3 MV Tandetron^{TM} for astrophysics studies

An educated selection of the main beam parameters - particle type, velocity and intensity, can result in a cutting-edge scalpel to remove tumors, sanitize sewage, act as a nuclear forensics detective, date an artefact, clean up air, improve a microprocessor, transmute nuclear waste, detect a counterfeit or even look into the stars. Nowadays more than 30.000 particle accelerators operate worldwide in medicine, industry and basic research. For example the proton therapy market is expected to attain 1 billion US$ per year in 2019 with almost 330 proton therapy rooms, while the annual market for the ion implantation industry already reached 1.5 G$ in revenue [1,2]. A brief history of the Tandem Accelerators Complex at IFIN-HH [3] emphasizing on their applications and the physics behind the scenes, is also presented [4-6]. The history of tandem accelerators at the “Horia Hulubei" National Institute for Physics and Nuclear Engineering - IFIN-HH started in 1973 with the installation of a 7.5 MV FN Tandem machine (HVEC, USA), that within a decade was upgraded to 9 MV, by introducing SF_6 into the insulating gas [7]. A second major improvement program started ten years ago and led to a higher performance and reliability of the accelerator. The HVEC belt was replaced by a NEC pelletron system, a new set of accelerator tubes was installed, the tandem injector was redesigned and two sputtering negative ion sources were mounted, the vacuum system was completely refurbished and the electric equipment was replaced, a beam pulsing system in the ns-ms range contributed to a facility that today is able to provide more than 6000 beam-hours [8].Due to the high beam-time demand, especially for nuclear spectroscopy studies with the ROmanian array for Spectroscopy in Heavy ion Reactions (ROSPHERE), two new HVE Tandetron^{TM} accelerators were commissioned in 2012 with the support of an infrastructure grant [9] funded by the National Authority for Scientific Research [10-12].

The 3 MV Tandetron^{TM} multipurpose facility overview

A 3 MV Tandetron^{TM} accelerator system [Fig.1 and Fig.2] is in operation at the “Horia Hulubei ”National Institute for Physics and Nuclear Engineering - IFIN-HH, Măgurele, Romania, since 2012 and delivers annually almost 5.000 hours of beam time. The accelerator system was developed by High Voltage Engineering Europa B.V. (HVE) and comprises three high energy beam lines. The first beam line is dedicated to Ion Beam Analysis (IBA) techniques: Rutherford Backscattering Spectrometry - RBS, Nuclear Reaction Analysis – NRA, Particle Induced X-ray and γ-ray Emission – IXE and PIGE and micro-beam experiments – μ-PIXE. The second beam line is dedicated to high-energy ion implantation experiments and the third beam line was designed mainly for nuclear cross-sections measurements used in nuclear astrophysics.

