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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Breakup of ^{9}Li to study the ^{8}Li(n,γ) reaction

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D. Gupta[1], K. Kundalia[1], Sk M. Ali[1], S. Maity[1], R. Mitra[1], Swapan K Saha[1,*], O. Tengblad[2], V. G. Tavora[2], A. Perea[2], M. J. G. Borge[2], I. Martel[3], J. Cederkall[4], M. Chishti[4], J. Park[5], A. M. Moro[6,7]

[1] *Department of Physics, Bose Institute, 93/1 APC Road, Kolkata 700009, India*

[2] *Instituto de Estructura de la Materia − CSIC, Serrano 113 bis, ES-28006 Madrid, Spain*

[3] *University of Huelva, Av. Fuerzas Armadas s/n. Campus "El Carmen", 21007, Huelva, Spain*

[4] *Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden*

[5] *Center for Exotic Nuclear Studies, Institute for Basic Science, 34126 Daejeon, South Korea*

[6] *Departamento de Física Atómica, Molecular y Nuclear, Facultad de Física, Universidad de Sevilla, Apartado 1065, E-41080 Sevilla, Spain*

[7] *Instituto Interuniversitario Carlos I de Física Teórica y Computacional (iC1), Apdo. 1065, E-41080 Sevilla, Spain*

* *Former Faculty*

Spokesperson: [Dhruba Gupta] [dhruba@jcbose.ac.in]
Co-Spokesperson: [Ismael Martel Bravo] [ismael.martel.bravo@cern.ch]
Contact person : [Ismael Martel Bravo] [ismael.martel.bravo@cern.ch]

Abstract:
In the scenario of an inhomogeneous early universe, nucleosynthesis in neutron-rich regions might produce an observable amount of A > 12 isotopes, while the standard big-bang nucleosynthesis ends after the production of ^{7}Li. The ^{8}Li(n,γ)^{9}Li reaction provides a leak in the reaction chain of neutron-rich nucleosynthesis, affecting significantly the primordial abundance and stellar production of heavy elements. Two previous experiments studied this reaction through the inverse process of Coulomb dissociation of ^{9}Li at 30-40 MeV/u in the virtual photon field of a heavy target. Only upper limits of cross sections were obtained as the nuclear dissociation could not be ascertained. In the proposed experiment we plan to study the breakup of ^{9}Li on ^{208}Pb target at a different energy regime of 7 MeV/u, utilizing the Silicon array and SAND array at the third beamline of HIE-ISOLDE. In particular, Coulomb and nuclear breakup events with low relative energy of the breakup fragments would be studied in the context of the (n, γ) reaction at astrophysical energies.

Requested shifts: 18 shifts
Installation: 3rd beamline, Scattering Chamber + SAND Array

1 Introduction:

If the early universe was rather inhomogeneous, it would have resulted in zones of different neutron-to-proton ratios [1]. High-density proton rich regions along with low-density neutron-rich regions would have formed as a consequence of neutron's longer mean free path, for which it could diffuse out of the high-density zones. Nucleosynthesis in the neutron-rich zones proceeds differently from that of standard big-bang. The stability gap at mass number A=8 may be bypassed and elements beyond ^{7}Li synthesized [1]. Although D, ^{3}He and ^{4}He are produced in the observed relative abundances, there may also be non-negligible production of A>12 isotopes. Some of the reactions, which can occur at the onset of neutron-rich nucleosynthesis, are displayed in Fig. 1. The main products sequence of heavy elements has been identified by Malaney and Fowler [2] and the recommended

