PET: a high threshold Nuclear Track Detector (NTD) for rare event search

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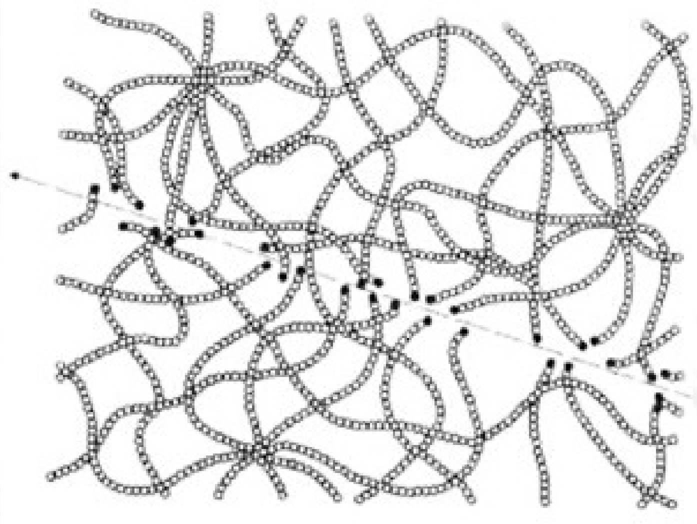
How Nuclear Track Detectors (NTDs) work ?

- Heavy charged particles on their passage through materials lose energy according to the Bethe formula :

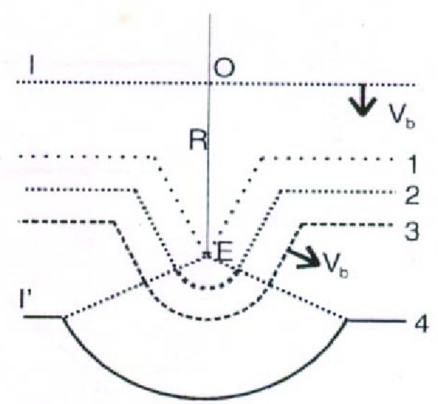
$$-dE/dx = K\mathbf{(z/\beta)^2}NZ[\ln(2m_0v^2/I)-\ln(1-v^2/c^2)-v^2/c^2]$$

- The ionization and excitation produced by the charged particles along their path causes molecular bonds of the plastic to break, thereby producing narrow (30-100Å) damage trails. Naturally the damaged portions become chemically more reactive to suitable chemical reagents (etchants) (e.g. ionic compounds like NaOH) compared to the undamaged bulk material.

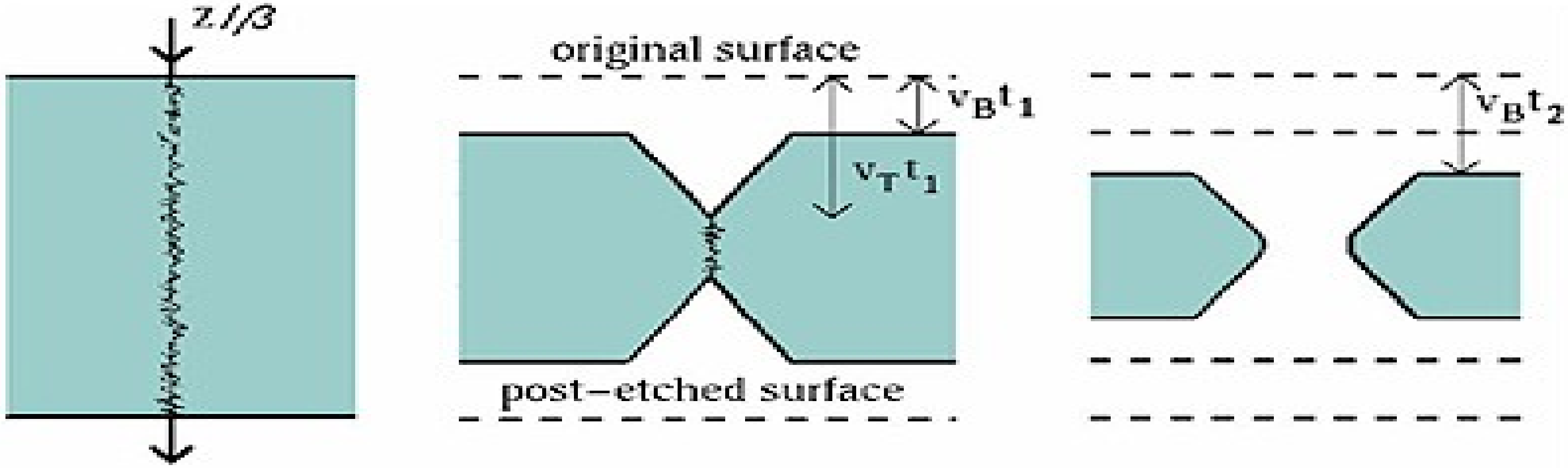


Formation of etch pits through etching

- During etching, the material along the damage trails are etched out at a much higher rate V_T (Track etch rate) compared to the rate of etching V_B also called V_G (Bulk etch rate) of the undamaged surface. The etch pits so formed can be closely approximated by geometrical cones with the damage trail along its axis and is observable under an optical microscope.

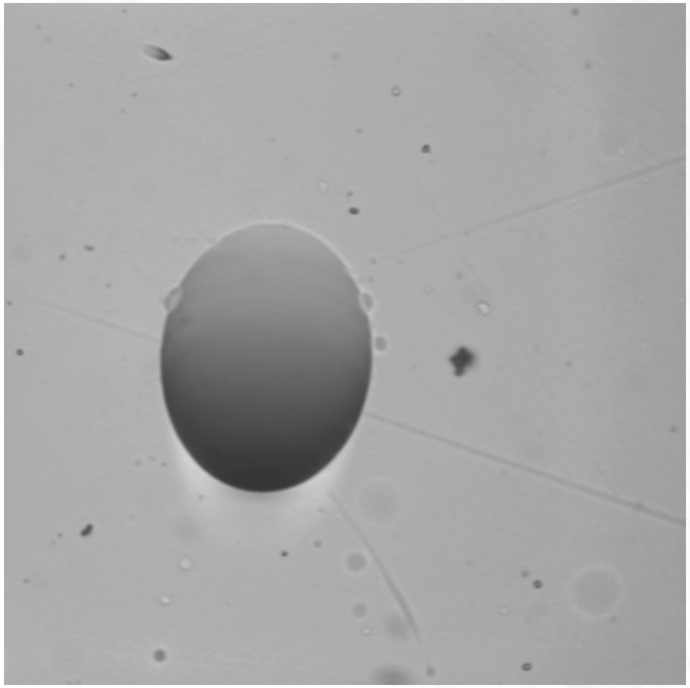


- For track formation $V_T/V_B > 1$ and corresponding Z/β is the detection threshold of the material