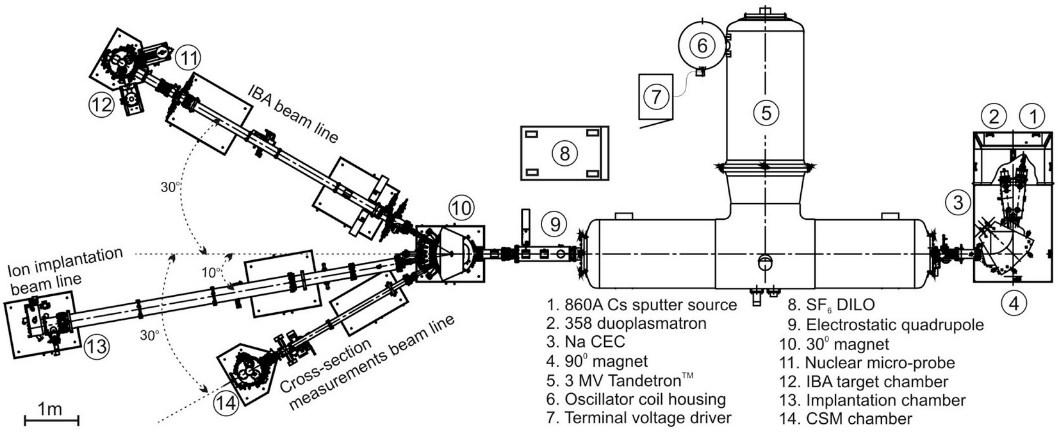


Figure 1. The general layout of the 3 MV multipurpose facility in Magurele, Romania. The main components are: an ion beam injector is equipped with (1) Cs-sputter type ion source of type 860A and (2) a duoplasmatron ion source of type 358 that uses (3) a Na charge exchange canal for He^+; (4) 90" analyzing magnet; (5) 3 MV Tandetron™ accelerator; (6) oscillator coil housing; (7) terminal voltage driver unit; (8) SF6 gas recovery equipment (DILO); (9) electrostatic quadrupole triplet; (10) 45" switching magnet; (11) nuclear micro-probe [20]; (12) IBA target chamber; (13) implantation chamber and (14) CSM chamber.

The accelerator system was developed by High Voltage Engineering Europa B.V. (HVE) and comprises three high energy beam lines (Fig. 2). Almost all the systems: vacuum, power supplies, high-voltage generator, etc., can be remotely operated from the control room and samples analysis can run in batch mode without human intervention.

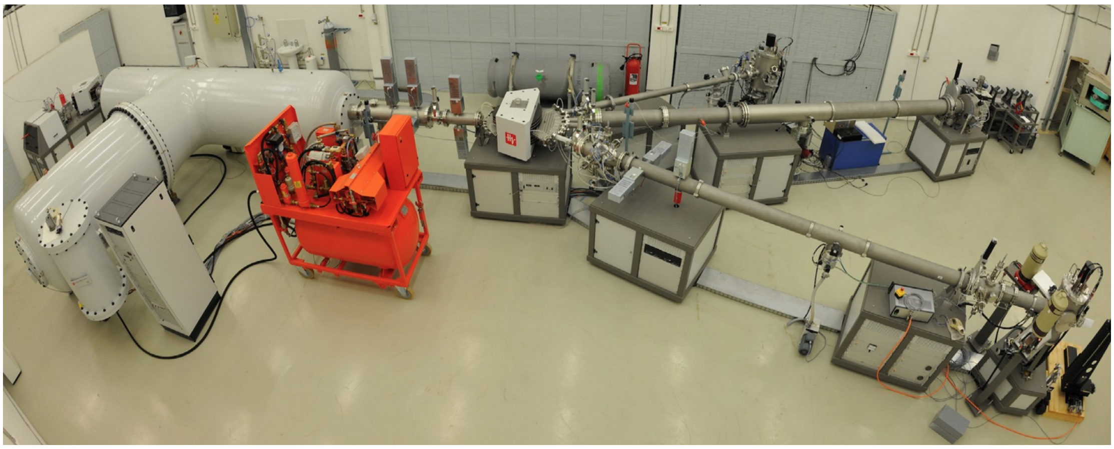
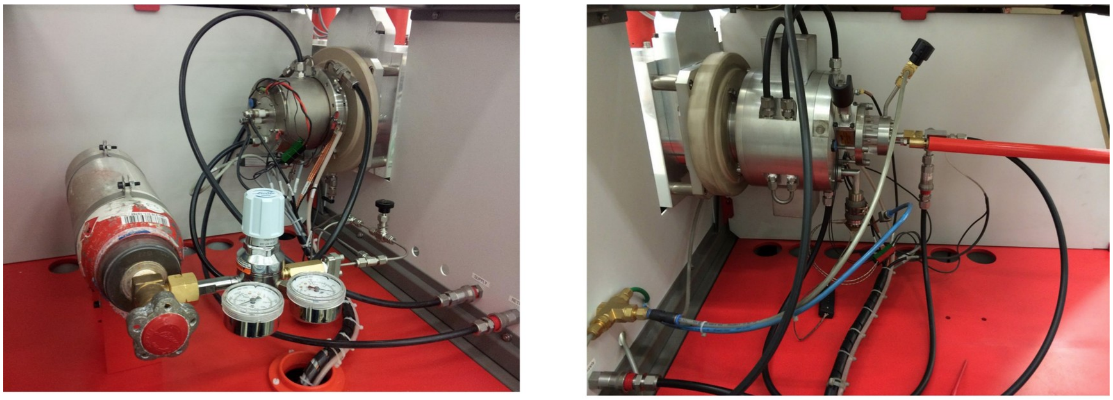


