# Breakup of $^{9}$Li to study the $^{8}$Li(n,$\gamma$) reaction

(INTC-P-639)

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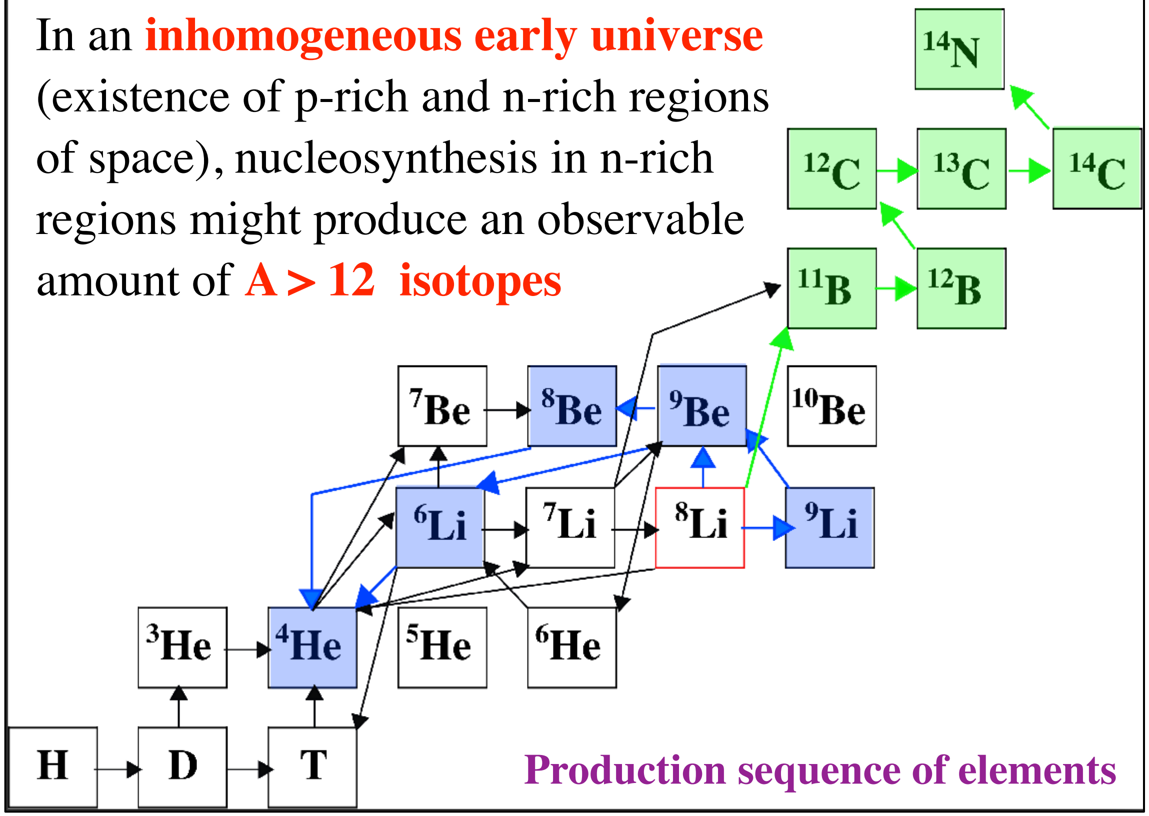
**71st Meeting of the INTC, CERN, November 8-9, 2022**

Standard BBN ends after production of $^7$Li.
In an **inhomogeneous early universe** (existence of p-rich and n-rich regions of space), nucleosynthesis in n-rich regions might produce an observable amount of **A > 12 isotopes**



**Production sequence of elements**

**$^8$Li(n,γ)$^9$Li** provides a leak in the reaction chain of n-rich nucleosynthesis, and also competes with $^8$Li β-decay in the r-process, thus affecting **primordial abundance and stellar production of heavy elements.**

*Depending on its rate, the A > 12 production may be reduced by even **50%***

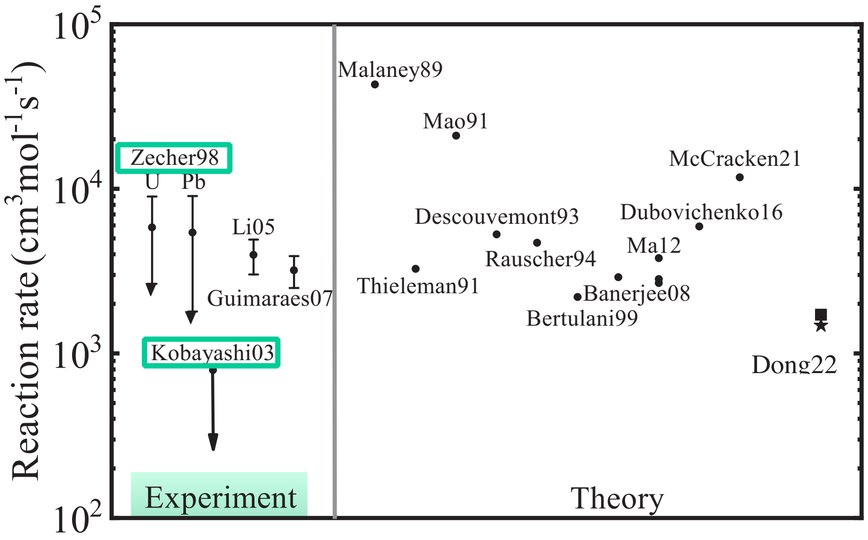
The main products sequence of heavy elements and recommended reaction rates
$^1$H(n,γ)$^2$H(n,γ)$^3$H(d,n)$^4$He(t,γ)$^7$Li(n,γ)$^8$Li(α,n)$^{11}$B(n,γ)$^{12}$B(β)$^{12}$C(n,γ)$^{13}$C(n,γ)$^{14}$C(β)$^{14}$N
Malaney and Fowler (1989)

The two branches important for heavy element production are **$^7$Li(n,γ)$^8$Li(α,n)$^{11}$B** and a weaker **$^7$Li(α,γ)$^{11}$B**. This 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.

