed for many studies in Nuclear Astrophysics, such as the current proposed experiment.

We intend to use an experimental setup that has already been extensively modeled by Monte Carlo simulations and used by the UConn-LLN group in experiments at Yale University to measure the $^2H(^7Li,^8Li)p$ reaction cross section with high precision (±5%). The same setup is now in use to measure the $^7Be(p,\gamma)^8B$ reaction with

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accelerated ^7Be beams at higher energies (1 MeV/u) at Louvain-La-Neuve, and the proposed ISOLDE experiment is complementary to the LLN experiment at higher energies. The procedures for producing an intense ^7Be beam with the LIS at ISOLDE have been succesfully established in the production of an implanted ^7Be target for the IS363 experiment. Also, large quantities of ^7Be and procedures for off line chemical separation of ^7Be from ^7Li are now routinely used at LLN and will prove very useful for the proposed measurement as it will facilitate experiments during CERN shut-down periods.

The experience gained at Louvain-La-Neuve (LLN) by routine handling of a large quantity of radioactive ^7Be in an ECR source (more than 10^{16} ^7Be atoms on the sputtering head) allows us to propose procedures for radiation safety at ISOLDE that will not adversely affect the operation of the lab, as radiation safety procedures already established and tested at LLN permit the use of the ECR source at LLN with a design goal of 10^{17} ^7Be atoms in the sputtering head without adversely affecting the use of the source by others at the lab at LLN.

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1 Introduction

The Solar Neutrino Problem (SNP) [1] represents an outstanding puzzle in Astrophysics and may reflect new physics and new neutrino properties beyond the standard model of Particle Physics. The $^7Be(p,\gamma)^8B$ with its associated astrophysical cross section factor $S_{17}(0)$ [$= \sigma_{17} \times E \times exp(2\pi\eta)$] has been identified [2] as the single most uncertain nuclear input to the standard solar model, and it needs to be measured with high accuracy (small systematic error) and high precision (small statistical error).

Six measurements of the $^7Be(p,\gamma)^8B$ cross section were originally carried out. Four of them have high precision (of the order of 10%) [3, 4, 5, 6], and of these only two span the low energy region down to 114-150 keV [4, 6]. From these measurements one extracts the astrophysical S-factor and extrapolates to solar energies

[$S_{17}(0)$]. However, the extrapolated $S_{17}(0)$ factors disagree by 25-35% between the various measurements.

Recent measurements using the Coulomb dissociation method [7, 8, 9] yield a weighted average $S_{17}(0) = 19.4 \pm 1.3\ eV - b$ [10], that appears to confirm the result of Filippone *et al.* [6] but is slightly lower. The new measurements with ^7Be targets quote $S_{17}(0) = 18.5 \pm 2.4\ eV - b$ [11, 12], and approximately $20.3\ eV - b$ [13]. These measurements (all direct measurement thus far are with ^7Be targets) are quite different from our intended experiment, and thus have different systematic errors. Clearly it is essential to measure $S_{17}(0)$ with several different methods to yield a reliable precise value. An earlier measurement with ^7Be beams, a Naples-Bochum collaboration [14], has thus far produced a low precision value of $S_{17} = 16 \pm 4\ eV - b$. We are currently involved in an experiment at LLN [15] to measure the $^1H(^7Be,^8B)\gamma$ reaction at higher energies, and a similar experiment was discussed in a LOI submitted to ISOLDE by the Bochum/Naples group. The measurement at very low energy, $E_{^7Be}$ = 1.2 MeV (E_{cm} = 150 keV) discussed here, with an estimated cross section of 8 nb, is most important as the energy is closer to the region of astrophysical interest. We also intend, after success and with improvements of the setup and beam intensity, to extend our measurement to lower energies, E_{cm} = 100 and 60 keV, where the estimated cross sections are 2 and 0.3 nb, respectively. Such measurements with intended accuracy of ±5% will allow us to test theoretical extrapolation procedures, as we discuss below.