Figure 2. The 3 MV Tandetron^{TM} photo.

The system has a dual-source injector and the necessary beam guiding and defining elements. The duoplasmatron 358 ion source with positive/negative ion extraction is used for He^+/H^- production. A Na charge exchange canal (CEC) produces the required He-for injection into the Tandetron^{TM}. Almost all the other chemical elements are produced in the HVE model 860A Cs sputter ion source by direct negative extraction. For both ion sources, a 90° magnet located at the exit of the dual-source injector is analyzing the negative ion beam. The first beam line at -30° is dedicated to IBA experiments: PIXE, PIGE, RBS, ERDA, NRA and μ-PIXE. The implantation end station is located at +10°, and the cross section measurement reaction chamber at +30°.



(a) (b)

Figure 3. The 358 duoplasmatron ion source (a) and the 860 sputtering ion source (b).

Table 1. Typical current values for the HVE model 860A Cs sputter ion source measured in the ACC Faraday cup after the 90" deflecting magnet.

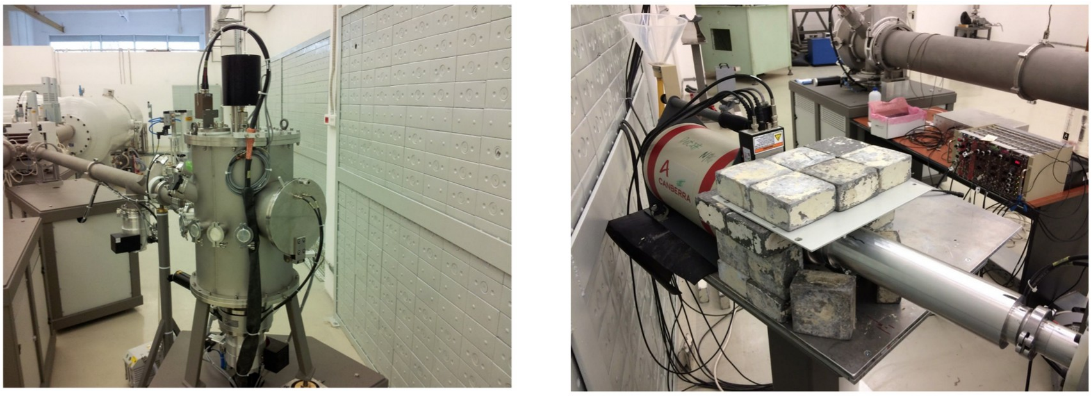
$^{11}B^{-}$	>40 µA
$^{12}C^{-}$	>80 µA
$^{16}O^{-}$	>80 µA
$^{28}Si^{-}$	>80 µA
$^{31}P^{-}$	>40 µA
$^{58}Ni^{-}$	>70 µA
$^{63}Cu^{-}$	>70 µA
$^{75}As^{-}$	>10 µA
$^{197}Au^{-}$	>80 µA

Table 2. Typical current values for 358 duoplasmatron ion source measured in the ACC Faraday cup after the 90" deflecting magnet.

