# BARC–TIFR Pelletron Linac Facility Beam Time Request @2024

## Title of the Experiment: Lifetime measurement of $\left(\frac{13}{2}\right)^+$ isomeric state of $^{205,\,207}$At nuclei

**Principle Investigator**: Dr. Buddhadev Mukherjee, Mr. Koustav Bhandary (Spokesperson)

**Local Collaborator / Spokesperson: Prof. Rudrajyoti Palit, TIFR**
**Note: Local collaborator is mandatory for non BARC (NPD) / TIFR (DNAP) user**
**Collaborators Name: Dr. R. P. Singh, IUAC; Prof. U. D. Pramanik, SINP; Dr. S. Ghugre, UGC-DAE CSR, Kolkata; Dr. U. Ghosh, IUAC;**
**Dr. A. Chakraborty, Visva-Bharati; Mr. Koustav Bhandary, Ms. S. Biswas, Mr. A Goswami, Mr. S. Maiti, Visva-Bharati**

**Beam details:** Beam spices, Beam energy in (MeV), Beam current in (pnA), Beam Port.

| **No of runs** | **No of shifts** | **Ion Species** | **Energy (MeV)** | | **Current (pnA)** | | **DC/Pulsed** |
|---|---|---|---|---|---|---|---|
| (1 shift = 8 hours) | | | **Min** | **Max** | **Min** | **Max** | |
| 1 | 30 | $^{6}$Li | 55 | 80 | 1 | 5 | DC |
| 2. | 30 | $^{7}$Li | 70 | 100 | 1 | 5 | DC |
| 3. | 30 | $^{14}$N | 74 | 110 | 1 | 5 | DC |

**Beam Port:** Linac Hall 1 – 15D **Beam: 6Li (First priority**)

**Buncher requirement: No**

**Experiment details:**

### 1. Objective of Experiment:

**Definition of the thesis problem:**
The study of neutron rich to neutron deficient nuclei in the Astatine isotope regime, has been studied for various spectroscopic aspects in the past. A lot of high spin states has been found in which some of them are ranging from fewer nano seconds to even 10s of μs . Articles have been published regarding the spectroscopic study along with lifetime measurements of the isomeric states such as, $\frac{9^-}{2}$ , $\frac{13^+}{2}$ , $\frac{21^-}{2}$ , $\frac{25^+}{2}$ , $\frac{29^+}{2}$ etc. Now a very recent spectroscopic study [2] on $^{207}$At has revealed a new higher state of $\frac{29^+}{2}$ in the level scheme along with a lifetime ranging from 2 to 4.5 μs. Similarly, a very earlier study [1] in the 1980s has obtained the level scheme of $^{205}$At with the spin states, up to $\frac{29^+}{2}$ and all other states with the lifetime in the nano second order. It has also been investigated that the state $\frac{29^+}{2}$ has been observed in $^{199\text{-}211}$At nuclei. But surveying the

literatures of those nuclei has shown that, the $\frac{13}{2}^{+}$ isomeric state is there with a life time in the ns range, for other nuclei in the vicinity, but not for $^{205}$At, $^{207}$At. The lifetime of this state for these two nuclei has not been explored. Also, the lifetime of the state with a spin-parity of $\frac{21}{2}^{-}$ is yet to be found for $^{207}$At. A systematic study has been revealed that, for odd mass astatine isotopes, the range of lifetime for $\frac{13}{2}^{+}$ will be in the range 1-10 ns for $^{205, 206}$At. Our aim is to study this state to get the exact value for them. Also, we want to explore the lifetime regime of $\frac{21}{2}^{-}$ state, which is in the range of 25-100 ns as obtained for the neighboring isotopes ($^{205, 209}$At).