The uncertainty in the measured absolute value of the cross section of the $^7Be(p,\gamma)^8B$ reaction is quite possibly best addressed with a ^7Be beam and a hydrogen target, allowing for a direct measurement of the beam-target luminosity by measuring the elastically scattered protons recoiling from the target. Our intended experiment, see below, will thus measure the ratio of the cross section of the $^7Be(p,\gamma)^8B$ reaction to the known elastic (Rutherford) scattering of p + ^7Be. Such a measurement will result in an $S_{17}(0)$ value with the design goal precision of ±5%, as we have already demonstrated in our measurements at Yale of the $^2H(^7Li,^8Li)p$ reaction using the same setup. However, additional uncertainty may exist in the theoretical extrapolation of the measured cross section to solar energies (approximately 20 keV). Several theoretical studies suggest extrapolation procedures amounting to 10% upward correction of the measured low energy cross section factors. One extrapolation is claimed to be accurate to ±1% [16]. Without discussing this rather strong statement we consider a similar situation that haunted Nuclear Astrophysics a few years back; the S-factor of the $^2H(d,\gamma)^4He$ reaction. It was assumed that in this case d-waves dominate and no nuclear structure effects should play a role at very low energy (as low as 100 keV). Much in the same way, it is stated today that s-waves dominate the $^7Be(p,\gamma)^8B$ reaction and we do not expect nuclear structure effects to play a role at low energies in the $^7Be(p,\gamma)^8B$ reaction. In Fig. 1 we show Fowler's extrapolated d-wave S-factor that is a mere factor of 32 smaller than measured, due to a small NON d-wave component in the d + d interaction [17]. A small nuclear structure effect, namely the d-wave component of the ground state of ^4He, gives rise to a change by a factor of 32 in the predicted astrophysical S-factor. Similarly we may ask whether a small NON s-wave component in the low energy interaction of p + ^7Be could alter the extrapolated $S_{17}(0)$ value by considerably more than one percent. A determination of $S_{17}(0)$ with an accuracy of ±5% mandates that the cross section be measured at lowest possible energies, as proposed here, so as to also test the extrapolation procedures.

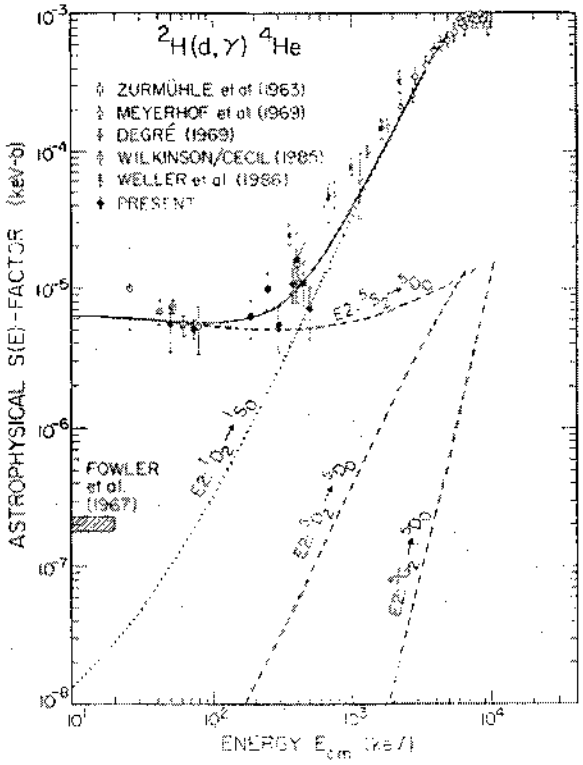

Fig. 1: Extrapolation of d-wave S-factor of the $^2H(d,\gamma)^4He$ reaction[17]. Note the presence of small NON d-wave components that yield a discrepancy from Fowler's extracted S-factor by a factor of 32.