$^{1}H^{-}$	>40 µA
$^{4}He^{-}$	>3 µA

Cross section measurement beam line (CSM)

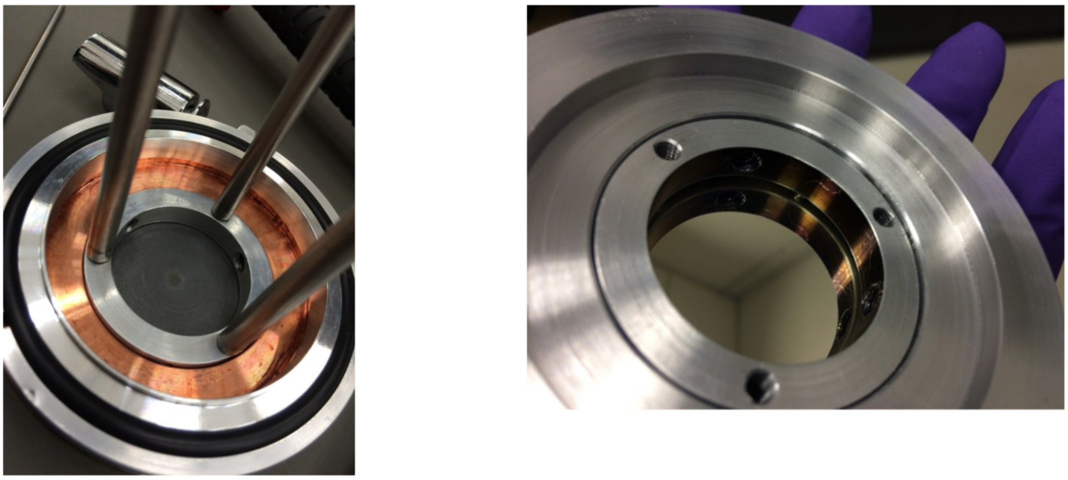
To enable cross section measurements a beam of a maximum 36 AMU x MeV/q^2 mass energy product can be tuned at the sample position. To diagnose the ion beam optics, the CSM Faraday cups can be used. The entrance opening of the CSM Faraday cup is 23 mm and the distance between sample and Faraday cup is 165 mm.



(a) (b)

Figure 4. CSM end chamber (a) and the setup for nuclear astrophysics measurements (b).

The CSM beam line is very versatile having 9 ports that can be used for different experiment configurations related to cross section measurements. Starting from October 2014 this chamber has been used for nuclear astrophysics studies like $^{13}C + {}^{12}C$ reaction at low energies. Taking advantage of the high currents of ^{13}C – (more than 25 μA) that can be obtained from the sputtering source and cooling the target, interesting and new results have been obtained [13-15].



(a) (b)

Figure 5. New target holders developed for experiments in the CSM chamber using cooling for high currents (a), and without cooling for low currents (b).

Nuclear astrophysics (NA) is for some time already an important part of the science program of most nuclear physics laboratories. The experimental studies can be divided as direct measurements – reactions studied at the low energies as they happen in stars, or as close to that as possible, followed by extrapolations into the so called Gamow window – and indirect methods, where information (nuclear data) is extracted from reactions at much larger energies, information that is then used to evaluate the reaction cross sections or the reaction rates in the region of energies relevant for astrophysics. This is due to the fact that at low energies the reactions involving charged particles – and this is a large part of reactions in stellar environments – are very much hindered by the Coulomb barrier, leading to considerable measurement difficulties [16]. The case of direct measurements calls for special experimental solutions. One of them is to install high intensity accelerators in underground laboratories. The first such and best known is the LUNA project [17] at the Laboratori Nazionali di Gran Sasso of INFN, in Gran Sasso, Italy. Several other projects are under development or in the planning phase in the USA and China. To install an underground facility is not an easy task and, therefore, dedicated projects for nuclear astrophysics could so far be planned around existing or planned larger underground physics laboratories. We present here the case where we combine the use of the 3 MV Tandetron accelerator situated at the surface on the premises of the IFIN-HH institute with an ultra-low background laboratory the institute has in a salt mine in Slanic-Prahova, about 120 km North of Bucharest. By combining these two we can obtain a facility for direct measurements at low and very low energies typical for nuclear astrophysics. Both belong to ‘‘Horia Hulubei’’ National Institute for Physics and Nuclear Engineering (IFIN-HH), but are situated 120 km apart. We argue that this facility is competitive for the study of nuclear reactions induced by alpha particles and by light ions at energies close to or down into the Gamow windows. A good case study was the $^{13}C+^{12}C$ fusion reaction, where the proton evaporation channel leads to an activity with $T_{1/2}$= 15 h, appropriate for samples’ transfer to the salt mine. Measurements were done using the thick target method down into the Gamow window for energies from $E_{c.m.}$= 2.2 MeV, which is the lowest energy ever reached for this reaction, up to 5.3 MeV, using ^{13}C beams from the 3 MV Tandetron. The activation method allowed us to determine a cross section of the order of 100 pb