# Previous Works $^8$Li(n,γ)$^9$Li

| Reference | Year of Publication | Reaction Rate ($cm^3\ mol^{-1}\ s^{-1}$) |
|---|---|---|
| Malaney & Fowler | 1988 | 43000 |
| Mao & Champagne | 1991 | 21000 |
| Zecher et al. | 1998 | <7200 |
| Dubovichenko | 2016 | *5900* |
| Descouvemont | 1993 | 5300 |
| Rauscher et al. | 1994 | 4500 |
| Li et al. | 2005 | 4000 |
| Banerjee et al. | 2008 | 2900 |
| Bertulani | 1999 | 2200 |
| Kobayashi et al. | 2003 | <790 |
| Dong et al | 2022 | 1720 |

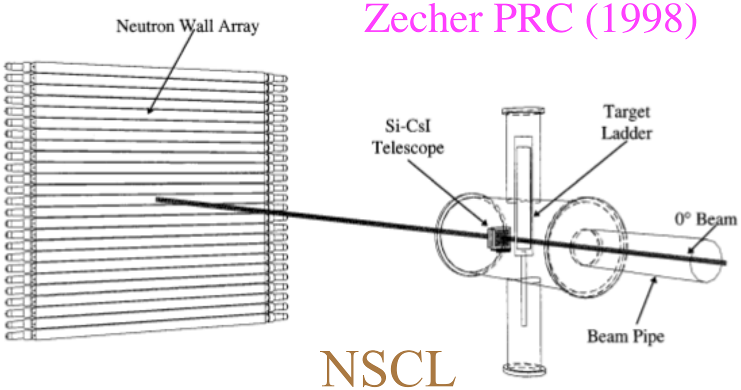
Theoretical predictions of the **reaction rate show huge differences.** Rate given by M&F is an estimate based on systematics of similar nuclei, other theoretical values based on more microscopic approaches. The rates from **experiments** correspond to upper limits, obtained using the Coulomb dissociation method combined with the detailed balance theorem.



Rate from GSM-CC approach consistent with the upper limit of Zecher and exceeds by a factor ~ 2 the limit of Kobayashi. One **order of magnitude difference** of rate justifies **re-measurement of this reaction**. GSM-CC (NCSMC) results are lower (higher) by ~ 20% (~ 30%) than the median value of other results.

*Since the half-life of $^{8}$Li is* ***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.*

Zecher PRC (1998)



NSCL

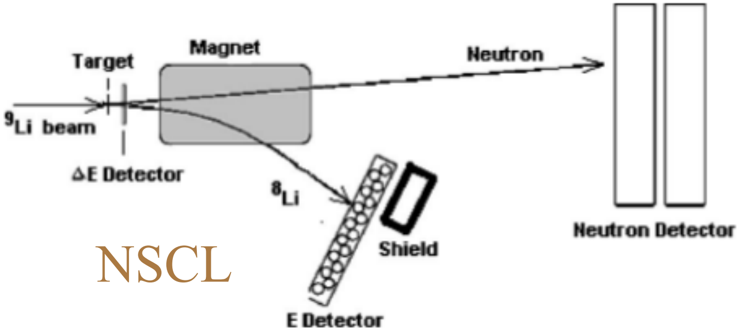
**Coulomb dissociation of $^{9}$Li**
in the virtual photon field of $^{208}$Pb target, observed counts 29.9 ± 20.0

Thus (n,γ) cross section obtained from **$^{9}$Li(γ,n)$^{8}$Li** inverse reaction. 28.5 MeV/u $^{9}$Li beam, I ~ 5000 pps. Fragment and neutron detectors at zero degrees w.r.t beam to accommodate forward focusing.

*Very small yield from low-Z targets prevented estimate of nuclear contribution.*
***Upper limit of reaction rate***

**Experiment using more sensitive equipment**

Kobayashi PRC (2003)

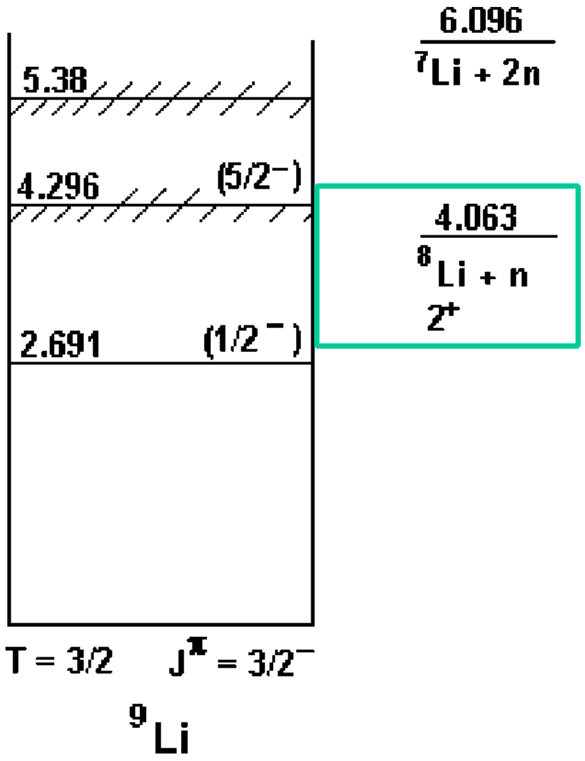


NSCL

39.7 MeV/u $^{9}$Li beam, I = $10^4$ pps. Magnetic deflection ~20° of unreacted projectile and fragments, no discernible $^{8}$Li peak in coincidence with neutrons. Counts 30 ± 29.