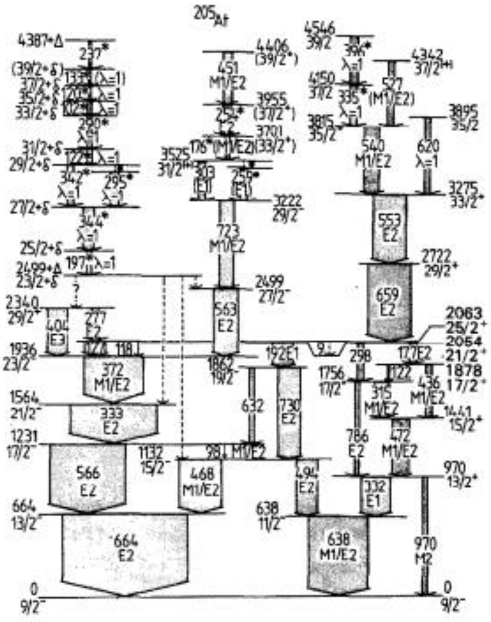

**Fig 1:** Level scheme of $^{205}$At as obtained from the work of R.F Davie et al. [1]

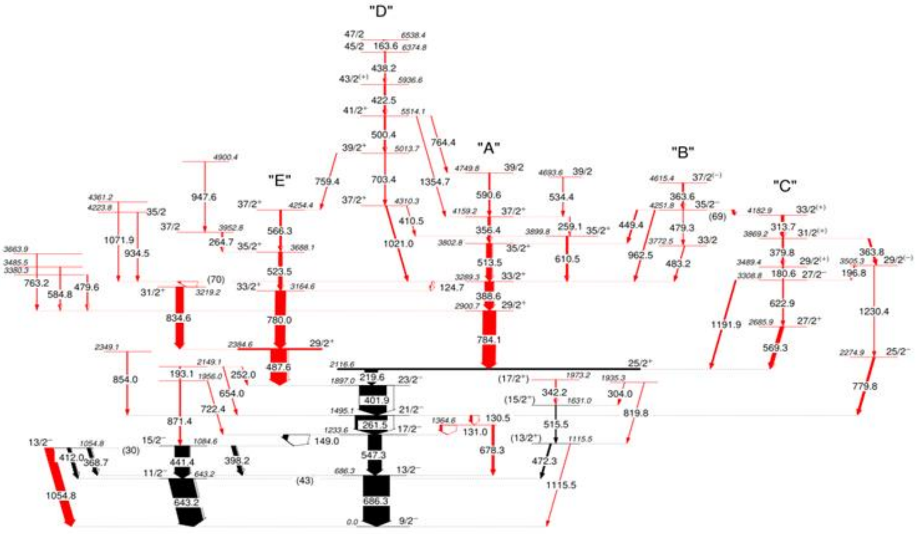

**Fig 1**. Level Scheme of $^{207}$At as obtained from the work of K. Yadav et al. [2]

## Literature survey and motivation:

The exploration of medium to high spin isomeric states within the Astatine isotopes spanning the mass region of A = 199-211 presents an exciting frontier in nuclear physics, offering profound insights into the fundamental properties of atomic nuclei. The region around lead nuclei and the Z = 82 magic shell gap offers a large variety of interesting nuclear phenomena. These include, for example, shape coexistence, sudden change in ground-state deformation and sudden changes in the ground state spin and parity. Coming from the most stable Astatine ($^{210}$At) isotope, the shape of the isotopes changes with decrease in the neutron number. Shape transitions from spherical structures toward oblate-deformed and onward to prolate-deformed collective bands, when approaching the N = 104, mid-shell has been observed in Po and Bi isotopes. Many theoretical calculations [10-11] predict well-defined secondary SD minima persisting in the Bismuth and Polonium nuclei. Thus far, two SD bands have been found in191Bi [13] and one in 193Bi [14]. Also, several Isomeric states with lifetimes ranging from nanoseconds to microseconds have been observed in these two isotopes.

Existing literatures have been studied for odd A, $^{199\text{-}207}$At [1, 2, 9, 10] mass nuclei, and it has been found that, the scope is there two re-investigate the high spin states of $^{205}$At along with their lifetimes. Also, for the $^{207}$At, we can simply observe the $\left(\frac{13}{2}\right)^{+}$ and $\left(\frac{21}{2}\right)^{-}$ state and calculate the lifetime via time stamps. Investigating the lifetimes of medium to high spin isomeric states within these nuclei provides a valuable opportunity to unravel the underlying nuclear structure and dynamics, shedding light on the mechanisms governing nuclear stability and deformation. Moreover, the study of isomeric states in the A = 199-211 mass region of Astatine nuclei holds significant implications for practical applications in fields such as nuclear medicine, materials science, and energy production.