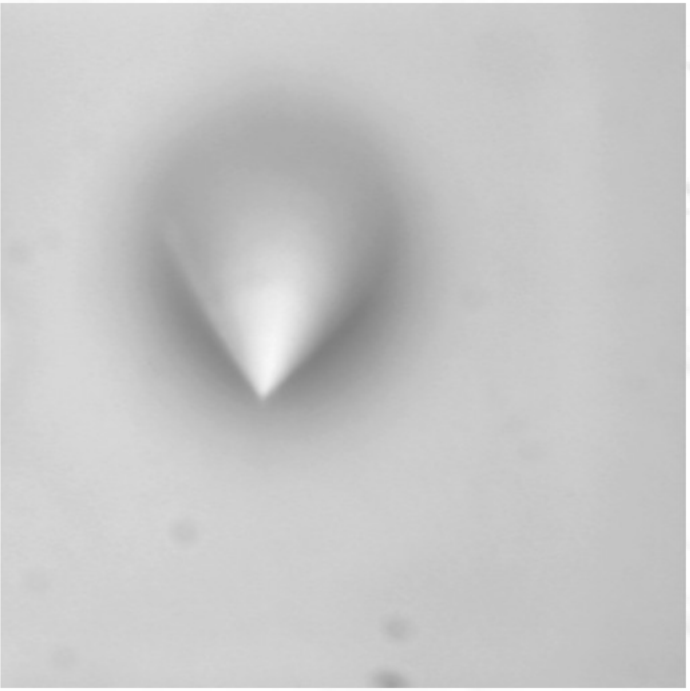


Etch pit image

Surface opening of a track



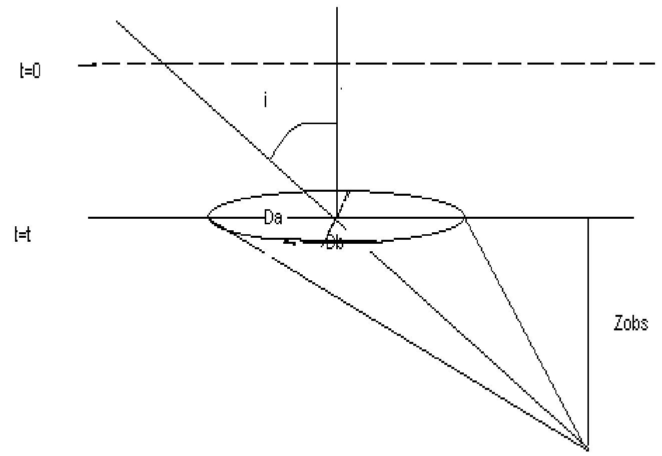
Conical profile of the etch pit



Charge response V_T / V_B

- The ratio V_T/V_B = f(dE/dx) and hence ∝ $(Z/\beta)^2$ of the incident ion is called the **charge response** of the detector
- It can be determined by studying the geometry of etch pit openings and is given by the formula:

$$V_T / V_B = Z_{obs} / [V_B \times t \times \cos(i)] + 1 / \cos(i)$$



i : incident angle

D_a : major axis of etch pit openings

D_b minor axis of etch pit openings

$\cos(i) = D_b/D_a$

Zobs : depth of the tip of the etch cone from the post-etch surface

t : duration of the etching process.

- The ratio V_T/V_B as well as the range **R** of the particle inside the detector are the two most important parameters which help us in identifying the particle forming the track.

Instruments

Etching tank

Leica DM 4000 M

Advantages of NTDs in rare event search

- Such detectors have various advantages :

(a) Simplicity and ease of use: Since they do not require power for their operation it is relatively easy and inexpensive to set up large arrays, even at remote locations.

(b) Existence of natural thresholds of registration. Helps supress background.

(c) They offer a good charge resolution.

- NTDs are particularly well suited to look for heavy, slow moving, heavily ionizing particles with very low fluxes against a large low-Z background, e.g. **strangelet** or **monopole** search in cosmic rays or particle accelerators.

What are Strangelets ?

- Normal baryonic matter is composed up and down quarks
- It has been suggested by various authors [e.g.Witten (1984), Farhi(1984), Madsen(1993)] that Strange Quark Matter (SQM) consiting roughly equal number of up, down and strange quarks is the true ground state of hadronic matter
- Small stable lumps of SQM is what is being referred to as **strangelets**.
- Such strangelets will have a small positive charge, thus an unique experimental signature of strangelets is an unusually low charge to mass ratio (**Z/A<<1/2**) compared to ordinary nuclei.
- The decay of normal nuclear matter into strange matter will require about a third of the up and down quarks to transform simultaneously into strange quarks via weak interactions, making it prohibitively unlikely.

Where can SQM be found and how can they reach earth ?

- SQM, if stable, is almost unavoidable in the core of dense steller objects like neutron stars.
- Strangelets may be produced when two such stars in a binary system collide.
- A strange star – black hole collision may also release lumps of quark matter.
- Certain calculations suggest a galactic production rate equivalent to $10^{-10}\ M_{\odot}\ yr^{-1}$
- Strangelets in many ways behave like ordinary cosmic ray nuclei and are accelerated by similar mechanisms e.g. Fermi acceleration in supernova shocks.
- Theoretical studies [Madsen (2005)] point to significant measurable strangelet flux in our part of the galaxy.

Inside the earth's atmosphere

- According to one model of strangelet propagation [S. Banerjee et.al (2000)] an initially small strangelet passing through the earth's atmosphere, would pick up mass by preferentially absorbing neutrons over protons from the nuclei of atmospheric atoms, protons being Coulomb repelled. As a consequence Z/A ratio gets even more skewed.

- At the same time the strangelet will lose energy through ionisation of the surrounding media which effectively puts a lower limit to the altitude at which it can be detected.

- For example a strangelet with initial mass ~ 64 amu , charge ~ 2 and $\beta \sim 0.6$ will evolve to mass ~ 340 amu and Z~10 -20 at an altitude of 3.6 Km above sea level and will have $\beta \sim 0.01$. So it will have a $Z/\beta \sim$ 1000-2000.

- The flux of strangelets at that altitude is estimated to be 5-10/100sq.m./yr.

Reports of events with unusual Z/A ratio

- There are several observations of exotic nuclear fragments with unusual charge to mass ratio in different cosmic ray experiments.

- In 1990, Saito *et al.* analyzed the data of 1981 balloon borne experiment and claimed to have identified two events which were consistent with A ~ 370 and Z ~ 14 and was explained in the scheme of strange quark matter.

- In 1993 Ichimura *et al*. reported an event with unusually long m.f.p. called the ‘exotic track’ event with Z ~ 20 and A ~ 460. The report was based on an analysis of a 1989 balloon borne experiment using solid state nuclear track detector.

