EPJ Web of Conferences **297**, 01005 (2024) https://doi.org/10.1051/epjconf/202429701005
*ISNA23*

# Nuclear Astrophysics at Bose Institute

*D.* Gupta[1,*]

[1]Department of Physical Sciences, Bose Institute, EN-80, Sector V, Bidhannagar, Kolkata-700091, India

**Abstract.** In this review, I give a brief introduction to Bose Institute and describe the research work pursued in nuclear astrophysics. The experiments are carried out at ISOLDE, CERN while Monte Carlo simulations and data analysis are done at Bose Institute. The review ends with future plans and an outlook.

## 1 Introduction

Sir Jagadish Chandra Bose (1858-1937), F.R.S, is acknowledged as the father of modern scientific research in India. His pioneering works include the invention of the first wireless detection device and the discovery of millimeter length electromagnetic waves [1]. He is also regarded as a founder of the field of biophysics [2]. He had the first US patent (1904) from Asia [3], although his aversion to any form of patenting was very well known. He also had legendary students like D. M. Bose, S. N. Bose and M. N. Saha, who were themselves famous for the first recording of $\mu$-meson tracks [4], Bose-Einstein statistics [5] and Saha Ionization equation [6] respectively. In the words of Sir Neville Mott, Nobel Laureate (1977) for his contributions to solid-state electronics, “J. C. Bose was at least 60 years ahead of his time" and "in fact, he had anticipated the existence of p-type and n-type semiconductors” [7]. J. C. Bose founded the Bose Institute on November 30, 1917, dedicating this “temple of science” to the nation. The institute has eventually developed into a multi-disciplinary research organization, pursuing studies in physics, chemistry, microbiology, biochemistry, biophysics, plant biology, environmental science and molecular medicine. There are six campuses in and around Kolkata and one campus in Darjeeling [8]. In the following, I would elaborate the recent research in nuclear astrophysics at Bose Institute. This includes the study of nuclear reactions relevant to astrophysics, involving the origin of elements, big-bang nucleosynthesis (BBN) and subsequent nuclear processes in stars.

## 2 Nuclear Astrophysics Activities

### 2.1 Cosmological lithium problem and study of the $^7$Be + d reaction

The cosmological lithium problem is a well-known unresolved problem in nuclear astrophysics, where there is an anomaly of about a factor of three, between big-bang nucleosynthesis (BBN) calculations and the observed abundance of $^7$Li in metal-poor stars [9, 10]. The BBN models rely on the experimentally determined nuclear reaction rates. Thus, to better

---

[*] e-mail: dhruba@jcbose.ac.in

constrain nuclear physics inputs to BBN theory, a re-examination of the relevant nuclear reaction cross sections is useful [11, 12]. Since $^7$Be is the main source of primordial $^7$Li, its destruction reactions deserve attention in search for a nuclear physics solution to the problem. We carried out an experiment on $^7$Be + d reaction at HIE-ISOLDE, CERN with a 5 MeV/u $^7$Be beam of intensity $\sim 5 \times 10^5$ pps incident on a 15 $\mu$m thick $CD_2$ target. An array of double-sided Silicon strip detectors (DSSD) covering $8^o$-$165^o$ (Micron S3, W1, BB7) was placed inside the Scattering Experiment Chamber to detect the emitted particles (Fig. 1). We studied resonance excitations in the (d,p) and (d,$^3$He) channels [13]. The theoretical calculations are normalized to the data and extrapolated to astrophysical energies. Inclusion of higher excited states of $^8$Be* in the (d,p) reaction leads to a substantially higher S factor than that used in BBN theory (Fig. 2). However, the reduction of the primordial Li abundance is found to be < 1% and the anomaly remains unsolved [13]. The measurement of the (d,$^3$He) reaction cross section shows that its effect on the Li anomaly is negligible.