2 The Proposed Experiment

2.1 Design Goals

We propose to measure the cross section of the $^7Be(p,\gamma)^8B$ reaction with the use of ^7Be beams produced at the ISOLDE laser source coupled to the proposed High Charge state breeding source (most likely an ECR source). With ^7Be in a charge state of 4^+ and platform plus High Charge state total acceleration voltage of 300 kV, we propose to use ^7Be beams at 1.2 MeV with a beam intensity of the order of 10^{11} /sec (16 pnA) on target. Currently at ISOLDE we have already used the most intense ^7Be beams of 2 pnA and the additional factor of 8 in beam intensity we expect by placing a sample of ^7Be produced off line (via the $^7Li(p,n)^7Be$ reaction at low energies) instead of using the (lower production rate of the) PS beams. The efficiency of the high charge breeding (ECR) source is yet to be measured but is expected to be high which is essential for our goal of obtaining high intesnity ^7Be beams.

The target center of mass energy window (target thickness) will be 12 keV. Thus the target contains 4×10^{18} hydrogen nuclei/cm^2 within a thin 50 $\mu g/cm^2$ polyethylene $(CH_2)_n$ foil. We intend to test the durability of the thin polyethylene target using beams of ^{10}B and ^9Be at the Weizmann Institute with similar energies and intensities. If needed a rotating target system already available by the UConn-Yale group will be used. The luminosity of our intended experiment will be 4×10^{29} $sec^{-1}cm^{-2}$ or a one day integrated luminosity of 30 nb^{-1}.

The UConn-LLN experimental setup discussed below is compact and can fit into the current (or future improved) High Voltage platform with minor modifications. With a measured alpha-particle detection efficiency of 52%, [15] and a ^8B transfer time of 0.06 sec, every 0.45 sec (already demonstrated for the UConn-LLN setup) we obtain a total alpha-particle detection efficiency of approximately 25% with virtually no background [15]. And for a cross section of 8 nb (at E_{cm} = 150 keV) we estimate a count rate of 60 counts per day, making this measurement and mesurements at further low energies possible. It should be noted again that these measurements are intended for the shut down period and thus could be longer than usual. While the design goal is to achieve precision of 5%, we must emphasize that a precision of for example 7% will already constitute an improvement of current world data.

2.2 Uniqueness of ISOLDE

Clearly the most intense ^7Be beams already achieved at ISOLDE, approximately a factor of 1,000 more intense than thus far available accelerated ^7Be beam, makes ISOLDE most suitable for studying the $^7Be(p,\gamma)^8B$ reaction with accelerated ^7Be beams. The ISOLDE laser source is indeed most suitable for producing a high intensity and clean (less than one part in a thousand ^7Li contaminant of the) ^7Be beams. A high charge state breeding is currently achieved at ISOLDE by using the EBIS source. This source however is limited by the space charge in the REX-trap and most likely can not be used for the current proposed experiment. A new high efficiency high charge state breeding ECR source is however proposed for ISOLDE (ECRIS) by the EU High Charge State Breeding group. Currently the proposed ECR source is intended merely for comparison studies of high charge state breeding and we hope that our program will enrich and enhance the Physics program of the ECR source at ISOLDE. This high efficiency ECR source will be most suitable for our proposed experiment with high intensity low energy ^7Be beams.

The new capability of the proposed ECR high charge state breeding coupled to the existing and future high voltage platform(s), will make ISOLDE a unique facility for studies in Nuclear Astrophysics with radioactive beams of approximately 100 keV/u and inverse kinematics. In this case a hydrogen and helium isotopes targets can be used with the hydrogen targets being a polyethylene foil (as proposed here) and for the helium target one may use helium implanted into a very thin aluminum foil [20]. On one hand our proposed experiment will utilize current and new ion sources proposed for ISOLDE, and on the other hand, we hope it will allow the use of these equipment (the ECR source and HV platform) for a strong and unique future program in Nuclear Astrophysics. For example one may consider, among many important examples, the study of $^8Li(\alpha,n)^{11}B$ [18] or the $^8Li(d,n)^9Be$ or $^8Li(d,t)^7Li$ [19] as a few typical examples of reactions of interest in Nuclear Astrophysics.