*Interpreted as consistent with zero, with a two-standard-deviation upper limit of 87 counts.*

***Upper limit of reaction rate***
**order of magnitude less** than Zecher

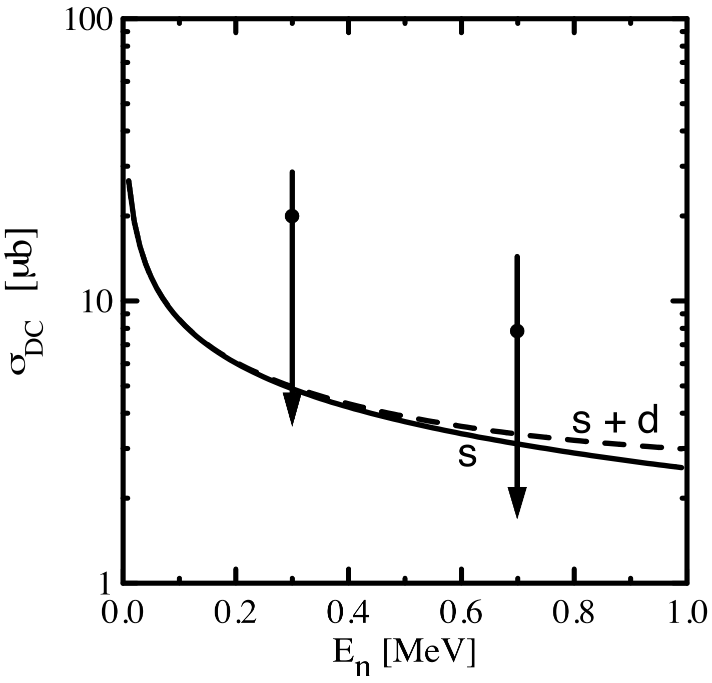


There can be both **direct capture** and **resonant capture** via the 4.296 MeV (5/2$^-$) state of $^9$Li. Since neutrons around 0.247 MeV are primarily *s*-wave, the **resonance is not expected to contribute much to the cross section**. The ground state of $^9$Li being 3/2$^-$, the dominant transition would be *E2* rather than *E1*, further suppressing its contribution.

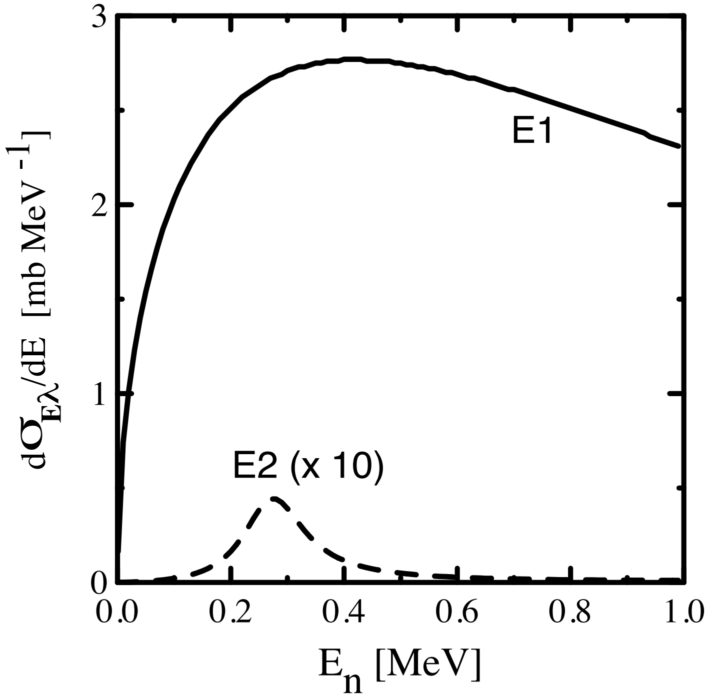
Since $J^\pi$ of $^8$Li is 2$^+$, capture of an s-wave neutron leads to **3/2$^+$ and 5/2$^+$ continuum states in $^9$Li**, and both can decay via *E1* to the ground state and only the 3/2$^+$ can decay via *E1* to the 2.691 MeV (1/2$^-$) excited state of $^9$Li.

At the bombarding energies of tens of MeV/nucleon, the *E2* virtual photon number is much larger than that of *E1*. As a consequence, even when the *E2* contribution to the radiative capture cross section is small, it may be amplified in Coulomb breakup experiments. This poses an additional experimental problem, since one needs to **separate the *E1* transition matrix elements from *E2***.

**Importance of *E2* excitations in the NSCL experiment?** A relatively simple but still realistic nuclear model by Bertulani (1999) yields agreement with data and suggests that ***E2* excitations are negligible** for the kinematical conditions of the experiment.