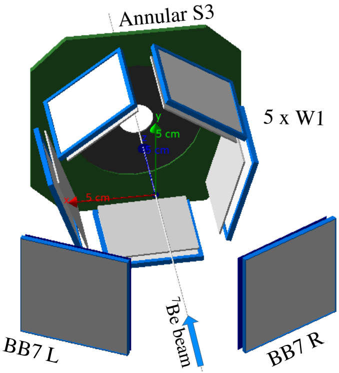

**Figure 1.** The detector setup for the $^7$Be + d experiment at 5 MeV/u.

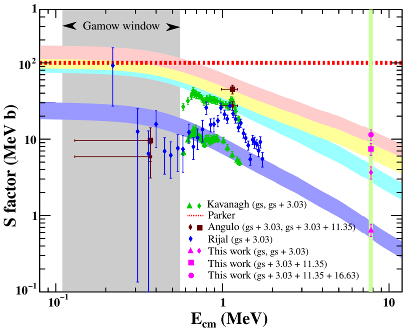

**Figure 2.** The $S$ factor for the $^7$Be(d,p)$^8$Be$^*$ reaction. The solid triangle, diamond, square and circles correspond to total cross sections due to gs, gs + 3.03, gs + 3.03 + 11.35 and gs + 3.03 + 11.35 + 16.63 MeV states respectively. The data in green, brown, blue are from earlier measurements and magenta represent the present work [13]. The violet (gs), cyan (gs + 3.03), yellow (gs + 3.03 + 11.35) and red (gs + 3.03 + 11.35 + 16.63) MeV bands are TALYS calculations normalized to the present data at 7.8 MeV (green vertical line). The bands do not include systematic uncertainty due to extrapolation. The red dotted line is the estimate from earlier work (See Ref. [13] for details).

### 2.2 Transfer reactions with $^{7}$Be + $^{12}$C to study the $^{12}$C($\alpha$,$\gamma$)$^{16}$O reaction

The $\alpha$-capture reaction $^{12}$C($\alpha$,$\gamma$)$^{16}$O has been studied for decades as a key reaction in the helium-burning phase of stars [14]. This reaction together with the triple-$\alpha$ process is critical for the abundance ratio of carbon to oxygen, a key input for subsequent stellar evolution. It is the underlying basis for all organic chemistry and development of biological life in the Universe. However, the extremely low cross section makes it impossible to measure directly at astrophysical energies. Indirect Asymptotic Normalization Constant (ANC) method provides an accurate tool to determine it from transfer reaction data. Studies of $^{6,7}$Li,$^{11}$B + $^{12}$C populating $^{16}$O states have been carried out earlier [15]. However, breakup contributions in these reactions affected the transfer channel to a great extent. For $^{7}$Be, it is seen that the transfer reaction is more probable than breakup [16]. Thus, such transfer reactions can be used as important tools to study high-excitation $\alpha$-clustering states in the residual nuclei. The starting point of such a study is the availability of a reliable set of optical model potential (OMP) parameters. We measured the elastic, inelastic and transfer reactions of $^{7}$Be + $^{12}$C at 35 MeV [17]. The elastic data provided the necessary OMP required for studying the $^{12}$C($^{7}$Be,$^{3}$He)$^{16}$O transfer reaction. Optical model analyses were carried out with Woods-Saxon and DDM3Y microscopic potentials (Fig. 3). The microscopic analysis of the elastic data indicates breakup channel coupling effect [17]. The breakup cross section of $^{7}$Be is estimated to be less than 10% of the reaction cross section. The total reaction cross section deduced from the analysis agrees very well with Wong's calculations for similar weakly bound light nuclei on $^{12}$C target. Analysis of the transfer data is currently in progress to deduce the $S_\alpha$, ANC, and resultant errors, corresponding to the ground state and two sub-threshold states 6.92 ($2^+$) and 7.12 ($1^-$) MeV of $^{16}$O (Fig. 4).

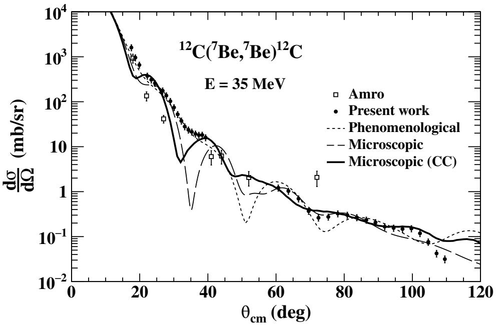

**Figure 3.** Elastic scattering angular distribution of $^{7}$Be + $^{12}$C at E = 35 MeV. The microscopic (phenomenological) fits to the data are given by the dashed (dotted) curves. The coupled-channel calculations are given by the solid curve. See Ref [17] for details.

