^{8}B production measurement at LNL

T. Marchi[1,2], *V. L. Kravchuk*[1], *M. Cinausero*[1] , *G. Collazuol*[2,3], *F. Gramegna*[1]
for the EUROnu collaboration
[1] INFN, Laboratori Nazionali di Legnaro, Legnaro (PD), Italy
[2] Università di Padova, Dipartimento di Fisica, Padua, Italy
[3] INFN, Sezione di Padova, Padua, Italy

Abstract
The cross section for the reaction ^{6}Li(^{3}He,n)^{8}B at the bombarding energy of 5.77 MeV was measured. Eight liquid BC501 scintillators were used for the detection of the recoil neutrons, while the ^{3}He elastic scattering was used for the absolute cross section normalization. The capabilities of digital electronics have been exploited both for the neutron time of flight measurement and the neutron/gamma pulse shape discrimination.
Theoretical calculations were performed by means of the "Zero Range Knock-out Distorted Wave Born Approximation". Results show a good agreement between the calculations, our experimental data and earlier experimental data based on the time of flight technique.

1 Introduction

The phenomenon of neutrino oscillations is explained by the so-called Standard Neutrino Model (SνM), which uses a lepton mixing matrix with four parameters and two neutrino mass-differences ($\Delta m^2_{12} = m^2_2 - m^2_1$ and $\Delta m^2_{23} = m^2_3 - m^2_2$) to describe the observed data. Three of the mixing matrix parameters take the form of mixing angles (θ_{12}, θ_{23}, and θ_{13}), while the fourth is a phase parameter (δ_{CP}) which, if non-zero, introduces a CP asymmetry in the leptonic sector of the Standard Model, causing the oscillations of neutrinos to be different from those of anti-neutrinos.
The current challenge of the neutrino community is to measure all the mixing angles as precisely as possible, to determine the mass splittings and to seek for CP symmetry violation in neutrino oscillations, if it occurs. To this purpose the EUROnu collaboration, an European Commission co-funded collaborative project, has been studying the design of three types of facilities to provide neutrino beams: the Neutrino Factory, an intense, high-energy neutrino source based on the decay of a stored muon beam; the Beta Beam, in which electron neutrinos (and anti-neutrinos) are produced from the decay of stored radioactive-ion beams; and Super-Beams, high intensity conventional neutrino beams facility. The determination of which of these facilities should be built requires performances and costs comparisons to be made.
Beta Beams are competitive to produce well collimated pure electron neutrino or antineutrino beams to explore primarily neutrino oscillation physics including CP violation in the leptonic sector. The decay of radioactive isotopes with suitable decay time and reaction Q-values is exploited, suitable pairs of isotopes are needed to provide neutrinos and anti-neutrinos beams. The isotope pair ^{8}B and ^{8}Li, accelerated in the CERN (PS-SPS) complex, could provide respectively neutrinos and antineutrinos of energies matched to their CERN to Gran Sasso 732 km travel path. To understand if such pair can be really used for the Beta Beam project, the correspondent EUROnu work-package (WP4) contained a task to measure cross sections and angular distributions of the reaction products ^{8}B and ^{8}Li from the reactions:

- ^{3}He + ^{6}Li $\rightarrow$ ^{8}B + n (subject of this paper);
- ^{7}Li + d $\rightarrow$ ^{8}Li + p.

The ^{8}B nucleus is considered as a neutrino source producing relatively high-energy neutrinos according to its beta decay [1]: ^{8}B $\rightarrow$ ^{8}Be + e$^+$ + ν_e (t$_{1/2}$ = 770 ms).

Accurate knowledge of the reaction rates is necessary to design the tabletop accelerator and the other necessary equipment that will be used for the production of these isotopes, in particular to assess the performance of an internal target that also serves as a stripper and an absorber for ionization cooling of the circulating beam, as originally proposed by C. Rubbia *et al.* [2].
The total cross section of the ^{8}B production in the ^{6}Li(^{3}He,n)^{8}B reaction was measured previously using two different techniques, namely the positron counting and the neutron time of flight. The value obtained through the measurement of the positron decay, reorted in [3] and considered in the original proposal by C. Rubbia *et al.*, is smaller at least by a factor 3 with restpect to the one evauated from the Time of Flight measurement reported in [4]. Moreover the experimental uncertainties of existing works are quite large reaching 15-20%. For this reason we proposed to measure with higher accuracy the absolute cross section and the angular distribution of the ^{8}B produced through the ^{6}Li(^{3}He,n)^{8}B reaction.For experimental reasons and for its higher reliability, the time of flight technique was chosen.