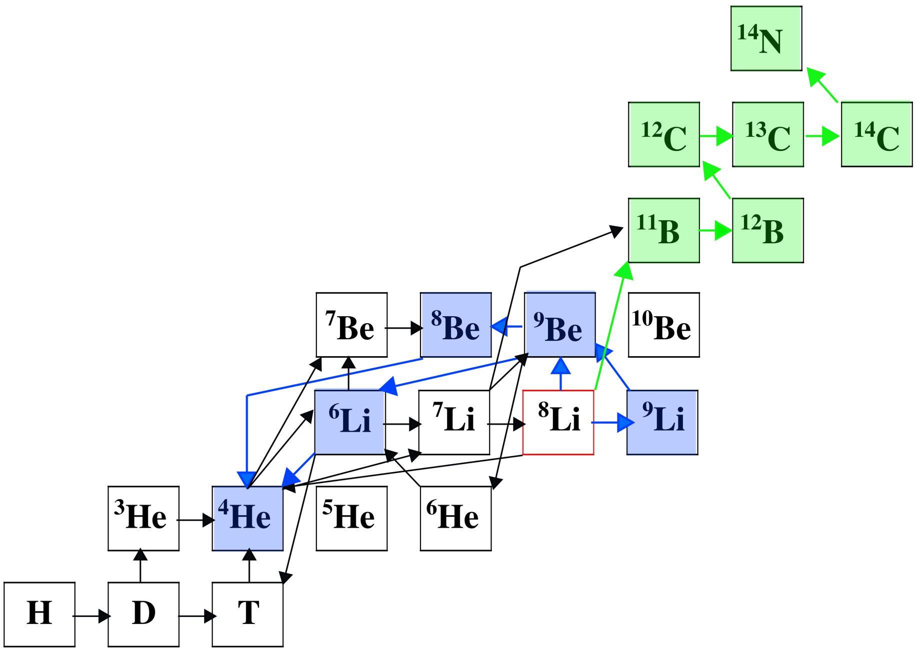

Figure 1: Production sequence of elements

reaction rates have also been given. The main product sequence, according to them, is ^{1}H(n,γ)^{2}H(n,γ)^{3}H(d,n)^{4}He(t,γ)^{7}Li(n,γ)^{8}Li(α,n)^{11}B(n,γ)^{12}B(β)^{12}C(n,γ)^{13}C(n,γ)^{14}C(β)^{14}N. However, from Fig. 1, it is clear that the reaction path becomes quite complicated between ^{6}Li and ^{9}Be. The two reactions that can be important for heavy element production are ^{7}Li(α,γ)^{11}B and ^{8}Li(α,n)^{11}B. This latter reaction must compete with ^{8}Li(n,γ)^{9}Li and ^{8}Li(d,n)^{9}Be which reduce heavy element production, by turning the flow back to ^{6}Li.

It is difficult to evaluate the merits of inhomogeneous nucleosynthesis versus standard big-bang nucleosynthesis, because rates of several important reactions mentioned above, are either not measured or not well established. For example, only few reactions involving

^{8}Li have been measured and thus any conclusions regarding A>6 nucleosynthesis must be regarded as tentative. The ^{8}Li(n,γ)^{9}Li neutron capture reaction plays an important role in heavy element production, as depending on its rate, the A $>$ 12 production may be reduced by even 50% [1, 3].

2 The Physics Case:

Thus we see that ^{8}Li(n,γ)^{9}Li plays a crucial role in determining the amount of heavy elements. Theoretical predictions of this reaction rate show huge differences (Fig. 2), leading to a significant uncertainty for the onset of neutron-rich nucleosynthesis of light and intermediate elements (A $\leq$ 56). While the rate given by Melaney and Fowler is an estimate based on systematics of similar nuclei, the other theoretical values are based on more microscopic approaches. The last two values correspond to upper limits of the reaction rate from existing experimental data [1, 3]. Since the half-life of ^{8}Li is

Reference	Reaction rate (cm^3 mol^{-1} s^{-1})
Malaney and Fowler [14]	43 000
Mao and Champagne [15]	25 000 [a]
Descouvemont [16]	5300
Rauscher *et al.* [11]	4500
Bertulani [28]	2200
Zecher *et al.* [23]	<7200
Present measurement	<790

[a]Average result of two wave function assumptions.

Figure 2: The reaction rate of ^{8}Li(n,γ)^{9}Li from Ref. [1]

0.178s, it is impossible to prepare a ^{8}Li target and bombard it with neutrons for a direct measurement of the capture cross section. Thus in the earlier two experiments, (n,γ) was studied through the inverse reaction ^{9}Li(γ,n)^{8}Li. Here the Coulomb dissociation of ^{9}Li was carried out in the virtual photon field of ^{208}Pb target, and using the principle of detailed balance the neutron capture cross section was obtained. The measurements were done at 30-40 MeV/u with low ^{9}Li beam intensities of $\sim 10^4$ pps. There can be both direct capture and, resonant capture via the 4.296 MeV ($5/2^-$) state of ^{9}Li. Since the ground state of ^{9}Li is $3/2^-$, the dominant transition would be $E2$. The experiment [1] was not sensitive to the resonant part of neutron capture and only direct capture was considered. Since J^π of ^{8}Li is 2^+, capture of an s-wave neutron leads to $3/2^+$ and $5/2^+$ continuum states in ^{9}Li, and both can decay via $E1$ to the ground state and only the $3/2^+$ can decay via $E1$ to the 2.691 MeV ($1/2^-$) excited state of ^{9}Li. In stellar nucleosynthesis, the ^{8}Li(β)^{8}Be(α)α decay sequence releases α particles needed for the production of light α-elements, while the ^{8}Li(n,γ)^{9}Li constitutes a leak in that sequence. The much lower value of the reaction rate obtained in Ref. [1] signifies that the obstruction to nucleosynthesis is small. In comparison to this value, the theoretical predictions exceeded by factors of 3–50. Indirect measurements [4] through ^{8}Li(d,p)^{9}Li reaction at $\sim$ 5 MeV/u to determine (n,γ) reaction rates, yielded values in between those from Coulomb dissociation measurements [1, 3]. This necessitates a new measurement of the cross section of ^{8}Li(n,γ)^{9}Li for better understanding of the neutron capture on light nuclei.