### 2.3 SSNTD with high detection threshold for rare events search in cosmic rays

Astrophysicists predicted the existence of exotic nuclear fragments called strangelets [18], consisting of roughly equal numbers of up, down and strange quarks with unusual charge to mass ratios (Z/A << 1/2). Interestingly, there is a likelihood of significant measurable strangelet flux in our part of the galaxy [19], but detectors are yet to record such events. The solid state nuclear track detectors (SSNTD) are particularly suitable for this purpose, due to their simplicity, ruggedness and existence of thresholds for registration. Certain models of

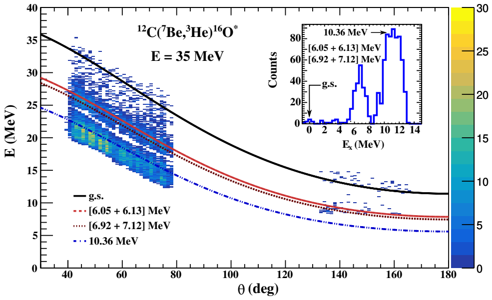

**Figure 4.** Energy ($E$) vs angle ($\theta$) plot of $^3$He from $^7$Be + $^{12}$C transfer reaction at 35 MeV. The inset shows the corresponding excited states of $^{16}$O from the reaction.

strangelet propagation predicts the flux of strangelets at mountain altitudes of 3000 m to be $\sim$ 10 per 100 m$^2$ [20]. We investigated the suitability of a polymer (overhead projector films, brand CENTURY de'Smart, India) to work as an SSNTD [21]. The polymer material is polyethylene terephthalate (PET) with chemical formula $(C_{10}H_8O_4)_n$. Our plan was to setup a large array of PET covering an area of 100 m$^2$ at Sandakphu (altitude 3600 m) in eastern Himalayas, to look for strangelets in cosmic rays. Later on, this is to be expanded to 400 m$^2$. In such situations, passive detectors are appropriate because it requires the deployment of large area detector arrays at remote terrains. We also found that PET has a higher detection threshold of $Z/\beta > 140$ compared to many other widely used SSNTDs like CR-39 with $Z/\beta > 6$ and Lexan with $Z/\beta > 57$. Here Z is the atomic number and $\beta$ = v/c. The $Z/\beta$ is related to the energy loss $dE/dx$ of charged particles through the detector material by the Bethe-Bloch formula. The charged particles passing through an SSNTD leave behind narrow damage trails, that are etched out by chemical reagents. But the rate of etching along the damage trails, called the track etch rate ($V_T$) is faster, compared to the rate of etching of the bulk material called the bulk etch rate ($V_B$). Such etching results in the formation of etch-pits that can be approximated by geometrical cones, observable under optical microscope. The etch-pit geometry can reveal the identity of the particle that carved the trail. The higher detection threshold of PET makes it particularly suitable for rare events search like strangelets in cosmic rays, by not recording e, $\mu$, p, $\alpha$ and thus eliminating the dominant low-Z background. The ratio $V_T/V_B$ is called the charge response of the SSNTD and is different for different ions. To study the charge response, PET films were exposed to various ion beams from accelerators, covering a wide range of $Z/\beta$. Beam currents and exposure durations were chosen so that the number of ions impinging on the detector $\sim 10^4 - 10^5$/cm$^2$, to prevent overlapping of tracks, detector burnout and optimize data analysis. The exposed PET samples were etched out in NaOH solution, studied under an optical microscope and analyzed using an image analysis software. The image analysis techniques incorporated sequential convolution/deconvolution followed by Artificial Neutral Nets (ANN) and have been developed to locate ion tracks in images of SSNTD surfaces under microscope [22]. The PET films were irradiated with 2.82 MeV/u $^{129}$Xe, $^{78}$Kr and $^{49}$Ti ions at ISOLDE and the charge response $V_T/V_B$ is shown in Fig. 5. The identification scheme is applied to tracks of 2.82 MeV/u $^{49}$Ti ions. The ascertained incident energy is 2.61 ± 0.24 MeV/u and the Z accuracy is ±1. So we can conclude that PET can be effectively used as an inexpensive nuclear track detector with a high detection threshold.