**References**:

1. Davie, R. F., Poletti, A. R., Dracoulis, G. D., Byrne, A. P., & Fahlander, C. (1984). *Nuclear Physics A*, *430*(2), 454-484.
2. Yadav, K., Deo, A. Y., Sahoo, D., Srivastava, P. C., Suman, S., Tandel, S. K., ... & Singh, R. P. (2023). *Physical Review C*, *107*(5), 054303.
3. Sjoreen, T. P., Garg, U., & Fossan, D. B. (1981. *Physical Review C*, *23*(1), 272.
4. Sjoreen, T. P., Fossan, D. B., Garg, U., Neskakis, A., Poletti, A. R., & Warburton, E. K. (1982). *Physical Review C*, *25*(2), 889.
5. Hagemann, U., Neubert, W., Schulze, W., & Stary, F. (1972) *Nuclear Physics A*, *181*(1), 145-152.
6. Palit, R., Saha, S., Sethi, J., Trivedi, T., Sharma, S., Naidu, B. S., ... & Hennig, W. (2012). *680*, 90-96.
7. E. Database (https://www.nndc.bnl.gov/ensdf/)
8. Roy, T., Mukherjee, G., Madhavan, N., Rana, T. K., Bhattacharya, S., Asgar, M. A., ... & Varughese, T. (2015).*The European Physical Journal A*, *51*, 1-8.
9. Jakobsson, U., Uusitalo, J., Juutinen, S., Leino, M., Nieminen, P., Andgren, K., ... & Sorri, J. (2010). *Physical Review C*, *82*(4), 044302.
10. Auranen, K., Uusitalo, J., Juutinen, S., Jakobsson, U., Grahn, T., Greenlees, P. T., ... & Stolze, S. (2015). *Physical Review C*, *91*(2), 024324.
11. R. R. Chasman et al., Phys. Rev. Lett. B 219, 227 (1989).
12. W. Satula, S. Cwiok, W. Nazarewicz, R. Wyss, and A. Johnson, Nucl. Phys. A 529, 289 (1991)
13. M. Nyman et al., Eur. Phys. J. A 51, 31 (2015).
14. I. Bergstr om, B. Fant, C. J. Herrlander, P. Thieberger, K. Wikstr om, and G. Astner, Phys. Lett. B 32, 476 (1970).

## 2. Description of Experiment:

**Facilities Required:** Indian National Gamma Array (INGA).

We would like to measure the lifetime of the proposed isomeric state using the DSP technique [6]. This will give us an opportunity to revisit some of the lifetime values that have been calculated before. As fast timing array consisting of LaBr3(Ce) scintillators, with the INGA, the lifetime measurements of isomeric states from 1 ns to few $\mu s$ during the usual $\gamma - \gamma$ coincidence measurement will be suitable.

**Target Sample details:**

| **Material** | **Thickness ($\mu$g/cm$^2$)** | **Backing if any** | |
|---|---|---|---|
| 1. $^{206}$Pb | 300 | No | |
| 2. $^{206}$Pb | 300 | No | |
| 3. $^{198}$Pt | 300 | No | |

**Target:** $^{206}$Pb (**First priority**)

**Beam time calculation for $^{205}$At:**

$$Yield = \frac{3.76}{A} \times \sigma_{total} \times I \times t$$

Where $A = 205, I = 5pnA, t = 300\frac{\mu g}{cm^2}, and\ \sigma_{total} = 855\ mb\ (Following\ PACE4\ calculations)$

**The production of $^{205}$At per second is given by,** $= 23.523 \times 10^3$ counts per second.

Considering INGA at TIFR comprising of **16 numbers of clover detectors, we have:** The efficiency of each clover detector w.r.to NaI(Tl) is **23% placed at 25 cm from target**, the efficiency of NaI(Tl) detectors is **1.2 * 10$^{-3}$.**