Radiative capture cross sections for $^8$Li(n, γ)$^9$Li in the direct capture model. The solid curve is obtained with s-waves, while the dashed curve includes d-wave transitions.

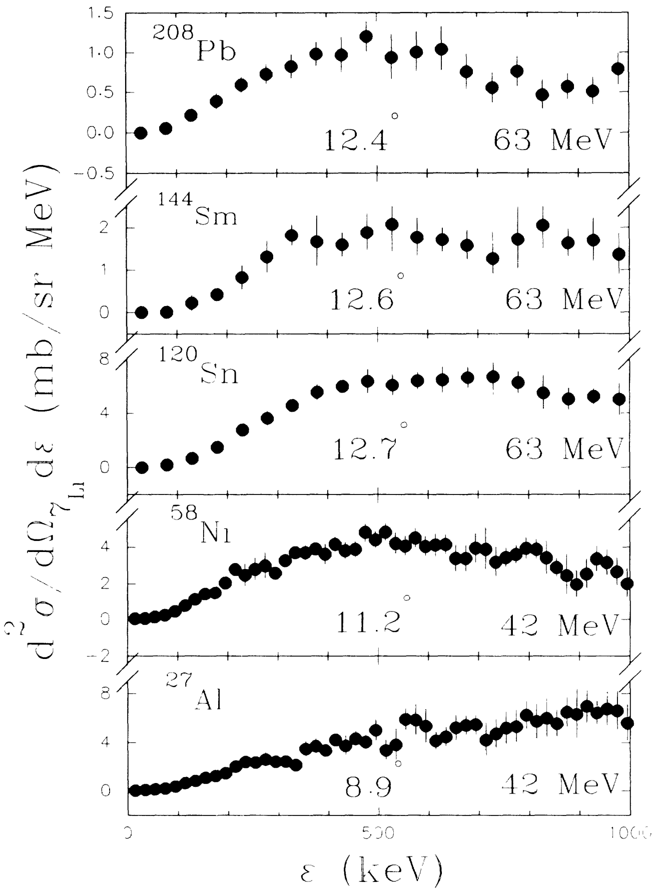


Angle integrated cross section, as a function of neutron energy relative to $^9$Li. *E2* contribution to the breakup cross section is **at least one order of magnitude smaller** than *E1*, even at the resonance region.

# **Breakup of $^7$Li near the $\alpha$-*t* threshold** to probe radiative-capture processes

## **9 MeV/u and 6 MeV/u $^7$Li**

H. Utsunomiya, PRL (1990)



*Method of Baur, Bertulani, and Rebel reduces the difficulty of direct measurements to the technical problem of observing astrophysical energies in* ***two-particle correlation experiments****. It requires a clean separation of Coulomb and nuclear contributions.*

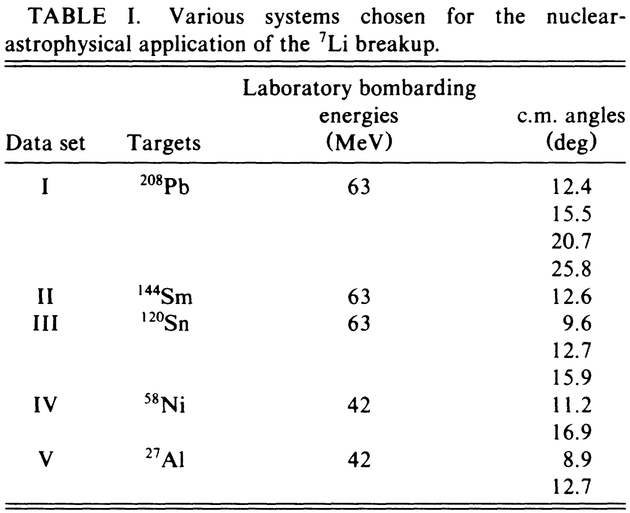
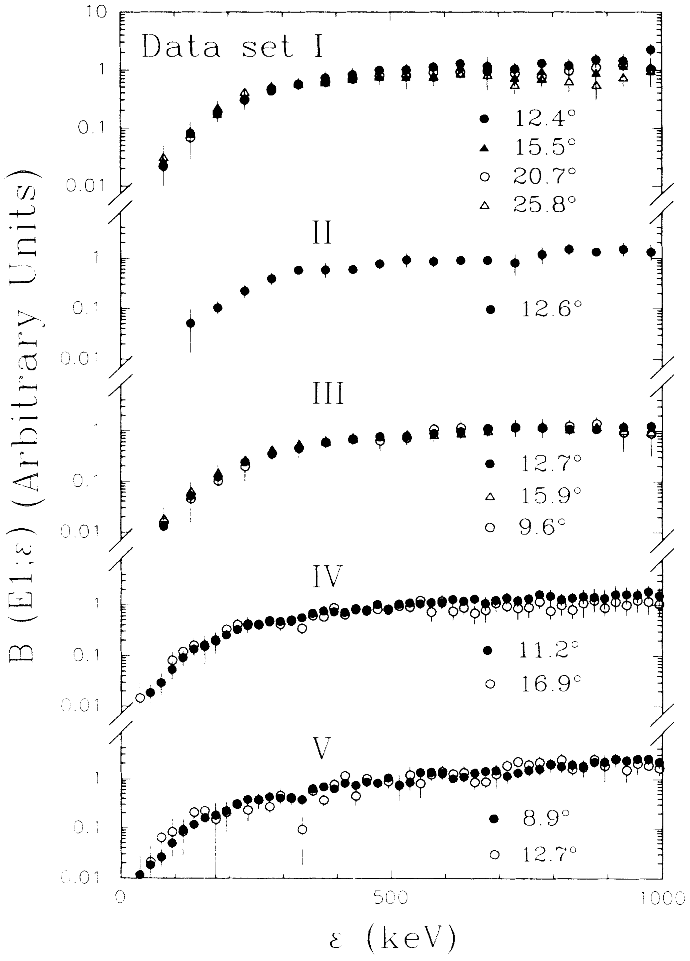