- In a paper in 2001 Fujii *et. al*. reported detection of a possible SQM candidate, an anomalous massive nuclei of charge Z~14 and M~370 amu in a hybdrid system combining active (Cherenkov and scintillation)and passive detectors (CR-39) in a 19 hr balloon flight.

- Analysis of data from AMS-01, which flew to space on board Space Shuttle Discovery, has given hints of some interesting events, such as one with Z=8, A=54 [Aguilar *et.al*.(2002)]

Ongoing searches for strangelets

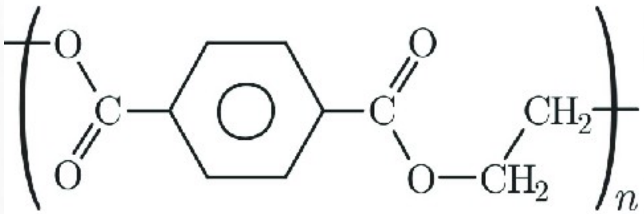
- AMS-02, a magnetic spectrometer currently installed on the ISS has the search for strangelets in primary cosmic rays as one o its main scientific goals

- Our effort, using large area NTD arrays at highmountain altitudes will be complimentary to such eforts.

Choice of NTD in strangelet search : PET

- Widely used polymer detectors like CR-39 and Lexan have low Z/β detection thresholds [for CR-39: $(Z/\beta)_{thres}$> 6, for Lexan:$(Z/\beta)_{thres}$>57] compared to the predicted Z/β values of strangelets of 1000 – 2000 at mountain altitudes. Will record a huge low-Z background (CR protons, radon alphas, neutron recoil tracks etc.)

- A particular brand of overhead projector (OHP) transparencies was found to be very suitable as a NTD. Elemental analysis revealed that the plastic was **Polyethylene Terephthalate (PET)**, a matrial widely used in making wrappers and bottles with chemical formula $(C_{10}H_8O_4)_{n}$.. This was reconfirmed with IR spectroscopy.

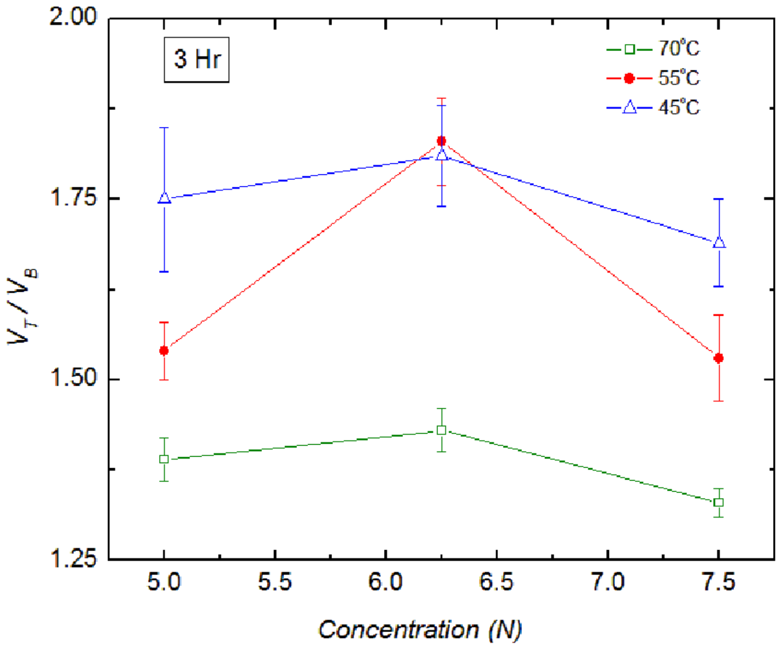


- Crucially, it was found that PET has a much higher detection threshold [$(Z/\beta)_{thres}$ > 140] compared to other commercially available NTDs and as such is significantly better at background suppression.

- Another advantage of PET is that it is substantially cheaper compared to detectors like CR-39.

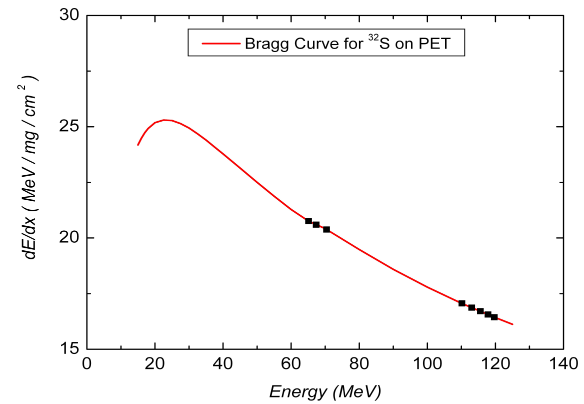
Ideal etching condition for PET

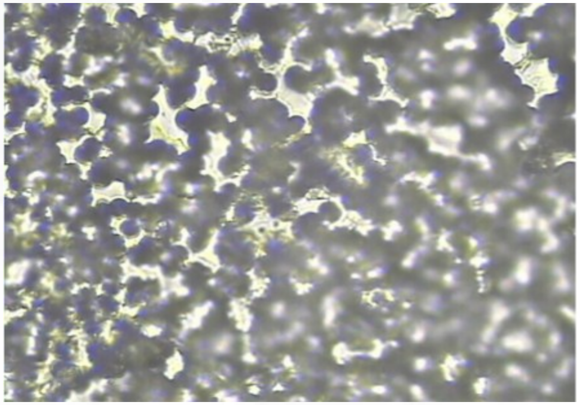
- The etch pit geometry depends on the temperature and the concentration of the etchant and also the duration of etching.
- The goal was to maximize the charge response V_T/V_B and to see whether the track quality is good.
- An exposed PET detector was etched in NaOH soln. at three different concentrations (5.0N,6.25 N,7.5N) and at three different temperatures (45°C,55°C,70°C).
- It can be seen that V_T/V_B is getting maximized at the concentration of 6.25 N and at the temp. of 55°C. Track quality was also good.
- So we have used **6.25 N NaOH** soln. at temp **55° ± 0.1°C** for subsequent etching processes.