**INGA efficiency (placed at 18ncm from the target position)**

$$\varepsilon_{INGA} = 16 \times 4 \times 23 \times 1.2 \times 10^{-3} \times \left(\frac{25}{18}\right)^2 = 3.407\%$$

Thus, the no. of gammas detected by INGA per second is given by, (Avg. gamma multiplicity = 6)

$$N_{\gamma\ per\ sec} = 23.523 \times 10^3 \times 6 \times 3.407 \times 10^{-2} = 4808$$

And, $N_{\gamma-\gamma\ per\ sec} = 4808 \times (13 \times 23 \times 1.2 \times 10^{-3}\%) \times \left(\frac{25}{18}\right)^2 \times 13 = 432$

**Thus, for the 30-shift beam time:**

$$N_{\gamma\ total} = N_{\gamma\ per\ sec} \times 30 \times 8 \times 60 \times 60 = 4808 \times 30 \times 8 \times 60 \times 60 = 4.15 \times 10^9$$

$$N_{\gamma-\gamma\ total} = N_{\gamma-\gamma\ per\ sec} \times 30 \times 8 \times 60 \times 60 = 432 \times 30 \times 8 \times 60 \times 60 = 0.37 \times 10^9$$

**Beam time calculation for $^{207}$At:**

Similarly, as $^{205}$At, $Yield = \frac{3.76}{A} \times \sigma_{total} \times I \times t = 27.246 \times 10^3$ counts / sec

$$N_{\gamma\ per\ sec} = 27.246 \times 10^3 \times 6 \times 3.407 \times 10^{-2} = 5569$$

And, $N_{\gamma-\gamma\ per\ sec} = 5569 \times (13 \times 23 \times 1.2 \times 10^{-3}\%) \times \left(\frac{25}{18}\right)^2 \times 13 = 501$

Thus

$$N_{\gamma\ total} = N_{\gamma\ per\ sec} \times 30 \times 8 \times 60 \times 60 = 5569 \times 30 \times 8 \times 60 \times 60 = 4.8 \times 10^9$$

$$N_{\gamma-\gamma\ total} = N_{\gamma-\gamma\ per\ sec} \times 30 \times 8 \times 60 \times 60 = 501 \times 30 \times 8 \times 60 \times 60 = 0.43 \times 10^9$$

**Theoretical simulation and cross-section measurement:**

In our research, we utilized the powerful statistical model code PACE4 to delve into the cross-section of residual nuclei generated during a specific reaction, carefully selecting the appropriate energy of the projectiles for our study. Our calculations showed that the nuclei we were interested in were exceptionally well-populated at these energies.

For our experiment, we have planned three runs. In the first run, we aim to develop the level scheme of the populated nuclei to the highest possible level. The PACE4 simulations we conducted allowed us to select the optimal beam energy for maximum residue production cross-section. Our results, shown in figures 3, 4, and 5, highlight the promising combinations of target-projectile: $^{6}$Li+$^{206}$Pb, $^{7}$Li+$^{206}$Pb and $^{14}$N+$^{198}$Pt.

These combinations offer an exceptional opportunity to produce the nuclei of interest at their maximum cross-section, with $^{205}$At and $^{207}$At boasting an impressive 47.9% & 75.7%, 62.5% & 38.1%, 44.5% & 72.8% out of the total fusion cross-section, respectively.

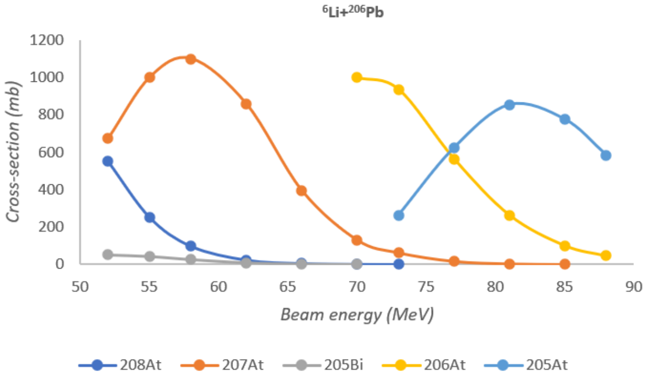

**Fig 3**. Production cross-section of evaporated channels for the reaction, $^{6}$Li on $^{206}$Pb predicted by the PACE4 code. With the input parameters tuned for mass A~ 200 regime, this simulation is performed with 100000 events.

