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Reducing experimental uncertainties on production and destruction of ^{7}Be in hydrogen burning

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The observational constrains given by the detected solar neutrino fluxes are weakened by the uncertainties affecting solar model calculations. This is the case of the uncertainty on the determination of $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ and $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$, since the neutrinos produced in the decay of ^{8}B and ^{7}Be represent a major contribution to the high energy component of the neutrino spectrum, to which many observations are sensitive. Moreover these cross sections play a significant role in the determination of the mixing during shell hydrogen burning, as well as in Big Bang Nucleosynthesis. With the aim of reducing the uncertainties on these reactions, eventually due to systematic effects, the ERNA collaboration has undertaken a research program based on the use of a recoil mass separator. The $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction was investigated recently, the results have given a substantial improvement in the understanding of this process. The follow up will be the study of $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ in inverse kinematics. The recoil separator, previously installed at the Ruhr University (Bochum, Germany), has been moved and recommissioned, after a significant upgrade, at the CIRCE laboratory of the Second University of Naples - INNOVA (Caserta, Italy). The experimental setup and the development of an intense ^{7}Be beam to allow measurements at energies as low as $E_{\mathrm{cm}} \sim 350\,\mathrm{keV}$,, is presented.

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1. Introduction

Observations of the Sun's neutrino fluxes are important tools for the study of neutrino physics and eventually to study the interior of the Sun. For this purpose the nuclear cross sections of the processes involved in hydrogen burning must be known with adequate precision. The experimental uncertainty on the ^{3}He$(\alpha,\gamma)^7$Be and ^{7}Be$(p,\gamma)^8$B reactions directly reflects on the predicted fluxes of ^{7}Be and ^{8}B neutrinos, see e.g. [1], that are a major contribution to the high energy component of the solar neutrino spectrum, to which most of the observations are sensitive.

The precision determination of the reaction rates of reactions producing and destroying ^{7}Be is also relevant for the production of Li isotopes during Big Bang Nucleosynthesis (BBN) that occurs at energies significantly higher than solar, i.e. $\sim 100-400\,$MK, see e.g. [2].

Another astrophysical relevant issue, related to the study of these reactions, is the nucleosynthesis of Lithium in Red Giants. It occurs by means of a complex interplay between the nuclear reaction rates and mixing phenomena induced by convection and other mechanisms, such as rotation or magnetic buoyancy, see e.g. [3].

The European Recoil Separator for Nuclear Astrophysics (ERNA) is an experimental setup dedicated to the study of nuclear radiative capture reactions of astrophysical interest [4–11]. A Recoil Mass Separator allows a measurement of the total reaction cross section by the direct detection of the recoil ions produced in the process. In such experiments the reactions are studied using a differentially pumped, windowless gas target. The recoils emerge from the target together with the intense incident beam. The subsequent separator, consisting of a series of beam focussing and analyzing elements, filters the intense primary beam by many orders of magnitude and allows a direct counting of the recoils, having a selected charge state, in the end detector. Also, the simultaneous detection of reaction γ-rays is possible, a coincidence mode with recoil detection reduces to a negligible level the background in the γ-ray spectra.

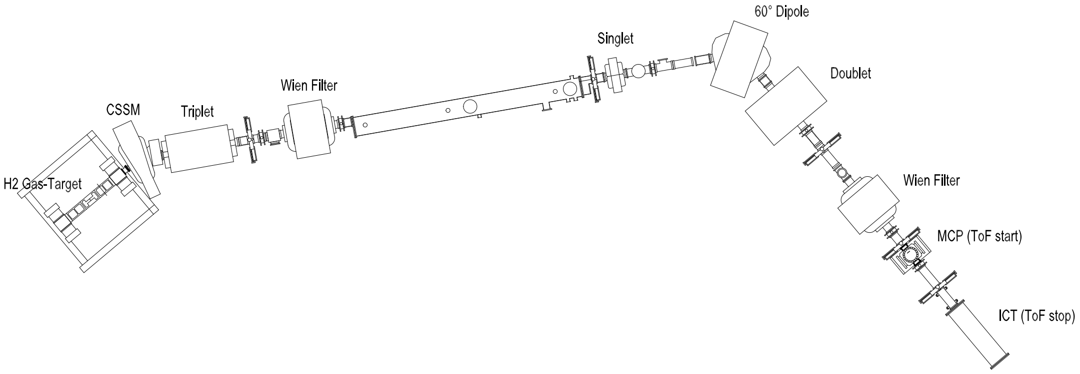

Figure 1: Schematic layout of the recoil separator ERNA. The filtering elements are indicated: Charge State Selection Magnet (CSSM), the two Wien filters and the 60° Dipole Magnet. The focussing elements are also indicated: the quadrupole Triplet, the quadrupole singlet, and a quadrupole doublet. The location of the Microchannel plate (MCP) that is used as the Time Zero detector of the Time-Of-Flight assembly is shown, as well as the Ionization Chamber Telescope (ICT), used to identify the ions, see [9] for details. Several slits assemblies as well as Faraday cups are also present along the beamline.