Figure 6. The location of the mBq laboratory inside the Slanic salt mine.

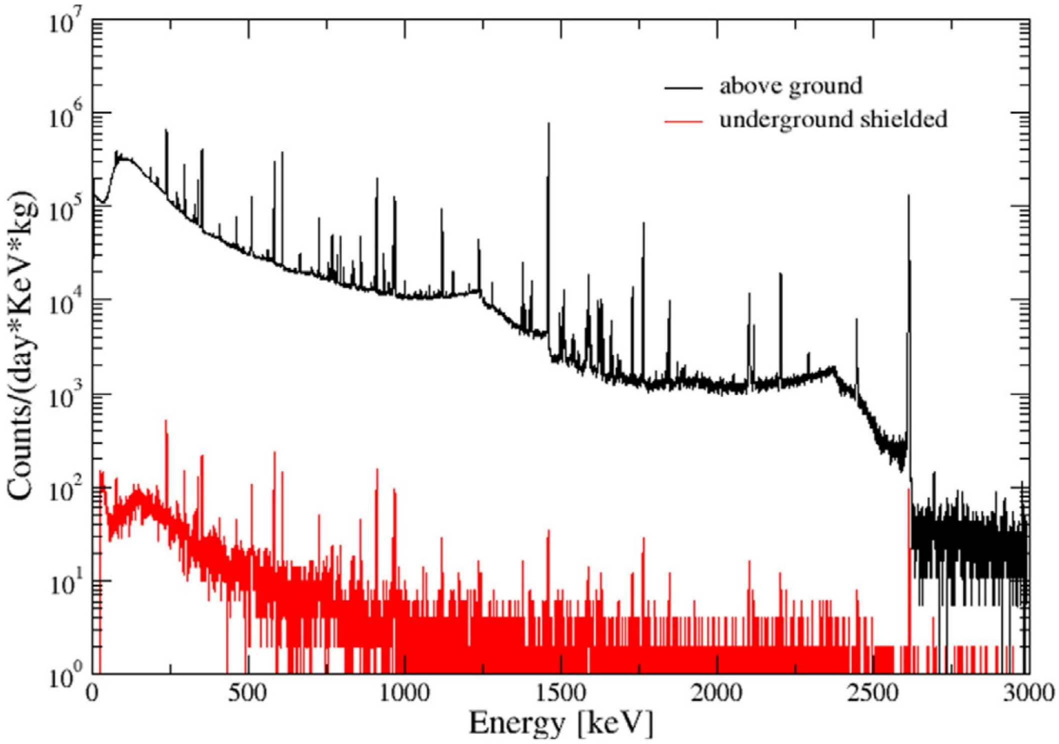


Figure 7. Natural background from the μBq laboratory collected with the same HPGe: top is above ground, bottom is underground shielded.