TABLE I. Various systems chosen for the nuclear-astrophysical application of the $^7$Li breakup.

| Data set | Targets | Laboratory bombarding energies (MeV) | c.m. angles (deg) |
|---|---|---|---|
| I | $^{208}$Pb | 63 | 12.4 |
| | | | 15.5 |
| | | | 20.7 |
| | | | 25.8 |
| II | $^{144}$Sm | 63 | 12.6 |
| III | $^{120}$Sn | 63 | 9.6 |
| | | | 12.7 |
| | | | 15.9 |
| IV | $^{58}$Ni | 42 | 11.2 |
| | | | 16.9 |
| V | $^{27}$Al | 42 | 8.9 |
| | | | 12.7 |

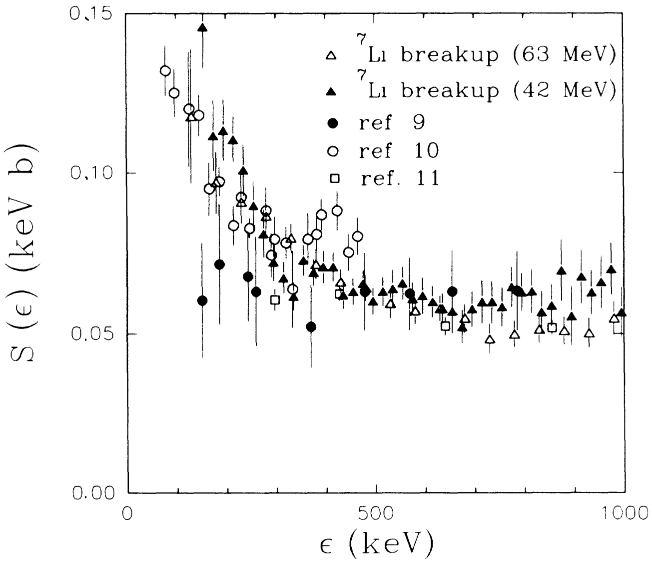
A **modified version** of the method is feasible in **this energy domain** where the **Coulomb and the nuclear interactions behave similarly** in exciting the $\alpha$-*t* continuum states.

**$\alpha$-*t* correlation cross sections** for a wide range of impact parameters (detection angles) and different intensities of Coulomb field (targets), two particles emitted in extremely close proximity.



It is remarkable that, for all the systems, the energy dependence of the reduced transition probability is nearly universal.

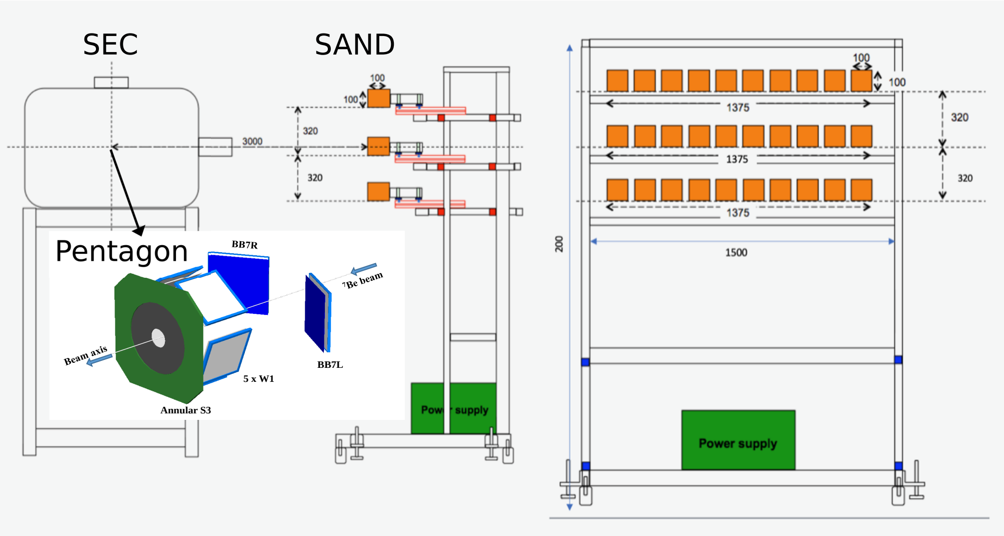
*Observed "universal" energy dependence may be interpreted as a signature that the nuclear and Coulomb interactions excite the continuum with the same relative energy dependence.*



Extracted S-factors agreed to those from radiative capture measurements

Projectile breakup **near particle thresholds** may provide indirect access to radiative-capture processes at astrophysical energies.