Calibration of PET

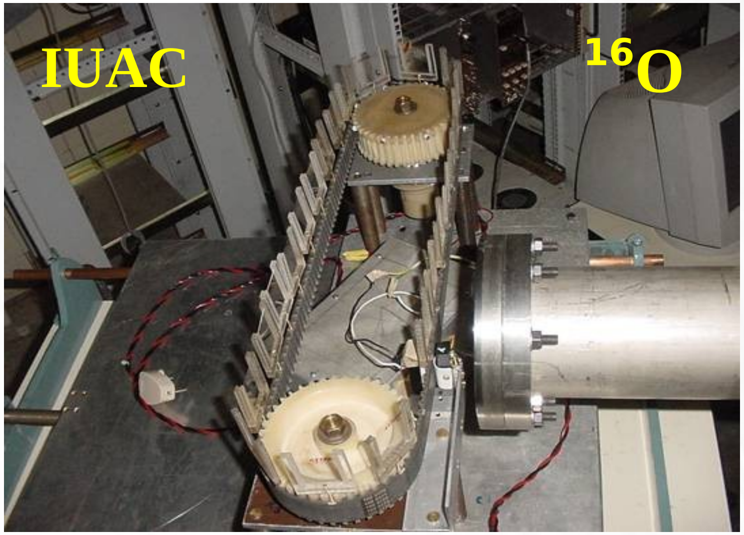
- PET films were exposed to various ion beams from diferent accelerators.
- Incident ion energies chosen to be higher than the Bragg peak energies for those ions on PET.
- Beam currents and exposure durations were chosen so that the number of ions impinging on the detector lies in the range (10^4 – 10^5)/cm^2. This is to prevent detector burnout and to optimize the data analysis process.