In this context, projectile breakup near particle emission thresholds could provide indirect access to radiative-capture processes at astrophysical energies where extrapolation leads to large uncertainties. Breakup of 6 MeV/u and 9 MeV/u ^{7}Li near the $\alpha - t$ separation energy were studied in the context of astrophysics [5]. The $\alpha - t$ correlation cross sections were measured for a wide range of impact parameters and thus detection angles. The extracted S-factors agreed with those obtained from radiative-capture measurements. It was shown [5] that a modified version of the original Coulomb dissociation method of Baur, Bertulani, and Rebel [6] is feasible in this energy domain, where the Coulomb and nuclear interactions behave similarly in exciting the $\alpha - t$ continuum states. One has to consider the Coulomb-nuclear interference effects in the present energy region. The original proposal of [6] requires a clean separation of the Coulomb and nuclear contributions. The dependence of the Coulomb and nuclear excitation functions on the excitation energy may be investigated within the framework of a distorted-wave Born approximation (DWBA). Studies of channel coupling between higher order excited states and the continuum is also required. The observed "universal" energy dependence in ^{7}Li breakup [5] was interpreted as a signature of nuclear and Coulomb interactions exciting the continuum with the same E_{rel} dependence. Similar studies involving ^{9}Li breakup on ^{208}Pb target at low relative energies of breakup fragments would shed light on the ^{8}Li(n,γ)^{9}Li reaction.

3 Experiment:

We plan to study the breakup of ^{9}Li on ^{208}Pb target at 7 MeV/u. The Si-detectors in the scattering chamber SEC and the SAND array (Fig. 3) at the third beamline of HIE-ISOLDE, would be used for detection of charged particles and neutrons respectively from the ^{9}Li + ^{208}Pb reaction. The Si-detectors (Fig. 3) consist of an array of $\Delta E - E$ telescopes in the angular range of $40° - 80°$ (W1, Pentagon) and $127° - 165°$ (BB7). An annular E detector (S3) covers the forward angles $8° - 25°$ [7]. The SAND array consists of 30 modules each a $10 \times 10 \times 10$ cm^3 plastic scintillator equipped with fast PM tubes. The intrinsic efficiency of the detectors for neutron energy range 3–10 MeV is about 30%, slightly depending on energy. The timing resolution is about 0.3 ns. The distance of the neutron detectors to target is 300 cm resulting in a total neutron detection efficiency of $\sim$ 0.1%. The array can also be brought closer to the target centre. When tested in lab, the random rate per neutron module was below 10 Hz. For beam-on situation with the array at a distance of 300 cm, the rate can be extrapolated to less than 1 cps, when running in coincidence. At this distance the gammas will arrive at $\sim$ 10 ns, and 10 MeV neutrons at 70 ns. With time resolution of 1 ns, they are well separated in time.