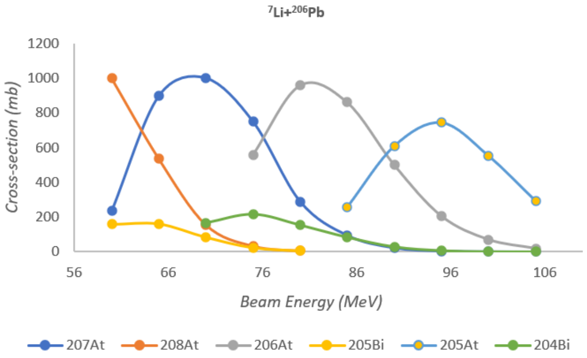

**Fig 4.** Production cross-section of evaporated channels for the reaction, $^{7}$Li on $^{206}$Pb predicted by the PACE4 code. With the input parameters tuned for mass A~ 200 regime, this simulation is performed with 100000 events.

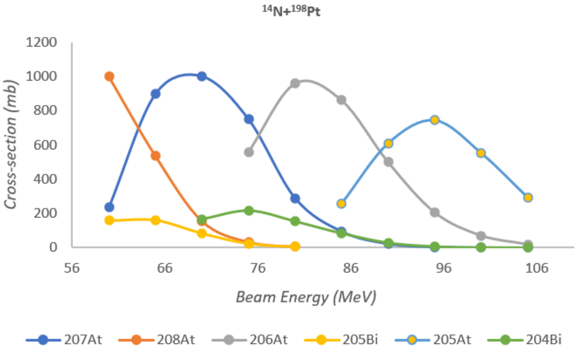

**Fig 5.** Production cross-section of evaporated channels for the reaction, $^{14}$N on $^{198}$Pt predicted by the PACE4 code. With the input parameters tuned for mass A~ 200 regime, this simulation is performed with 100000 events.

- **Whether the experiment is part of PhD /Post Doc. Work:** PhD Work
  This work is a part of the PhD thesis work of Mr. Koustav Bhandary, Research Scholar, Visva Bharati University.
- **Details of Beam time availed of in recent past on this experiment and / or by the PI:** Nil
- **Details of papers published / presented in journals / symposia, etc. based on recent experiments:**

1. “High spin states in 63Cu” S.Rai, B.Mukherjee, …. A.Chakraborty et al., Eur. Phys. J. A 54 (2018) 84
2. “Evolution of collectivity and shape transition in 66Zn” S. Rai, U. S. Ghosh, …… A. Chakraborty et al., Phys. Rev. C 102 (2020) 064313
3. In-beam spectroscopic study of 63Zn” U.S.Ghosh, S.Rai, ……, A. Chakraborty et al., Phys. Rev. C 100 (2019) 034314
4. “Spectroscopic investigation of complex nuclear excitations in 66Ga” U. S. Ghosh, S. Rai, … A. Chakraborty, et al., Phys. Rev. C 102 (2020) 024328
5. Ghosh, U. S., Mukherjee, B., & Rai, S. (2020). *International Journal of Modern Physics E*, *29*(07), 2050045.
6. Kharpuse, B., Mukherjee, B., Chakraborty, A., Biswas, S., Debnath, K., Bairagya, A., ... & Ghosh, U. S. Shell Model Description of Octupole Correlation in 66Zn & 66, 68Ge. (ICTRP-2023)
7. Ghosh, U. S., Rai, S., Mukherjee, B., Mondal, A. K., Mandal, K., Barman, S., ... & Singh, R. P. (2022). In *Proceedings of the DAE Symp. on Nucl. Phys* (Vol. 66, p. 144).
8. S. Biswas et al, Proceedings of DAE-BRNS symposium 67 (2023) A61.
9. B. Kharpuse et al, Proceedings of DAE-BRNS symposium 67 (2023) A32.
10. S. Barman et al. In *Proceedings of the DAE Symp. on Nucl. Phys* (Vol. 66, p. 258).