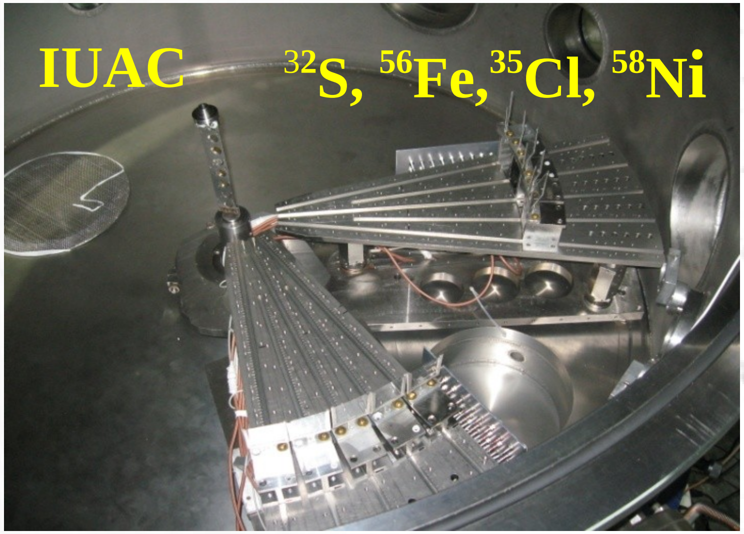


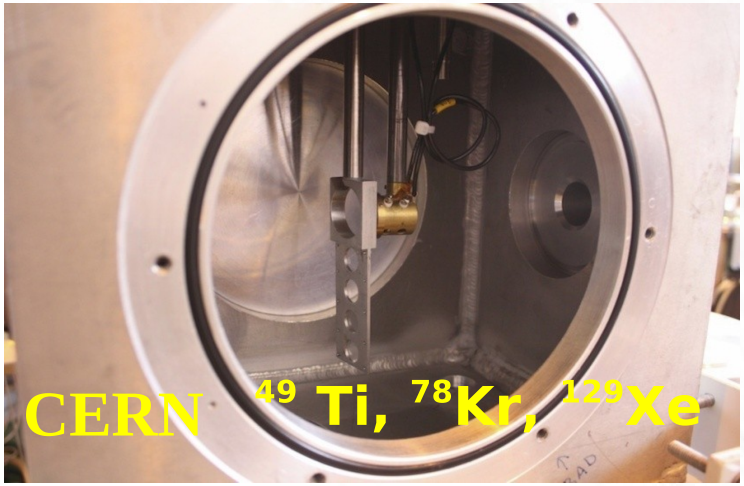


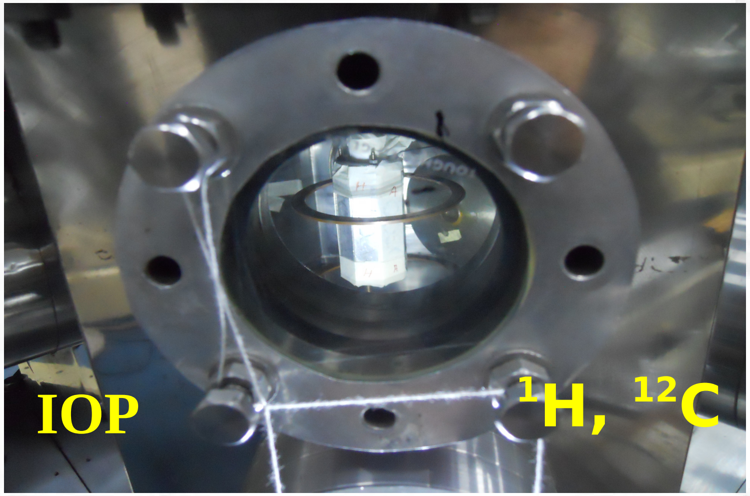
Detector Burnout

Experimental setups

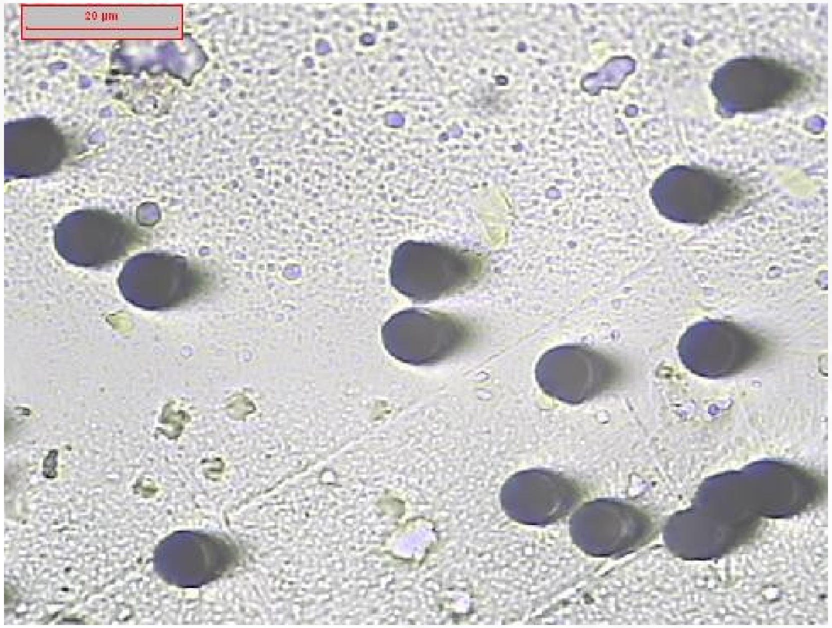




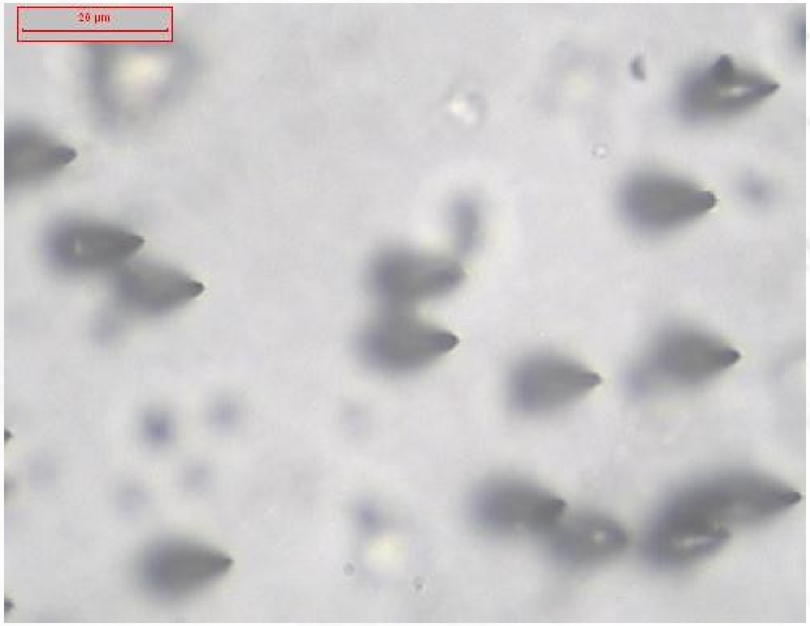




Fe tracks on PET

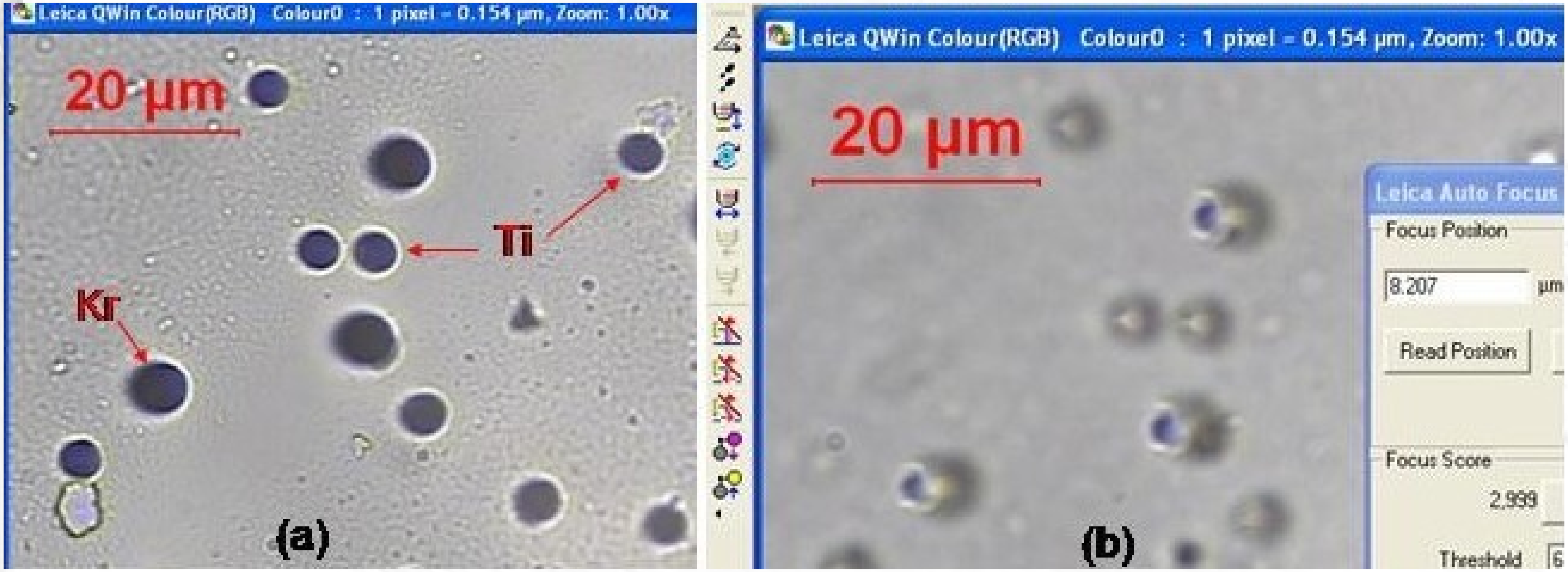


Surface



Depth ~ 6 μm

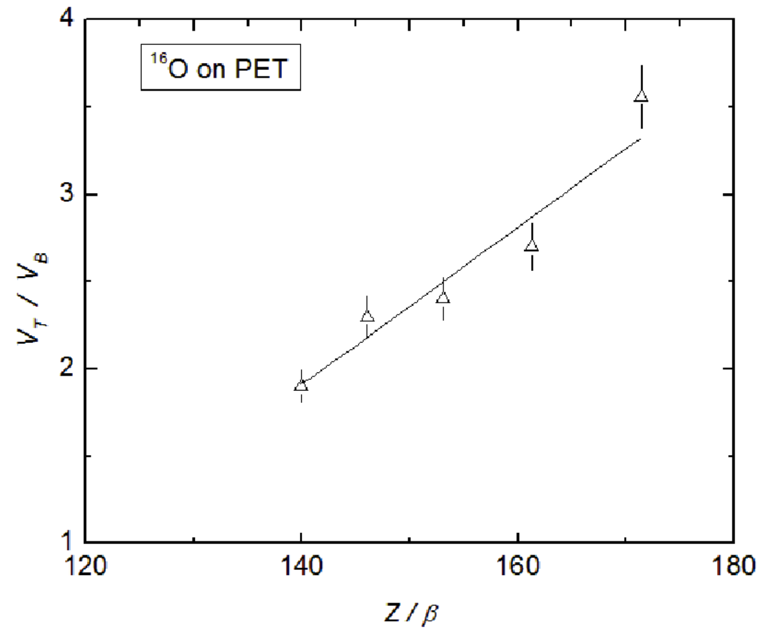
Kr and Ti tracks on PET



The different dimensions for ^{78}Kr and ^{49}Ti tracks can be seen with the microscope focused (a) on the surface and (b) at a depth of 8.2 micron from the surface.