2.3 Inverse-kinematics Detection Setup

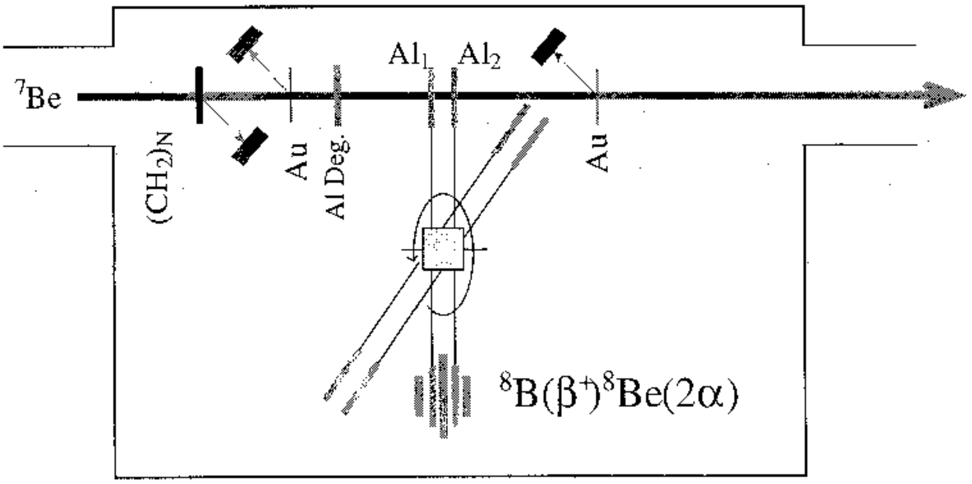

Fig. 2: The proposed experimental setup.

The experimental setup is shown in Fig. 2. We emphasize again that this setup was already used to measure the $^2H(^7Li,^8B)p$ reaction at Yale University with a precision of ±5%. An improved setup has been constructed by the UConn group and used at LLN. This second setup can also be used at ISOLDE with minor modifications.

In the target region, two monitors measure the beam intensity by measuring the elastic scattering from a thin Au foil and by measuring the elastically scattered recoil protons. The recoil ^8B are degraded in a 100 $\mu g/cm^2$ Al foil and stopped in the middle of a 500 $\mu g/cm^2$ aluminum catcher foil arrangement as shown in Fig. 2. After irradiation the foils are quickly (60 msec) moved to the first counting station positioned at 90°, followed by a second counting station at 180° and a third one at

270° where the resulting back to back alpha-particles are measured in coincidence by the detector array shown in Fig. 2. Our Monte Carlo simulations show that our alpha-alpha coincidence efficiency is approximately 98%, due to the large diameter of the central detector (69 mm), as compared to the small (25 mm) diameter of the front and back detectors. While the recoil ^8B are stopped in the catcher foils, the ^7Be is transmitted, hence reducing the background from the 477 keV gamma line of ^7Be. The exiting ^7Be beam is used for monitoring purposes by measuring the elastic scattering from a thin Au foil placed after the catcher foils, as shown in Fig. 2.

The recoil ^8B are equally spread on the alternating catcher foils, half of the activity is deposited in the front foils (Al1) and half in the back foils (Al2). We achieve this by using 0.5 mg/cm^2 Al foils placed in alternating positions on the two catcher wheels, two in the front and two in the back of the two wheel arrangement. The spread of the ^8B on the four foils allows us to measure in all cases alpha-alpha coincidences, but more importantly the detection geometry is closed (each detector covering 52% of 2π) which makes the absolute efficiency of the alpha detection insensitive to the exact location of the catcher foils. All the detectors and catcher foils are at a fixed relative distance owing to a rigid mounting structure, and thus an increase in the efficiency of the front detectors gives rise to a decrease in the back detectors. Our Monte Carlo simulation shows that a global shift of two catcher wheels relative to the fixed detectors by 2 mm results in a change of only 1.5% in the total alpha-particle detection efficiency, although the efficiency of each individual front and back detector varies by approximately +40% and −40%. This closed geometry allows us to quote a cross section with a very small systematic uncertainty.