Salt mining has in Romania a history that goes back to ancient times, but in Slanic-Prahova the first mine was only opened in 1688. Slanic Prahova is situated about 100 km north of Bucharest. The Unirea salt mine has been open since 1943 with salt exploitation performed until 1970 [18]. After the latter, sections of the mine were opened for visitors. In 2006 the microBequerel (μBq) laboratory of IFIN-HH was constructed and fully commissioned. The depth of the mine is around 210 m ($\sim$600 m water equivalent) [19]. The consideration for which this location has been chosen is the very low natural radioactivity, due to the fact that walls do not present cracks and due to the high purity of the salt [20] (see Fig. 6). The Underground Laboratory in the Unirea salt mine, Slanic Prahova (μBq), is located at about 2 h drive North of Bucharest. Environmental conditions in the salt mine are very stable year-round: temperature between 12 and 13 °C, humidity 60% – 65% approximately, area of 70 000 m2, height between 54 and 58 m, the distance between the walls is between 32 and 36 m, volume is 2.9 x 10^6 m^3. In this mine a laboratory was built and it performs measurements using gamma ray spectrometry in ultra-low radiation background. The average dose underground was found 1.17 ± 0.14 nGy/h, approximately 80–90 times lower than the dose at the surface. Ambient background radiation comes from:

(i) natural radioactivity (especially from the decay of ^{238}U, ^{232}Th and ^{40}K);
(ii) neutrons from (α, n) reactions and fission;
(iii) cosmic rays (μ, ^{1}H, ^{3}H; ^{7}Be, ^{14}C ...).

Test case: the ^{13}C+^{12}C reaction studies

The first reaction that we studied was ^{13}C+^{12}C, together with the group from IMP (Institute of Modern Physics) Lanzhou, China. This reaction leads to an activation appropriate for our tests: ^{24}Na, which has a half-life of 15 h and is formed by one proton evaporation from the compound nucleus ^{25}Mg. Our choice of test case was motivated by the need to test the characteristics of the facility as well as to study the fusion reaction mechanism deep under the Coulomb barrier in a system close to the ^{12}C+^{12}C reaction of great importance in nuclear astrophysics. We studied the ^{13}C+ ^{12}C fusion reaction in the energy range of E_{lab} = 4.6 up to 11 MeV using the activation method and gamma-ray spectroscopy. That translates into an energy range E_{cm} = 2.2 – 5.6 MeV, which is deep into the Gamow window for the ^{12}C+^{12}C burning at relevant stellar temperatures [21]. Beams of ^{13}C were obtained from the sputtering source with intensities of 0.4 up to 15 pμA and different charge states. The targets used were made of pure natural graphite with a thickness of 1 mm. For the energies where the irradiation time was longer it was necessary to cool-down the targets using a dielectric coolant system. After a number of tests, we found a situation where the current was reliably measured with the target that was also a Faraday cup (see Fig. 6). A total of 71 targets were irradiated and measured. For prompt gamma-ray measurements, a HPGe detector of 100% relative efficiency was placed at 550 with respect to the beam axis in forward direction. We succeeded to determine the contributions from p, n and α evaporation channels for the energies where reaction cross sections were high enough to be measured in the accelerator hall (above 6.4 MeV).

We use the underground counting lab with an extremely low background to perform an activity measurement for the ^{12}C+^{13}C system with energies down to $E_{c.m.}$ = 2.323MeV, at which the ^{12}C(^{13}C,p)^{24}Na cross section is found to be 0.22(7)nb [22, 23]. The ^{12}C+^{13}Cfusion cross section is derived with a statistical model calibrated using experimental data. Our new result of the ^{12}C+^{13}C fusion cross section is the first decisive evidence in the carbon isotope systems which rules out the existence of the astrophysical S-factor maximum predicted by the phenomenological hindrance model, while confirming the rising trend of the S-factor towards lower energies predicted by other models, such as CC-M3Y+Rep, DC-TDHF, KNS, SPP and ESW. After normalizing the model predictions with our data, a more reliable upper limit is established for the ^{12}C+^{12}C fusion cross sections at stellar energies.