# Experiment @ ISOLDE



$^{9}Li + ^{208}Pb \rightarrow ^{8}Li + n + ^{208}Pb$

E = 7 MeV/u

($\tau$ = 2.5 mg/cm$^2$)

Beam intensity I ~ $10^5$ pps

## Charge particle detector setup (Pentagon)

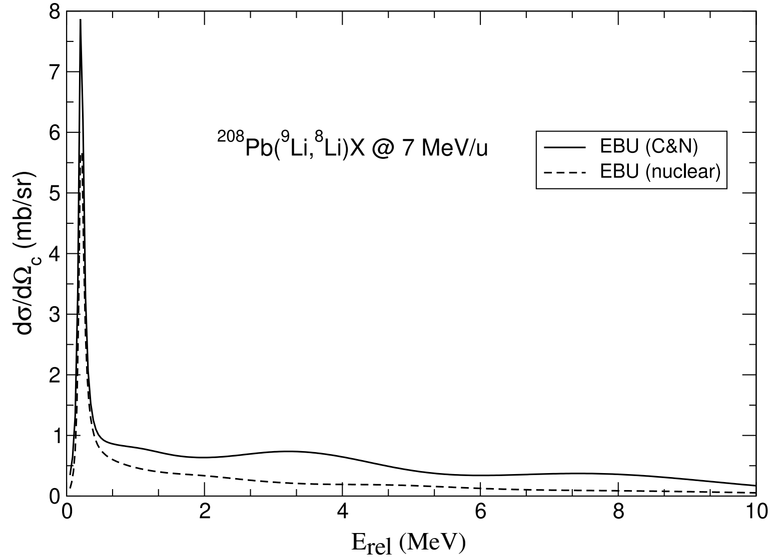
**1 x S3 annular DSSD (24 x 32 strips, 1000 μm) covering front angles 8° – 25°**
**5 x W1 DSSD (16 x 16 strips, 60 μm) in pentagon geometry covering angles 40° – 80°**
**2 x BB7 DSSD (32 x 32 strips, 60 μm and 140 μm) at backward angles 127° – 165°**
**The W1 and BB7 DSSDs are backed by 1500 μm thick unsegmented pads**

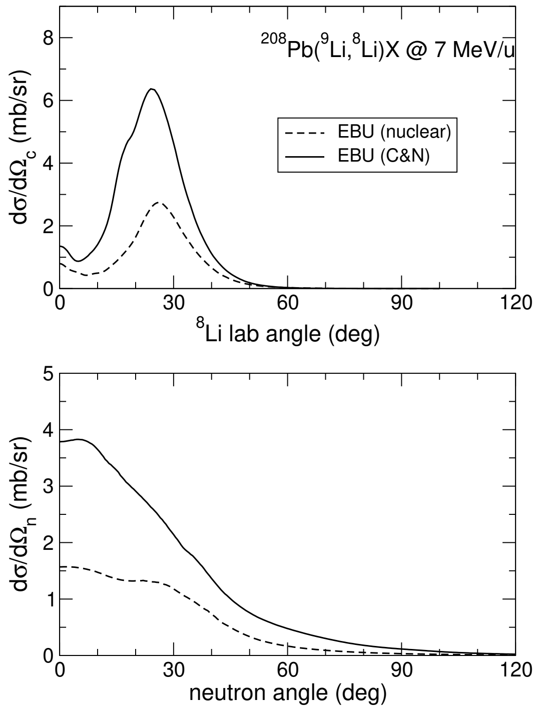
## Neutron detector setup (SAND)

**30 modules each a 10 × 10 × 10 cm$^3$ plastic scintillator equipped with fast PM tubes. Intrinsic efficiency of the detectors for neutron energy range 3–10 MeV is about 30%, slightly depending on energy. Timing resolution is about 0.3 ns. Distance of the neutron detectors to target is 300 cm resulting in a total neutron detection efficiency of ~0.1%.**