Calibration curve for ^{16}O - ions

- The adjoining image shows the charge response parameter V_T/V_B of PET plotted against corresponding Z/β values.
- If the response curve is extrapolated towards lower values of Z/β, we could see that corresponding to V_T/V_B ~ 1 we have Z/β ~ 120
- Since $V_T > V_B$ for track formation, this indicates that the threshold for PET ~ 120

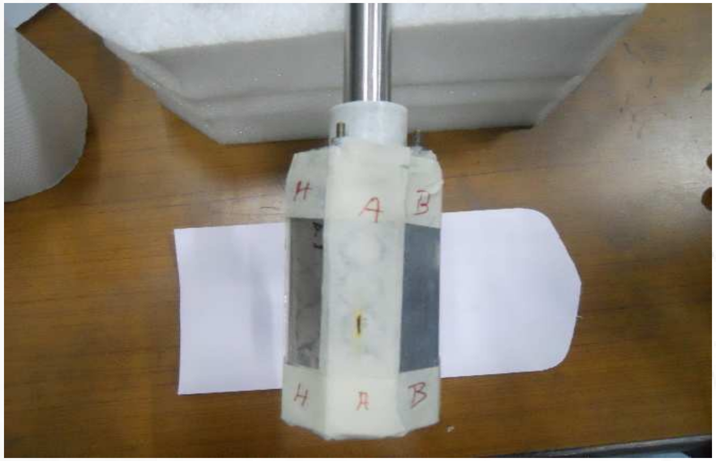


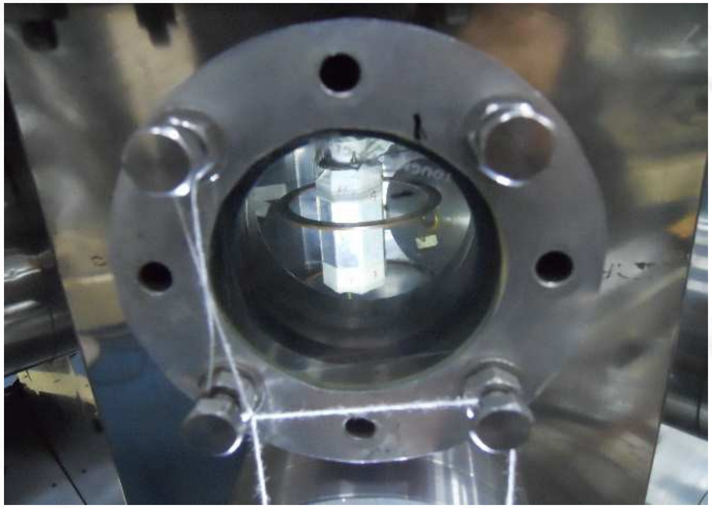
Experiment at IOP

CR-39 and PET films exposed to 11 MeV ^{12}C and 2 MeV proton beams from the particle accelerator at the Ion Beam Laboratory, Institute of Physics (IOP), Bhubaneswar

Experimental setup

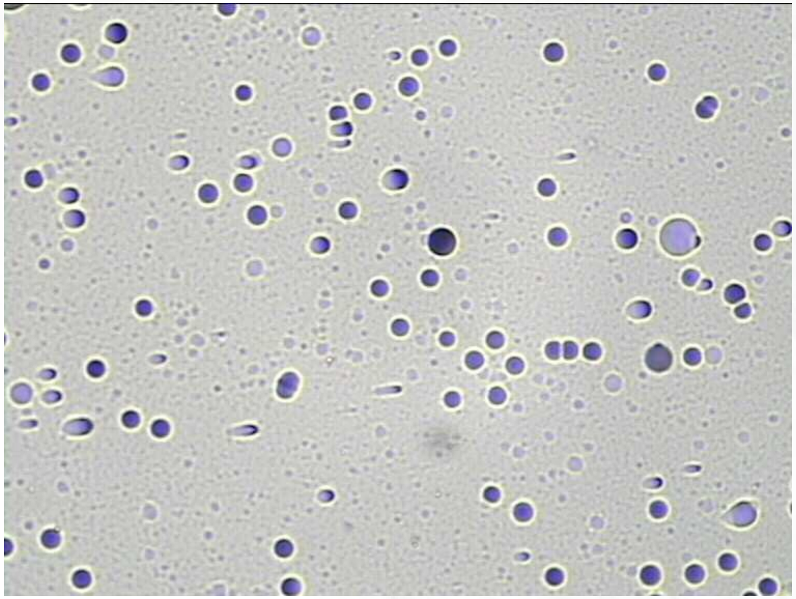
- PET and CR-39 films of thickness 100 µm and 700 µm respectively, were cut into pieces (8.5 cm ×1.5 cm) and mounted on the different faces of a target ladder, one face of which was covered with a glowing tape for beam monitoring.
- Initially beam current was set at 500 nA to enable beam monitoring and necessary adjustments. Then the beam current was reduced to a very low value 0.5nA to prevent detector burnout
- During every run the target ladder was given one full rotation within 10 sec to irradiate all the detector films attached to the different faces.