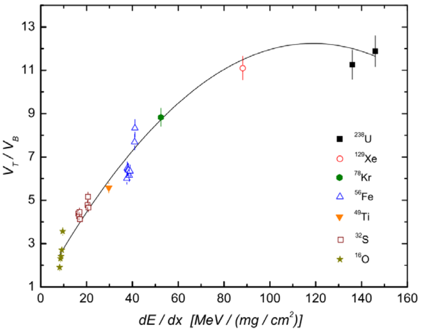

**Figure 5.** The calibration curve for PET [21]. See text for details.

### 2.4 Inhomogeneous Nucleosynthesis and breakup of $^9$Li to study the $^8$Li(n,$\gamma$) reaction

We plan to study the $^8$Li(n,$\gamma$) reaction through breakup of $^9$Li, in the context of inhomogeneous nucleosynthesis [23–25]. The standard BBN ends after the production of $^7$Li. However, in an inhomogeneous early universe scenario, nucleosynthesis in neutron-rich regions might produce an observable amount of A > 12 isotopes. The $^8$Li(n,$\gamma$)$^9$Li reaction provides a leak (Fig. 6) in the reaction chain of neutron-rich nucleosynthesis, affecting significantly the primordial abundance and stellar production of heavy elements. Depending on its rate, the A > 12 production may be reduced by even 50%. Theoretical predictions of the reaction rate show huge differences and there are only two experiments [26, 27], which studied this reaction through Coulomb dissociation of $^9$Li. Only upper limits of cross sections were obtained as the nuclear dissociation could not be ascertained. Similar works exist on the breakup of $^7$Li near the $\alpha$-t threshold to probe radiative-capture processes at 9 and 6 MeV/u [28]. We plan to study the breakup of $^9$Li on $^{208}$Pb at 7 MeV/u, detecting charged particles and neutrons. In particular, Coulomb and nuclear breakup events with low relative energy of the breakup fragments (astrophysical energies) could be studied. Since there will be both nuclear and Coulomb contributions to the cross section at this low beam energy, one has to consider deducing the purely Coulomb contribution of the breakup cross section from the data [29, 30]. The inhomogeneous BBN (IBBN) model has been recently revised in Ref [31, 32]. The purpose is also to solve the "Li overproduction problem" by taking into account the fluctuations/inhomogeneities of the primordial magnetic field (PMF), which satisfies the cosmological constraints on observed Cosmic Microwave Background (CMB) anisotropies. In this case, the $^7$Li may be destroyed by $^7$Li(n, $\gamma$)$^8$Li(n, $\gamma$)$^9$Li and could also enhance intermediate-mass nuclear abundances in IBBN.

## 3 Outlook

Recent developments in nuclear physics research facilitated the study of very neutron and proton rich exotic nuclei. We can study nuclear structure, reactions and astrophysics using rare isotope beams in state-of-the-art accelerators. Several new facilities as well as upgrades are coming up all over the world. At Kolkata, a Facility for Research in Experimental Nuclear Astrophysics (FRENA) is coming up and the K500 Superconducting Cyclotron is also delivering beams. Bose Institute is collaborating in projects utilizing these facilities. Our founder had the vision for advancement of science and free dissemination of knowledge.

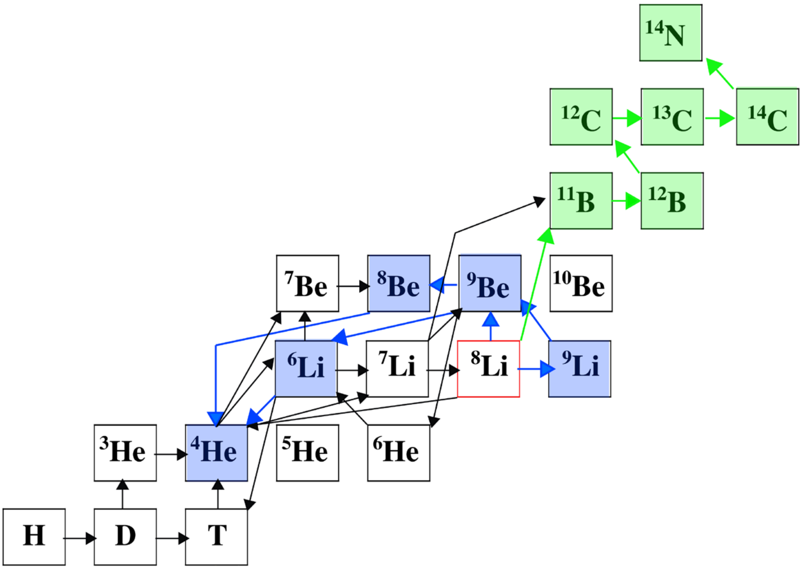

**Figure 6.** The main production sequence of A > 12 isotopes (green arrows) in IBBN [24]. The $^{7}$Li($\alpha$,$\gamma$)$^{11}$B and $^{8}$Li($\alpha$,n)$^{11}$B reactions can play important roles in such production. The $^{8}$Li($\alpha$,n)$^{11}$B competes with $^{8}$Li(n,$\gamma$)$^{9}$Li and $^{8}$Li(d,n)$^{9}$Be, which reduce heavy element production by turning the flow back to $^{6}$Li (blue arrows).