# CDCC calculations $^{9}$Li + $^{208}$Pb → $^{8}$Li + n + $^{208}$Pb E = 7 MeV/u

A. Moro (2022)





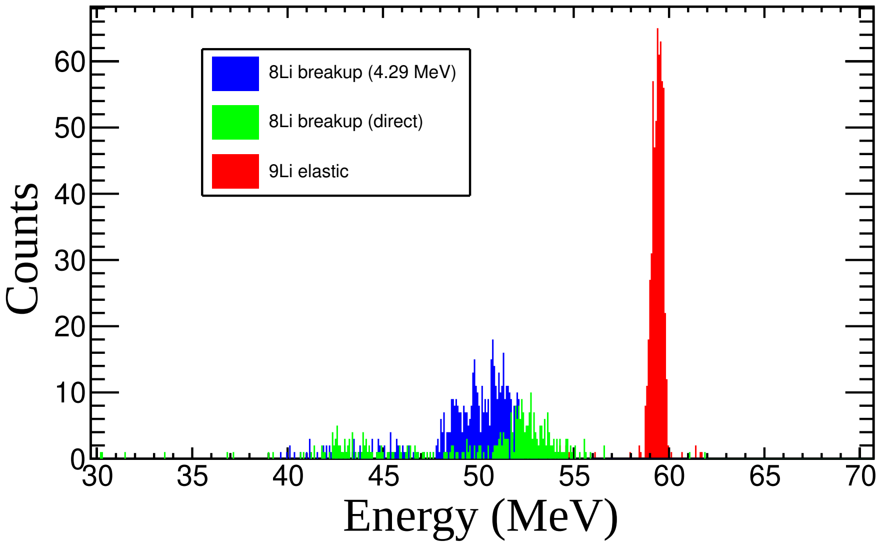
Relative energy distribution

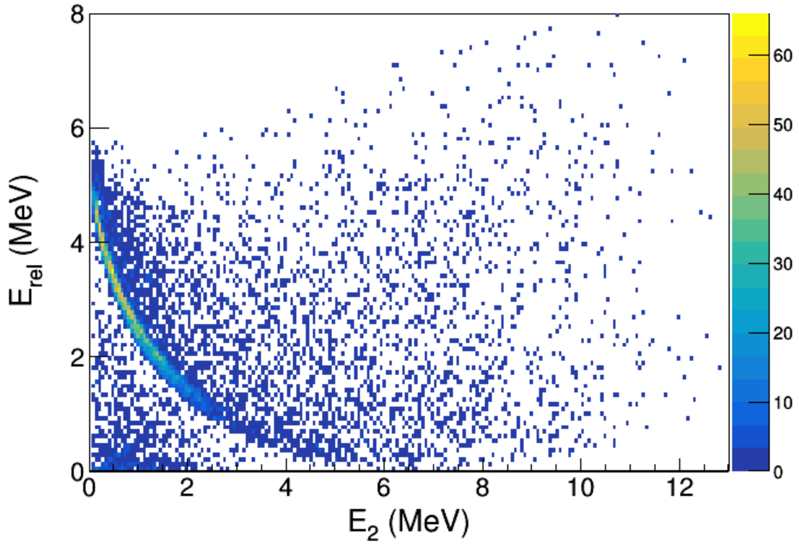
(n + $^{8}$Li relative energy following $^{9}$Li breakup)

$^{8}$Li and n angular distributions

*Narrow peak at low excitation energies comes from the 5/2⁻ resonance, which is modeled with a p1/2 configuration. Considering experimental energy resolution, this peak will be completely washed out.*

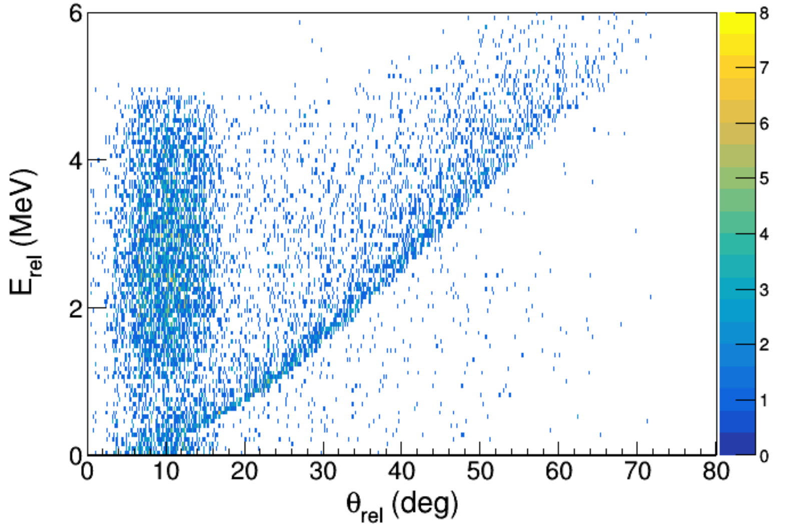
Calculated elastic breakup (*breakup in which the neutron is not absorbed by the target*) cross section is **5.8 mb. Nuclear breakup is significant** (~ 50% of the breakup cross section).