2 Experimental Setup

The experiment was performed at the CN 7 MV Van de Graaff accelerator facility of the Laboratori Nazionali di Legnaro (INFN). A pulsed ^{3}He$^+$ beam of 6.1 MeV energy and 40 pnA intensity was provided by the electrostatic accelerator with a bunch width of less than 3 ns FWHM and a repetition rate of 3 MHz. A ^{6}LiF target with the thickness of 500 μg/cm^2 evaporated on a ^{197}Au 500 μg/cm^2 thick backing was used. The target was water cooled during the experiment to avoid Lithium evaporation and, for the same reason, placed with the Gold backing towards the incoming beam. The resulting beam energy at the middle of the ^{6}LiF layer was 5.77 MeV.
The emitted neutrons were measured using 8 large volume BC501 liquid scintillators of the RIPEN modular array [6] upgraded with digital electronics. The detectors were placed at the distance of 2 m from the target in the 15° - 140° angular range of the laboratory reference frame.

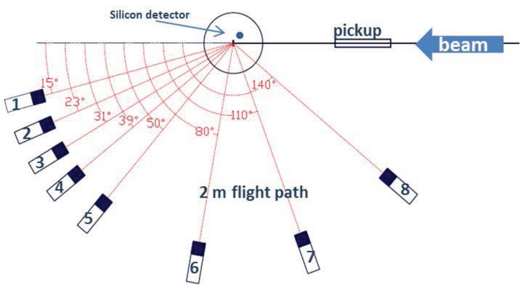

Fig. 1: Schematic view of the experimental setup.

In order to obtain a beam time reference, an inductive "pickup" was placed into the beam line. This tool emits a two-lobes signal every time a beam bunch gets through it and this signal can be properly shaped to be used as a stop for the time of flight measurements.
A ΔE (15 μm) - E (200 μm) Silicon Telescope was used for the detection of the ^{3}He particles elastically back-scattered from the Au backing. It was placed inside the scattering chamber at 150° in the laboratory reference frame and at the distance of 56 mm from the target. As already stated, this information served as a normalization to determine the ^{8}B production absolute cross section. A schematic view of the experimental setup is given in figure 1.
The energy calibration of the BC501 detectors was performed using ^{137}Cs, ^{60}Co and ^{88}Y gamma sources. This procedure is necessary to determine the neutron detection thresholds. Silicon detectors calibration

was performed using a triple Am-Pu-Cm alpha source.
Three different types of background measurements were performed:

- ^{3}He on ^{7}LiF with the thickness of 500 μg/cm^2 evaporated on the Au 500 μg/cm^2 thick backing (as the original ^{6}LiF target contained a small amount of ^{7}Li);
- ^{3}He on ^{12}C target 70 μg/cm^2 thick (to monitor the buildup of a carbon layer on the target during the experimental runs);
- a measurement without target in order to carefully subtract the environment background.

2.1 Digital Data Acquisition System

The setup was completely equipped with digital electronics. Signals from the liquid scintillators, the silicon detectors and the pickup were recorded using two CAEN V1720 digitizers (12 bit, 250 MS/s) in the 8 channels VME version. The two acquisition boards were synchronized propagating a master clock and a common software trigger but real triggers were handled on each module independently. Because of this the pickup and ΔE-E telescope signals were split and acquired in both boards. In this configuration each board is recording data from 4 neutron detectors, 2 silicon detectors and the pickup and the dead-time correction is no more required since each neutron detector channel is normalized to a number of ^{3}He particles measured at exactly the same count rate.
The Digital Front-End was interfaced to the data storage using a VME Bridge and an optical link connection (CAEN V1718 and A2818). The software used for the data acquisition is a customized version of CAEN WaveDump, properly updated in order to handle and synchronize the two (or more) digitizers. Sampled detector signals are written on disk in binary form using 2 μs acquisition windows and stored shapes are then offline analyzed to extract the required parameters.
Three different kinds of information are expected to be obtained processing the scintillators signals: the energy release of the impinging radiation, its time of flight and the pulse shape discrimination between neutrons and gammas. After proper baseline subtraction, the energy release is estimated by signal integration and time of flight is obtained as the difference between a digital constant fraction discriminator filter output value on the shape and the one obtained from the reference pickup signal.
The neutron/gamma discrimination is achieved using a digital implementation of the Zero-Crossing method, the result is a mono dimensional variable that can be directly plotted against time of flight or deposited energy to remove uncorrelated neutrons and gammas background and obtain clean time of flight spectra. This procedure will be illustrated in the next section.