The continuous alpha-spectrum of ^8B is cut below 300 keV due to absorption in the 0.5 mg/cm^2 aluminum catcher foil. Our measurement of the beta-delayed alpha-emission from ^8Li carried out at Yale University, as well recent and old measurements of the beta-delayed alpha-particle spectrum of ^8B [21, 22], demonstrate that this cut amounts to less than 3% of the total alpha yield and is included in our estimate of the detection efficiency.

3 Radiation Safety

The half-life of ^7Be is 53.3 days, with a 10% branching ratio for electron captures to the first excited state of ^7Li, leading to 477 keV gamma-radiation with $\lambda \times B.R. = 1.5 \times 10^{-8}\ sec^{-1}$. Note that the residual gamma-activity will be reduced by a factor of 10 after six months and a factor of 100 after one year.

A ^7Be beam of 10^{11} $/sec$ yields an accumulated irradiation over 2 days of approximately 10 mCi gamma activity. Our experience with handling larger amounts of activity at LLN shows that it can be safely handled with the use of a dedicated plasma source chamber of the ECR source and with beam line components covered with foils to protect them from deposition of ^7Be. For example the lab at LLN routinely handles an ECR source with a sputtering head including 10 mCi of gamma activity with a design goal of 100 mCi. It has been shown that this amount of activity can be safely handled using precautionary measures without adversely affecting the operation of the lab at LLN and we expect the situation at ISOLDE to be as safe.

We nevertheless recognize that the issue of a long period use of the ECR source has to be addresed in detailed manner and we commenced a review with the Radiation Safety of ISOLDE. We note that similar activities are expected for the other proposed experiments at ISOLDE, as for example is the case for the Naples-Bochum collaboration mentioned above aimed at using higher energies ^7Be beams from REX ISOLDE.

4 The High-Voltage Platform and the High Charge State Breeding

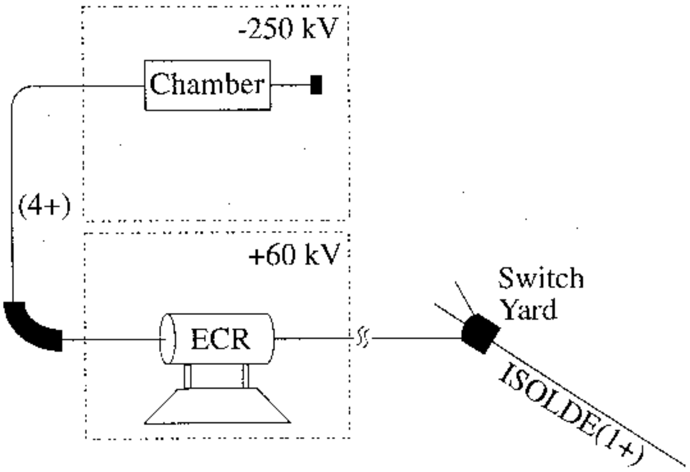

Fig. 3: Possible floor plan with the ECR source located underneath the HV platform.

One possible floor plan for the proposed ECR source plus High Voltage platform is shown in Fig. 3. The 60 keV ^7Be beam from the ISOLDE source enters the ECR source and is stopped by a positive 60 kV potential. The ^7Be is ionized to a high charge state (4^+) and exits from the other side of the ECR source. The ECR source in this (one possibly proposed) floor plan is placed at the current location of the HV platform after the switch yard, and the HV platform will be moved to a higher level above the ECR source. The ^7Be beam exiting the ECR source in a charge state of 4^+ is bent upward using the ECR charge state selecting magnet and then it is bent again and travel anti parallel to the original ^7Be beam with (a charge state of 1^+) and enters the HV platform (at a potential of negative 250 kV). When ISOLDE beams (charge state 1^+) are being used, the ECR source will be used as drift space or alltogether removed out of its positions so as to allow a normal use of the HV platform as of today.

5 Resources: Funds and Manpower

Our collaboration offers resources (manpower and funds) for the construction of such and other possible floor plan(s) and we request input from the ISOLDE collaboration for this and other possible floor plan(s). Costs estimates are currently being reviewed by the PS division and will become available soon.

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