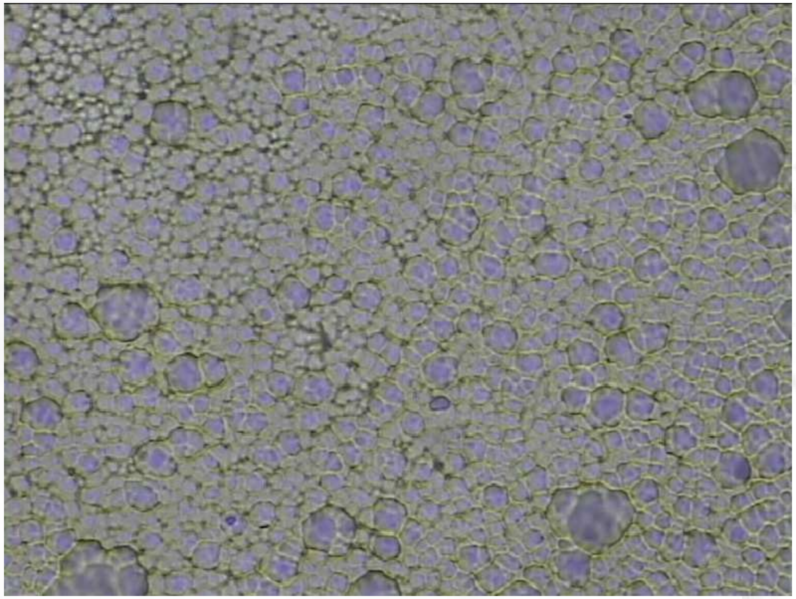
Exposure to 2 MeV proton beam

CR-39



Proton tracks after
4 hr etching

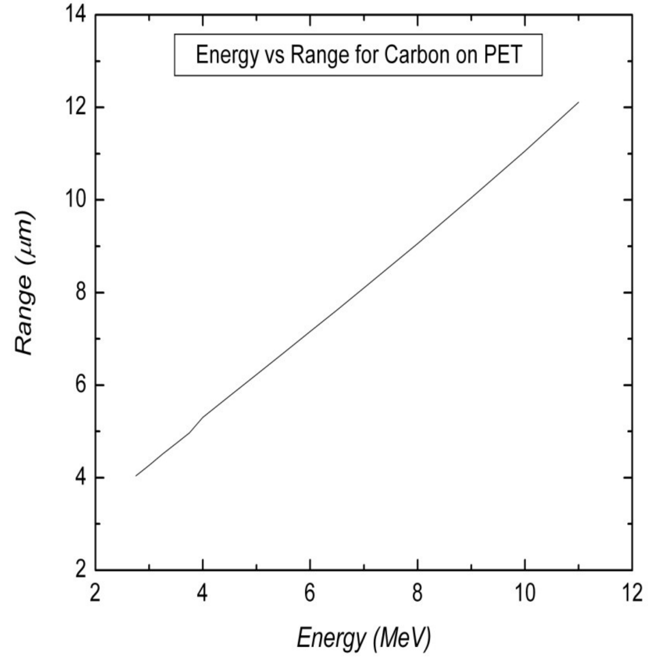
PET



No tracks could be seen even
after 9 hr etching

Exposure to 11 MeV ^{12}C beam

- Exposed PET detectors were etched in successive stages to determine the point where the tracks become visible and measurable.
- As a charged particle moves through the detector, its energy is steadily reduced. This implies that the corresponding value of β decreases and Z/β increases
- The aim was to determine the Z/β value corresponding to which the tracks become visible as it will give us the detection threshold of PET.
- To determine the energy of the particles at different depths inside PET, the passage of the ions through PET was simulated using the standard Monte Carlo code SRIM

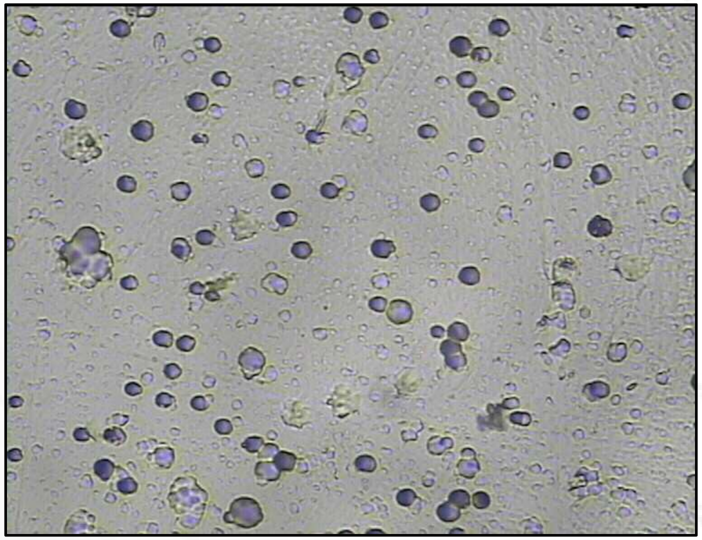


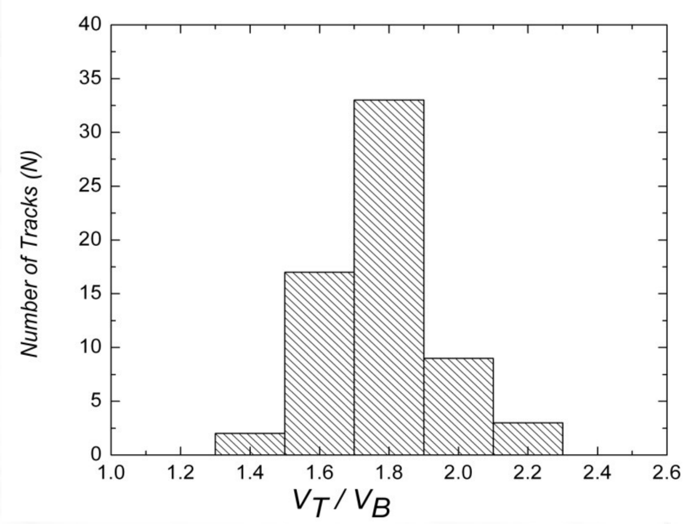
Energy and corresponding Z/β of carbon ions at various points inside PET

Duration of Etching (h)	Length traversed in PET (μm)	Reduced energy (MeV)	Corresponding Z/β
1	1.3	9.74	144
2	2.6	8.43	155
3	3.9	7.08	170
4	5.2	5.68	190

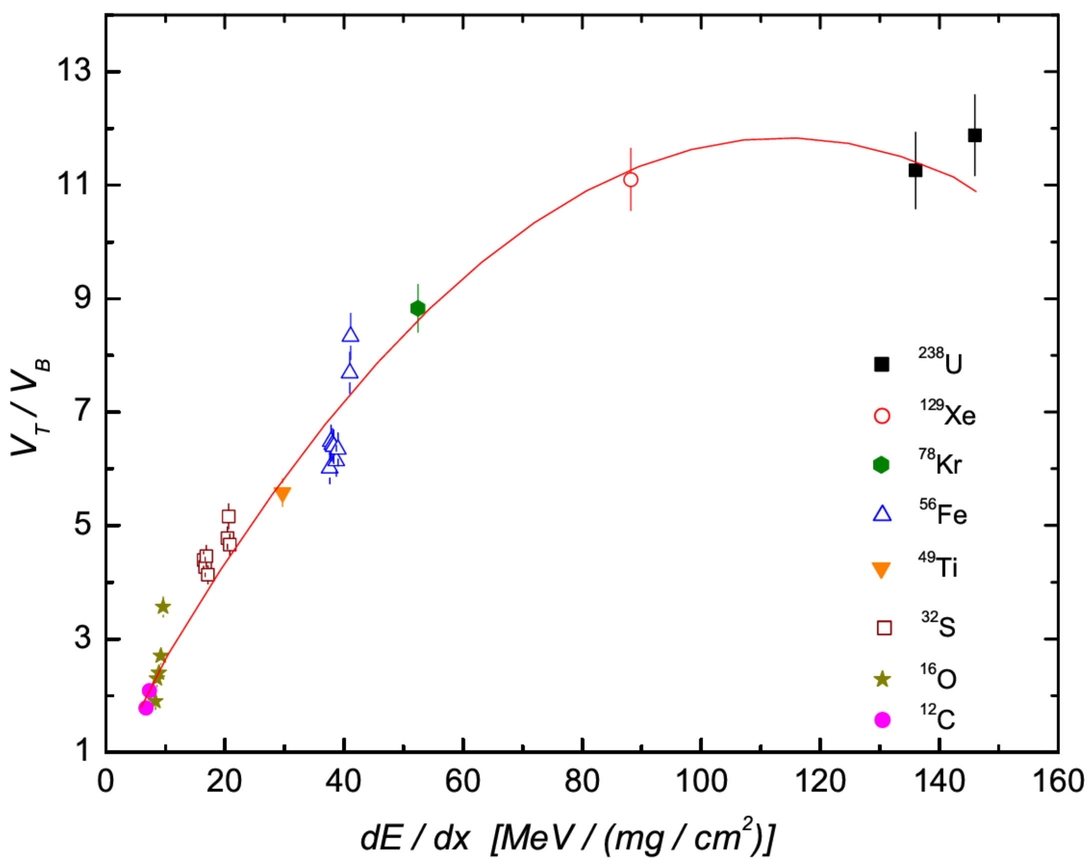
Detection threshold

- Tracks due to 12C visible on PET after 1 h etching. Corresponding Z/β ~ 140
- So Z/β ~ 140 is the practical detection threshold for PET. But tracks too small to be measured as they fall within the margin of error of ± 1µm of our measuring microscope.
- Only after 4 h etching do the tracks become measurable. Corresponding Z/β ~ 190
- So Z/β ~ 190 can be said to be the measurement threshold in PET.