The recoil separator ERNA had been originally installed at the Dynamitron Tandem Labora-

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tory of the Ruhr Universirty Bochum (Germany). It has has been recently moved to the CIRCE laboratory (Center for Isotopic Research on Cultural and Environmental heritage, of the Second University of Naples - SCrl Innova, in Caserta (Italy) [12], where a 3MV pelletron tandem accelerator is installed. The separator underwent a major upgrade with the installation of the Charge State Selection Magnet (CSSM) right after the target and is now in the re-commisioning phase, a schematic view is presented in figure 1. The old separator layout allowed beam particles in any charge state to enter the quadrupole triplet, that was an issue for the measurement of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction cross section. In fact C projectile ions, gaining in the target gas a charge state larger than the one for which the separator was set, were over focussed by the quadrupole triplet and impinged on the plates of the first Wien filter impeding its proper operation [13]. This issue is solved by the CSSM, that will allow only recoils, and primary beam particles (since $p_{\mathrm{recoil}} \simeq p_{\mathrm{projectile}}$), in the proper charge state to enter the separator.

The measurement program of the ERNA collaboration so far concentrated on α capture reactions. The total cross section of the $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ reaction was measured with high precision over a wide energy range, $E_{\mathrm{cm}} = 0.65$ to $3.2\,\mathrm{MeV}$ [9, 10]. Because of the different systematics with respect to other measurements it was possible to solve a long lasting discrepancy between the results obtained by grouping experiments by measurement technique.

The most interesting finding was an unexpected energy dependence of the cross section at energies larger than $\sim 1\,\mathrm{MeV}$. Since the extrapolation of the S-factor to zero energy, $S_{34}(0)$, needs the choice of a model, the ERNA data did allow to make a selection among the several theoretical models available. Indeed the energy dependence deduced from the experimental data could not be described by the simple direct capture model, despite several calculations were supposed to accurately predict the energy dependence of the S-factor in the investigated energy range. A better description is obtained by calculations based on microscopic models, the recent calculation of [14] shows a good agreement with the ERNA results. This selection of the models leads to more robust extrapolations to astrophysical relevant energies. Details of the experimental procedures and data analysis are given in [10].

2. Measurement of $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ with ERNA

The next step in the experimental program of the ERNA collaboration on the study of pp-chain reaction is the $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ reaction. Its cross section at low energies is predominantly due to external nonresonant $E1$ direct capture into the ground state of $^{8}\mathrm{B}$. A narrow 1^{+} resonance is present at $E_{\mathrm{cm}} = 630\,\mathrm{keV}$ but has little influence on solar rates. The extrapolation of the S-factor at the solar Gamow peak energy must be taken from models.

The experimental determination of the $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ cross section suffers similar problems as was for $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$, see e.g. [15] for a detailed discussion. Briefly direct measurements of the cross section were performed using the same experimental approach, i.e. a $^{7}\mathrm{Be}$ radioactive target and an intense proton beam. Systematic differences are observed between results of the different experiments, for both the absolute scale and for the energy dependence. To solve such discrepancies measurements performed with an alternative approach, with different systematic uncertainty sources is desirable.

We expect to significantly improve the knowledge on $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ by using ERNA in conjunction with a unique ^{7}Be radioactive beam of tandem accelerator quality and an extended windowless H_2 gas target.

Previous works, the NaBoNA experiment [16] and the measurements at ORNL [17], showed the feasibility of the recoil separator approach to the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ cross section measurement, but those experiments did not reach precision and accuracy comparable with direct kinematics experiments, mainly because of the limited ^{7}Be beam intensity. With ERNA we plan to measure in the energy range $E_{\mathrm{cm}} = 0.4 - 1.0\,\mathrm{MeV}$, that is below and above the resonance, to assess absolute scale and slope of the S-factor. We expect to obtain useful results thanks to a more intense ^{7}Be beam and a thicker H_2 gas target.

The key for a measurement with a separator is its acceptance, i.e. the ability to transport 100% of the recoils, in a selected charge state, from target to the end detector, an aspect that has to be carefully evaluated in the experiment [18].
The low Q-value of the reaction $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ makes the requirements for the separator easy to achieve. In fact the reaction kinematics determines a maximum angle for the recoils of just 3.8 mrad in the planned measurement energy range. The additional angular straggling of the recoils due to the interaction with the H_2 target and the post-stripper gas (see section 4) makes the needed angular acceptance to be about 8 mrad, that is well within the acceptance of ERNA. It has been evaluated with beam optics calculations, see figure 2, that 100% transmission of the recoils through the separator can be achieved over a very long distance allowing the use of an extended gas cell.