3 Data Analysis

In figure 2 we show the two-dimensional plot of the Zero Crossing - deposited energy correlation for one of the BC501 detectors. The upper locus is connected to the detection of a neutron, while the lower one is due to a detected gamma; from this plot it is possible to estimate a neutron detection threshold of about 150 keVee, which corresponds to a minimum neutron energy close to 0.5 MeV. From two-body kinematics calculations the energy range of the neutron coming from the ^{6}Li(^{3}He,n)^{8}B reaction at 5.77 MeV is from 0.8 MeV at the most backward angle to about 3 MeV for the most forward detector that means mainly above and in few cases quite close to the detection threshold. These thresholds determine the efficiency of the BC501 detectors that can be calculated by a Monte Carlo code as reported in ref. [6].
As a cross check concerning the pulse shape analysis, figure 3 shows the Zero Crossing - time of flight correlation. Also here the neutron/gamma discrimination is evident and a gate on the neutron contribution can be done.

After the neutron signal selection previously discussed, one obtains the desired neutron time of flight spectrum, figure 4 shows one example for the most forward RIPEN detector. One can easily identify the two ^{8}B peaks (ground state and the first excited state at 0.78 MeV) and the peak from the reaction

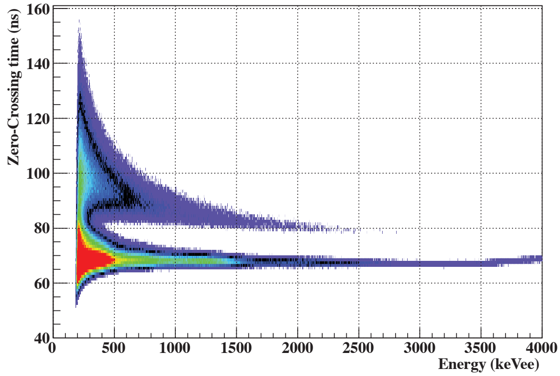

Fig. 2: Two-dimensional plot of the Zero-Crossing time vs the deposited energy for one BC501 detector where detected neutrons (upper blob) and gammas (lower blob) are clearly separated.

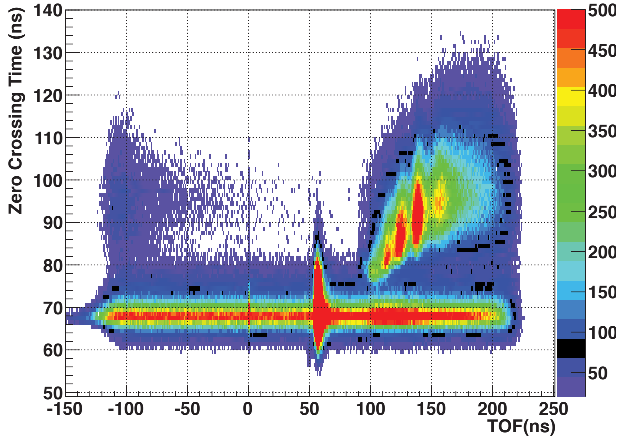

Fig. 3: Two-dimensional plot of the Zero-Crossing parameter vs Time of Flight for one of the BC501 detector. Detected neutrons (upper-right blob) and gammas (lower band) are identified. Prompt gammas can be separated from the uncorrelated background using time of flight information.

^{12}C(^{3}He,n)^{14}O due to the Carbon deposited on the target. The overall continuum is due to the three-body reaction ^{6}Li(^{3}He,np)^{7}Be and can be subtracted. This is done using the Sensitive Nonlinear Iterative Peak (SNIP) clipping algorithm implemented within the ROOT class TSpectrum [7]. The measured neutron energies extracted from the time of flight peaks are consistent with the values calculated from the reaction kinematics.