The institute served the nation for 107 years and also carries out several public outreach programs involving rural people, general public, school students and undergraduate students. In the end, it may be said that J. C. Bose left a lasting impact in science and remains a constant inspiration in scientific research.

## Acknowledgement

D. Gupta thanks the ISOLDE engineers in charge, RILIS team and Target Group at CERN for their support, and acknowledges research funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 654002 (ENSAR2) and ISRO, Government of India under grant no. ISRO/RES/2/378/15−16.

## References

[1] J. C. Bose, “On the determination of the wavelength of electric radiation by a diffraction grating,” Proc. Roy. Soc.,60, 167-178 (1897)

[2] J. C. Bose, The Nervous Mechanisms of Plants, Longmans, Green and Co. London (1926).

[3] Bose, J. C. "Detector for electrical disturbances," U. S. Patent 755,840 (Filed September 30, 1901. Issued March 29. 1904).

[4] D. M. Bose and B. Choudhuri, Nature 147, 240 (1941)

[5] Bose (1924), “Plancks Gesetz und Lichtquantenhypothese“, Zeitschrift für Physik (in German), 26 (1): 178–181
[6] M.N. Saha, Ionisation in the solar chromosphere, Phil. Mag, 40, 472 (1920)
[7] Darrel T. Emerson, IEEE Transactions on microwave theory and techniques 45, 12 (1997)
[8] Bose Institute, http://www.jcbose.ac.in/home
[9] A. Coc *et al.*, Astro. Jour. 600, 544 (2004)
[10] R. Boyd *et al.*, Phys. Rev. D 82, 105005 (2010)
[11] B. D. Fields, Annu. Rev. Nucl. Part. Sci. 61, 47 (2011)
[12] R. H. Cyburt *et al.*, Rev. Mod. Phys. 88, 015004 (2016)
[13] Sk M. Ali *et al.*, Phys. Rev. Lett. 128, 252701 (2022)
[14] R. J. Jaszczak *et al.*, Phys. Rev. C 2, 63 and 2452 (1970)
[15] Y.P. Shen, et al., Prog. in Part. and Nucl. Phys. 119, 103857 (2021) and references therein
[16] H. Amro *et al.*, Eur. Phys. J. Special Topics 150, 1-4 (2007)
[17] K. Kundalia *et al.*, Phys. Lett. B 833, 137294 (2022)
[18] R. Klingenberg, J. Phys. G 27 (2001) 475; J. Sandweiss, J. Phys. G 30 (2004) S51
[19] J. Madsen, Phys. Rev. D 71, 014026 (2005)
[20] S. Banerjee *et al.*, Phys. Rev. Lett. 85, 1384 (2000)
[21] S. Dey *et al.*, Astroparticle Physics, 34, 805- 808 (2011); Research Highlight in Nature India, https://www.nature.com/articles/nindia.2011.56
[22] J. Chatterjee *et al.*, Radiation Measurements 144, 106581 (2021)
[23] J. H. Applegate, C. J. Hogan and R.J. Scherrer, Astrophys. J. 329 (1988) 572
[24] R. A. Malaney and W. A. Fowler Astrophys. J. 333 (1988) 14
[25] T. Kajino and R. N. Boyd, Astrophys. J. 359 (1990) 267
[26] H. Kobayashi et al, Phys. Rev. C 67, 015806 (2003); see references therein
[27] P.D. Zecher et al, Phys. Rev. C 57, 959 (1998)
[28] H. Utsunomiya et al, Phys. Rev. Lett. 65, 847 (1990)
[29] G. Baur, C. A. Bertulani, and H. Rebel, Nucl. Phys. A458, 188 (1986)
[30] C. Bertulani; private communication
[31] Luo *et al.*, Astrophys. J 872 (2019) 172
[32] T. Kajino; private communication