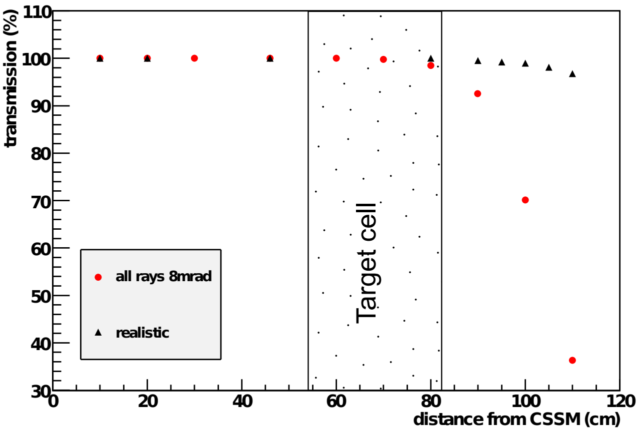

Figure 2: Transmission of the recoils through the separator, at $E_{\mathrm{cm}} = 0.4\,\mathrm{MeV}$, as a function of the distance from the CSSM magnet. Two calculations, performed with COSY Infinity [19], are shown: realistic assumes recoils angular divergence according to reaction kinematics plus angular straggling; the other one is a calculation assuming that all of the recoils emerge from target with an angle of 8 mrad, the result represents a very conservative lower limit for the separator acceptance.

3. ^{7}Be beam production

The main challenge of this measurement is to achieve a ^{7}Be beam intensity sufficiently large to allow measurement below the resonance. At CIRCE ^{7}Be beams with intensity up to $\sim 3\,\cdot$

10^8 particles/s were already produced [20]. Briefly, the ^{7}Be nuclides are formed via the $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ reaction bombarding metallic Li targets with an intense proton beam. Final activities are typically about 1 GBq. The irradiated targets are subsequently processed through a radiochemical procedure in order to extract the ^{7}Be from the Li bulk. The ^{7}Be is then deposited into cathodes, about 200 MBq each, that are subsequently installed into a dedicated multi-sample Cs-sputtering source (model SNICS, manufacturer National Electrostatics Corporation).

An important requirement for a measurement with a recoil separator is a beam of good quality, i.e. at target position it has to be sufficiently small in diameter, not to produce too much *leaky* beam by scattering on target apertures, and has to have a small angular divergence in order not to increase the maximum angle of the recoils. Therefore a characterization of the ^{7}Be beam, in terms of its size and divergence, was performed using a double slits system. The results are shown in figure 3, the beam at approximately target position is about 3 mm in diameter and has 3 mrad divergence in both the horizontal and the vertical plane.

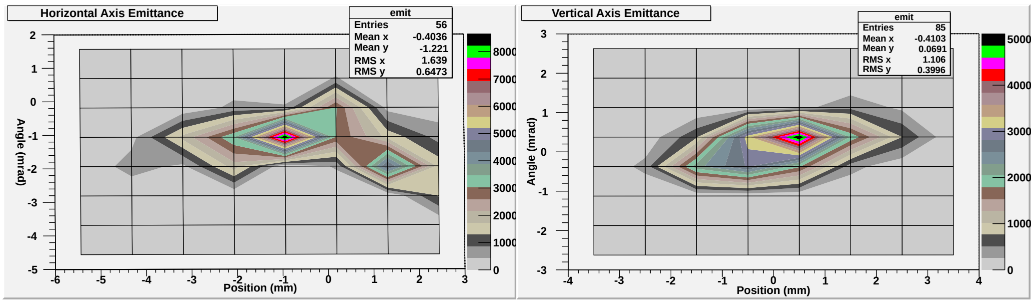

Figure 3: Beam emittance measured using two slits, left emittance in the horizontal plane, right vertical plane.

The ^{7}Be production method leads to a significant contamination of the beam by the isobar ^{7}Li. It was found that the beam composition is 20% ^{7}Li and 80% ^{7}Be. We expect an enhancement in beam intensity by a factor of 50 by increasing of the same factor the activity of the cathodes loaded into the SNICS source. For this the laboratory was equipped with an hot chemistry box where up to 10 GBq can be handled. Also a dedicated injector with a second SNICS sputter source was installed and its performance will be tested in the near future. The ^{7}Be activation for the production of the high activity cathodes will take place at the ATOMKI Institute, Debrecen (Hungary).

4. Extended H_2 target

The relatively small angular acceptance required gives the possibility of exploiting a long cell in order to achieve the needed target thickness.

The gas target is an extended gas cell of about 30 cm length. The cell is differentially pumped with 2 RootsBlower and 2 turbo pump stages on both sides. Total thickness and density profile measurements were performed by observing the $^7\mathrm{Li}(p,p')^7\mathrm{Li}$ γ-ray yield with a tight collimated HPGe detector. Additionally energy loss measurements were also performed. Thickness is controlled by setting the cell pressure, densities up to $1 \cdot 10^{19}$ atoms/cm^2 can be reached, while the pressure profile remains essentially unchanged. An additional gas layer (post-stripper), nitrogen or argon, is present after the target in order to let the recoils achieve charge state equilibrium. All the details about characterization of the target will be given in [21].

5. Outlook

The presented experiment aims at the measurement of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction cross section with the recoil separator ERNA. It has been shown that the conditions for a successful measurement are fulfilled: the separator has the full acceptance, a more intense ^{7}Be beam and a thicker target, with respect to previous recoil separator measurements, are available.
We plan measurements with improved precision above and below the 630 keV resonance. The results will be affected by systematic uncertainties that differ from those of widely used measurements techniques, and will give a substantial improvement in the determination of the slope and absolute scale of the S-factor.

Acknowledgments

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