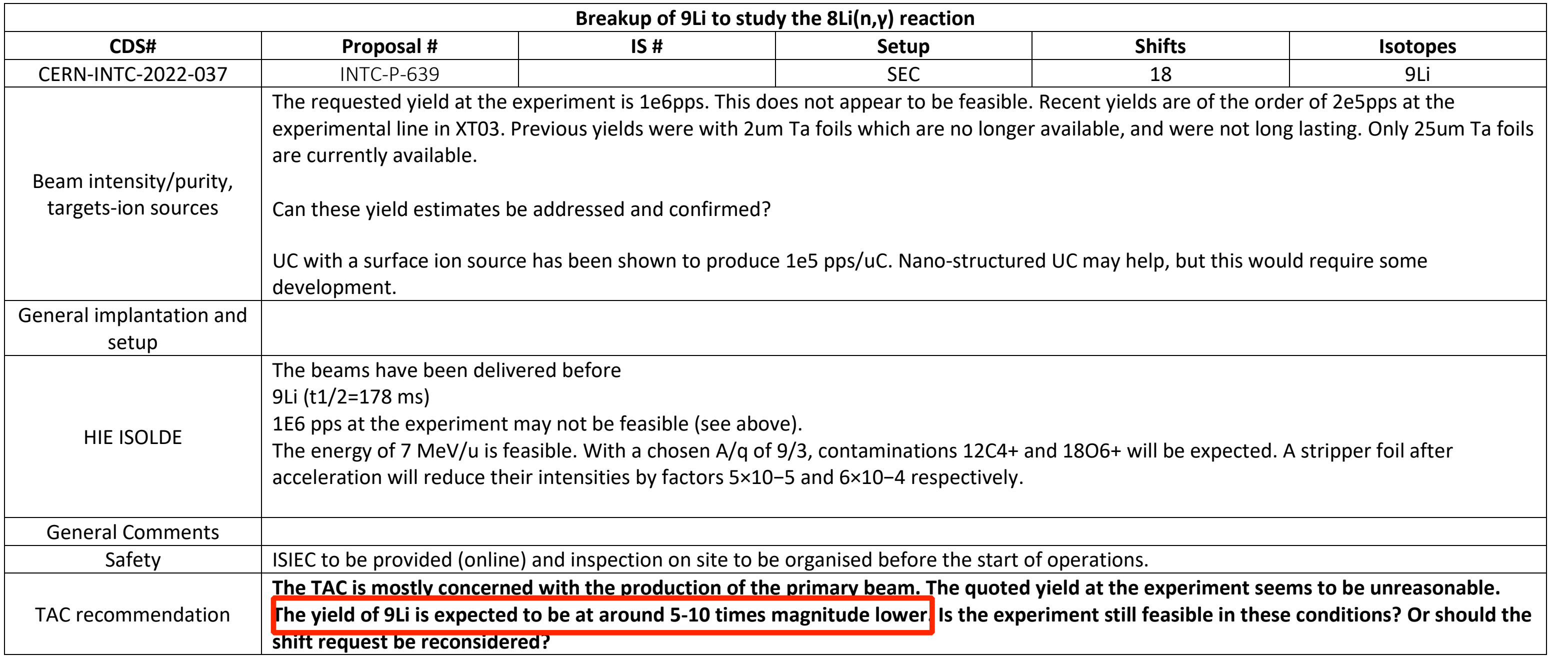


Monte Carlo simulations for the energy spectrum of the **scattered $^9$Li** at $\theta_{lab}$ = 52°(Pentagon). The breakup threshold of $^9$Li is 4.063 MeV. The $^8$Li from both **direct** and **sequential breakup** from the 4.296 MeV (5/2-) state of $^9$Li is also shown.

$^8$Li : $E$ ~ 50 - 59 MeV (8° - 60°)
n: $E$ ~ 0 - 13 MeV (5° - 50°)



$^9$Li - **$10^6$ pps**, $^{208}$Pb $\tau$ -**1 mg/cm$^2$**, $^8$Li + n breakup cross section - **1 mb/sr**, count rate of produced $^8$Li ~ $9\times10^{-3}$ s$^{-1}$ which corresponds to about **260 counts per shift**.



| Breakup of 9Li to study the 8Li(n,γ) reaction | | | | | |
|---|---|---|---|---|---|
| **CDS#** | **Proposal #** | **IS #** | **Setup** | **Shifts** | **Isotopes** |
| CERN-INTC-2022-037 | INTC-P-639 | | SEC | 18 | 9Li |
| Beam intensity/purity, targets-ion sources | The requested yield at the experiment is 1e6pps. This does not appear to be feasible. Recent yields are of the order of 2e5pps at the experimental line in XT03. Previous yields were with 2um Ta foils which are no longer available, and were not long lasting. Only 25um Ta foils are currently available.<br>Can these yield estimates be addressed and confirmed?<br>UC with a surface ion source has been shown to produce 1e5 pps/uC. Nano-structured UC may help, but this would require some development. | | | | |
| General implantation and setup | | | | | |
| HIE ISOLDE | The beams have been delivered before<br>9Li (t1/2=178 ms)<br>1E6 pps at the experiment may not be feasible (see above).<br>The energy of 7 MeV/u is feasible. With a chosen A/q of 9/3, contaminations 12C4+ and 18O6+ will be expected. A stripper foil after acceleration will reduce their intensities by factors 5×10−5 and 6×10−4 respectively. | | | | |
| General Comments | | | | | |
| Safety | ISIEC to be provided (online) and inspection on site to be organised before the start of operations. | | | | |
| TAC recommendation | **The TAC is mostly concerned with the production of the primary beam. The quoted yield at the experiment seems to be unreasonable. The yield of 9Li is expected to be at around 5-10 times magnitude lower. Is the experiment still feasible in these conditions? Or should the shift request be reconsidered?** | | | | |

1) Increase **target thickness** from 1.0 to 2.5 mg/cm$^2$

2) TOF: if time resolution 1 ns and considering 10 MeV neutrons

| **Distance of SAND from target centre** | | | **SAND solid angle** |
|---|---|---|---|
| 3 m : | gamma (10 ns) | n(70 ns) | 0.09% of 4pi |
| 2 m : | gamma (7 ns) | n(50 ns) | 0.26% of 4pi |
| 1 m : | gamma (3.5 ns) | n(25 ns) | 0.91% of 4pi |
| 0.6 m : | gamma (2 ns) | n(14 ns) | 2.08% of 4pi |

We can **move SAND to 0.6 m from target centre** to gain ~ 20 times.

Effectively
2.5x20x2 = **100**
**fold increase in yield**

**2600 counts per shift**

3) Can use **double number of n-detectors** to gain factor of 2.

# 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 $10^5$ pps, and 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 $5\times10^{-5}$ and $6\times10^{-4}$ respectively, which 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.

**Order of magnitude difference** of rate between NSCL (1998, 2003) experiments justify **re-measurement of this reaction**. Theoretical calculations (1999, 2022) consistent with upper limit of 1998 data and exceeds 2003 data by a factor ~ 2. GSM-CC (NCSMC) results are lower (higher) by ~ 20% (~ 30%) than the median value of other calculations. Indirect measurements through $^{8}$Li(d,p)$^{9}$Li reaction at ~ 5 MeV/u to determine (n,$\gamma$) reaction rates, yielded values in between NSCL measurements.

***This necessitates a new experiment to study the $^{8}$Li(n,$\gamma$)$^{9}$Li reaction in the context of A>12 production.***

# References

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**Thank You**

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