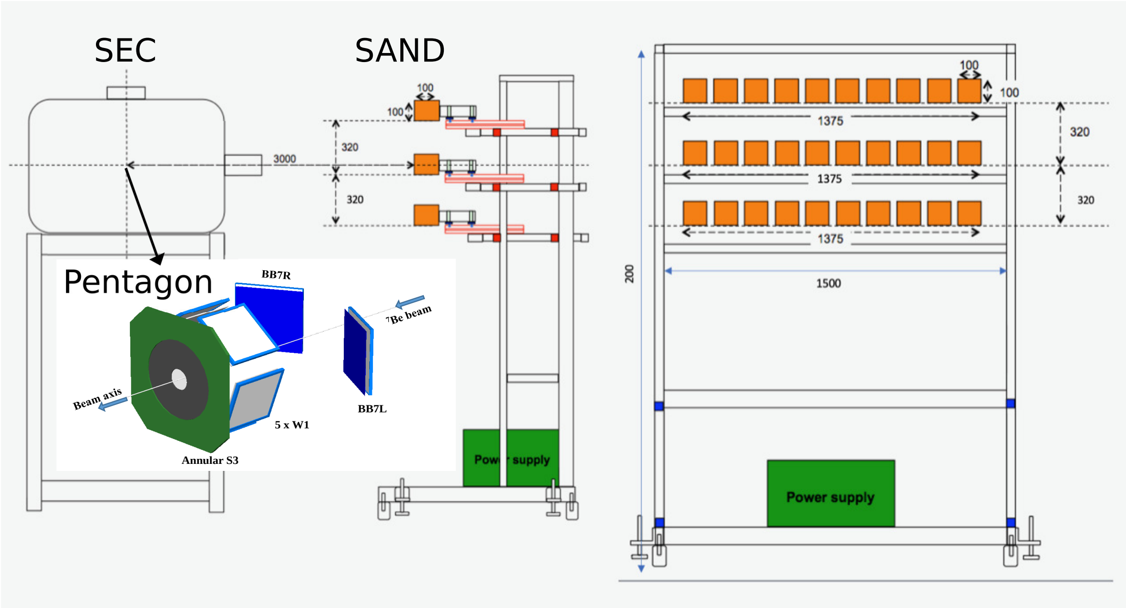

Figure 3: The SEC and SAND array in the third beamline of ISOLDE. The Pentagon detectors inside the SEC are shown in the inset.

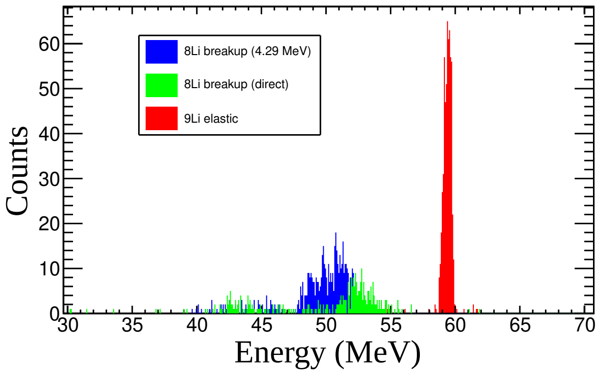

Figure 4: Monte Carlo simulations for the energy spectrum of the scattered ^{9}Li at θ_{lab} = 52°. The ^{8}Li from both direct and sequential breakup of ^{9}Li is also shown.

The ^{8}Li would be detected with an energy between 40 - 55 MeV in an angular range of 8° - 165° while the neutrons would be detected in the angular range 0° - 10° with an energy up to $\sim$ 13 MeV. The Fig. 4 shows the Monte Carlo simulations of the energy spectrum at the pentagon detectors. The scattered ^{9}Li and the ^{8}Li from direct breakup as well as sequential breakup of ^{9}Li from the 4.296 MeV ($5/2^-$) state is shown at θ_{lab} = 52°. The breakup threshold of ^{9}Li is 4.063 MeV. With a ^{9}Li beam intensity of 10^6 pps, a ^{208}Pb target thickness of 1 mg/cm^2 and a ^{8}Li + n breakup cross section of 1 mb/sr, we obtain a count rate of the produced ^{8}Li of about 9×10^{-3} s^{-1} which corresponds to about 260 counts per shift.

4 Beamtime Request:

The requested beamtime is 15 shifts of ^{9}Li at 7 MeV/u on ^{208}Pb target, and 3 shifts for preparation. We request a beam intensity of 10^{6} pps, and we plan to run on fully ionized ^{9}Li so that A/q = 3. The contaminants that might appear are ^{12}C^{4+} and ^{18}O^{6+}. A stripper foil after acceleration will reduce their intensities by factors 5×10^{-5} and 6×10^{-4} respectively and that is expected to give an acceptable background. The levels of radiation from the beam and its decay (and any reaction-induced activity) will be sufficiently low and will not cause any problems. The Si detectors for detection of charged particles and plastic detectors for detection of neutrons do not pose any safety risks.

Summary of requested shifts: 15 shifts of 7 MeV/u of ^{9}Li beam and 3 shifts for preparation.

References

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DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*HIE-ISOLDE 3rd beamline, reaction chamber and neutron detector array*)

Part of the experiment	Design and manufacturing
Si detector array	☒ To be used without any modification
SAND array	☒ To be used without any modification ☐ To be modified ☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT: Hazards named in the document relevant for the fixed [Si detector array + SAND array] installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	V=3 kV max, I= 10 μA max (neutron detector photomultipliers)		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)	^{9}Li		

Beam intensity	10^6 pps		
Beam energy	7 MeV/u		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒ ISOLDE triple alpha source		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		

Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		