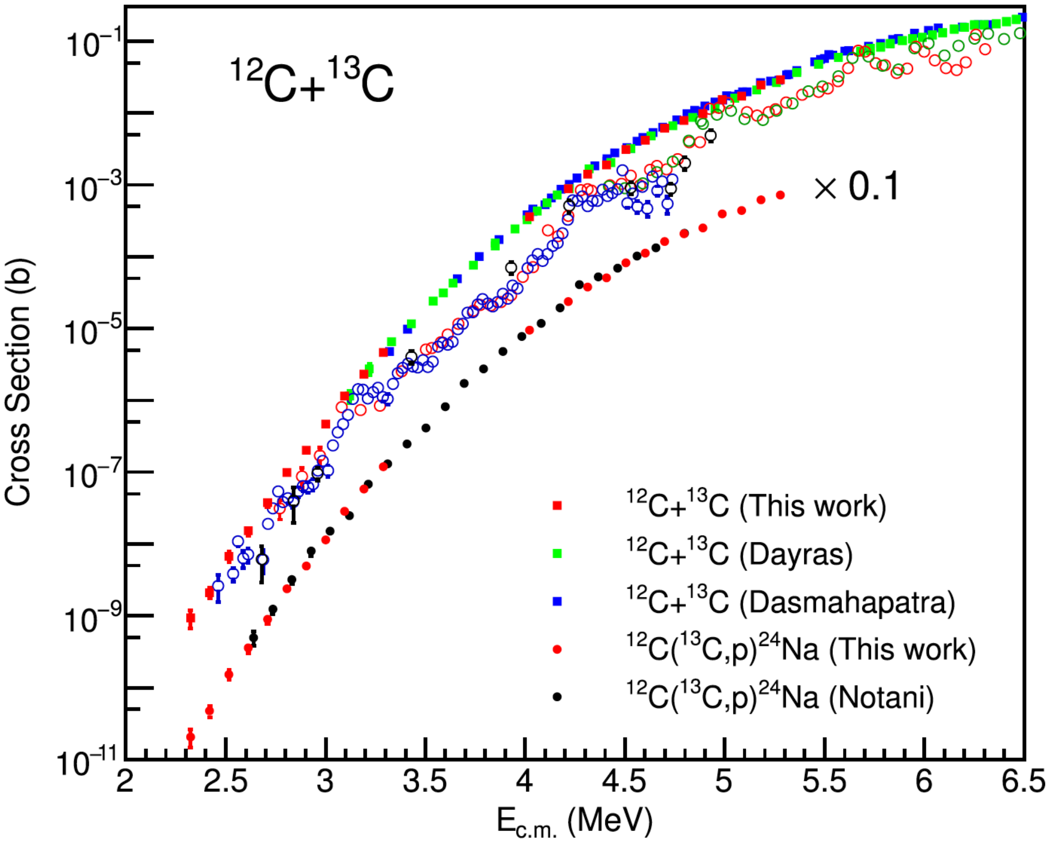


Figure 8. Cross sections of $^{12}C(^{13}C,p)^{24}Na$ obtained this work presented in red points. The latter represent the first measurements to reach the energy region $E_{c.m.} < 2.6$ MeV. A 10% experimental systematical uncertainty is included in both data. The $^{12}C+^{12}C$ total fusion cross sections are also shown as open circles with symbols [23].

The 3 MV Tandetron Accelerator is dedicated to Ion Beam Analysis experiments and Ion Beam Implantation, but has the proper beam energy and intensity to be used in nuclear astrophysics experiments. Small electrostatic accelerators are great education instruments for students who will continue the research in nuclear physics at relatively low energy, keV to tens of MeV range, while representing an outstanding opportunity for the young generation to get prepared for the work in a large scale facility as ELI-NP [24], CERN [25], FAIR [26] or ILC [27].

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