From the area under the peaks of interest one can infer the differential cross section at the considered angles after correction for the detection efficiency and normalization to the Rutherford scattering on the Gold backing. The experimental angular distribution obtained for the ^{8}B ground state population is shown in figure 5 (solid dots). The error bars take into account all the uncertainties of the measure (solid

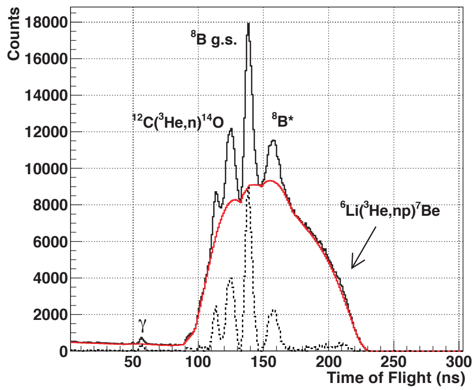

Fig. 4: Neutron time-of-flight spectrum at 15° in the laboratory reference frame from the reaction ^{6}Li(^{3}He,n)^{8}B at 5.77 MeV. The time calibration is 1 ns per channel. See text for details.

angle of the detectors, target thickness, detection efficiency) and are of the order of 10%.

4 Results and discussion

The ^{8}B ground state extracted cross sections were compared to theoretical calculations performed by S.A. Goncharov ([8]) in the "Zero Range Knock-out Distorted Wave Born Approximation" (ZR-KO-DWBA) framework [9] for two-nucleon transfer with microscopic Bayman-Kallio form factors [10] using the code DWUCK4 [11]. Results are given in figure 5 where the experimental and theoretical differential cross sections in the center of mass frame show a reasonably good agreement. The trend is not very well reproduced at center of mass angles higher than 120° (backward angles in the laboratory frame) where the neutrons energy is lower than 1 MeV. In this energy range the efficiency curve drops dramatically while approaching the detection threshold. This introduces a strong dependence of the evaluated cross section on the threshold estimation and requires more accurate information about the RIPEN detectors efficiency in this delicate energy range.
The integrated experimental cross section is 58±7 mb to be compared with the 75 mb calculated value.

5 Conclusions and outlook

The present result is in good agreement with the findings of earlier measurements using the neutron time of flight method [4], thus confirming the disagreement with the positron counting results [5].
To investigate this difference using the two methods we performed DWUCK4 calculations extending the projectile energy range up to 25 MeV. Even if the neutron angular distributions are more focused at the forward angles when increasing the projectile energy, the integrated cross section is not changing very much. Values are going from 75 mb of our case to 66 mb at 25 MeV with a maximum of about 85 mb at 10 MeV. The results of these calculation are thus in strong disagreement with the experimental results reported in ref. [5] and the difference is strongly increasing with the projectile energy reaching about a factor of 30 at the highest considered energy. This is strongly encouraging the experimental measurement of such differential cross sections in the 8 - 25 beam energy range.

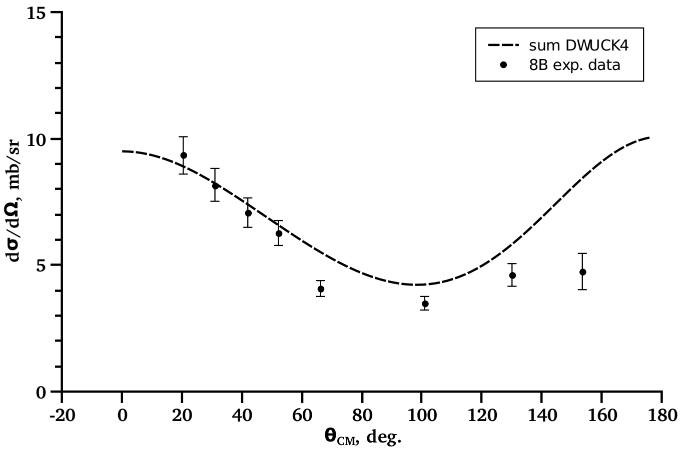

Fig. 5: Measured and calculated angular distributions. Experimental data are shown for the ^{8}B ground state.

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