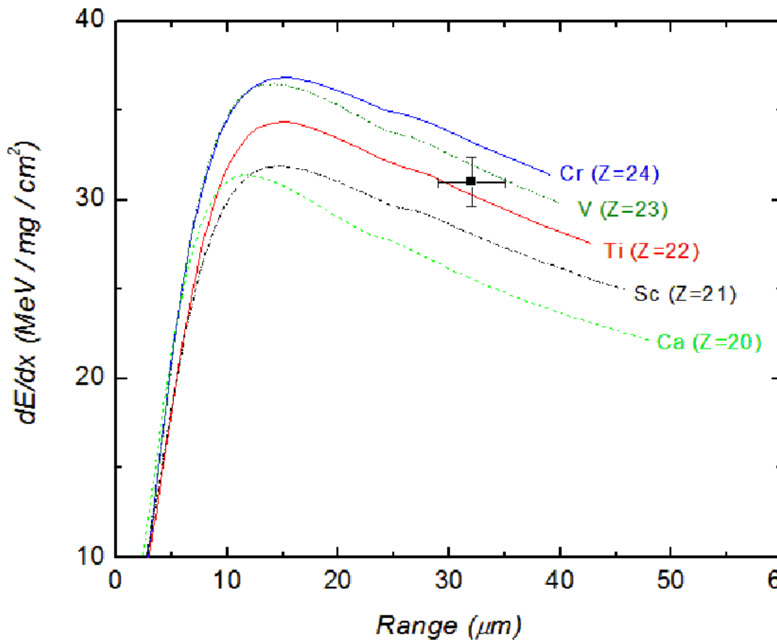


Calibration curve for PET

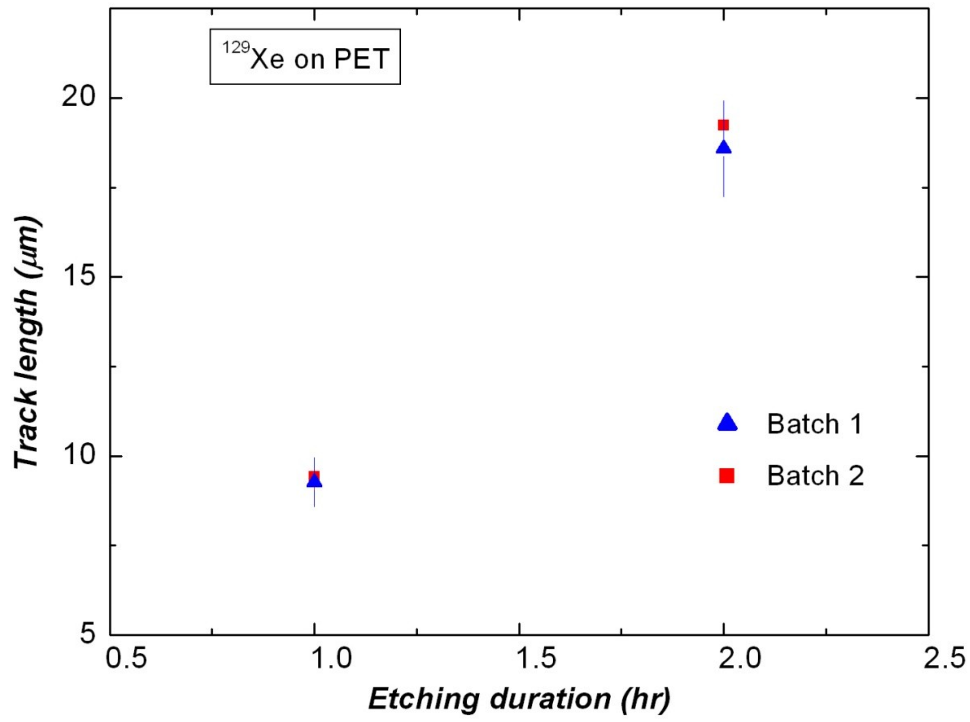


Charge and energy resolution of PET

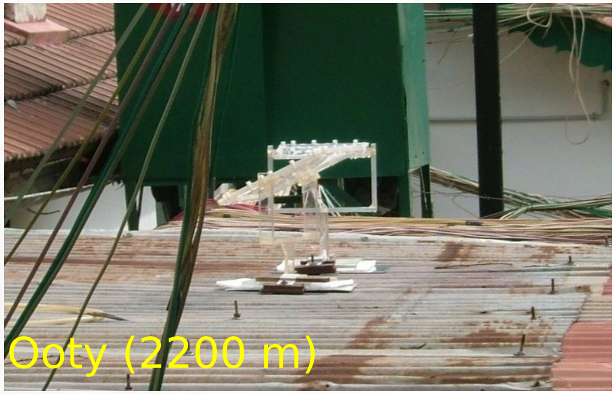
- The identification scheme applied to tracks of 2.82 MeV/u ^{49}Ti ions.
- Calibration curve without REX-ISOLDE data used.
- Charge Z could be ascertained with an accuracy of ± 1
- Corresponding incident energy is 2.61 ±0.24

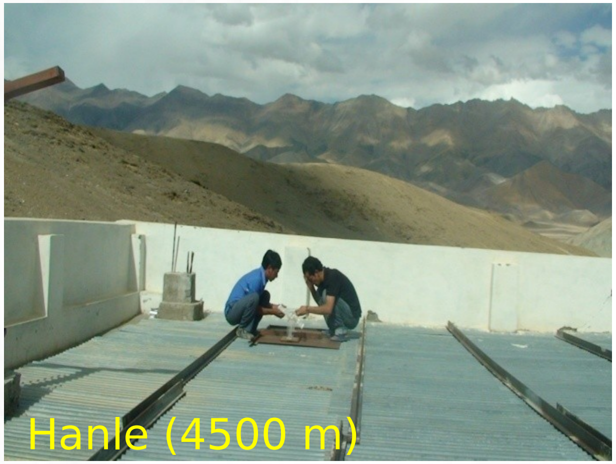


Response of PET from different batches (Procured 4 yrs apart)



Detectors given open air exposures





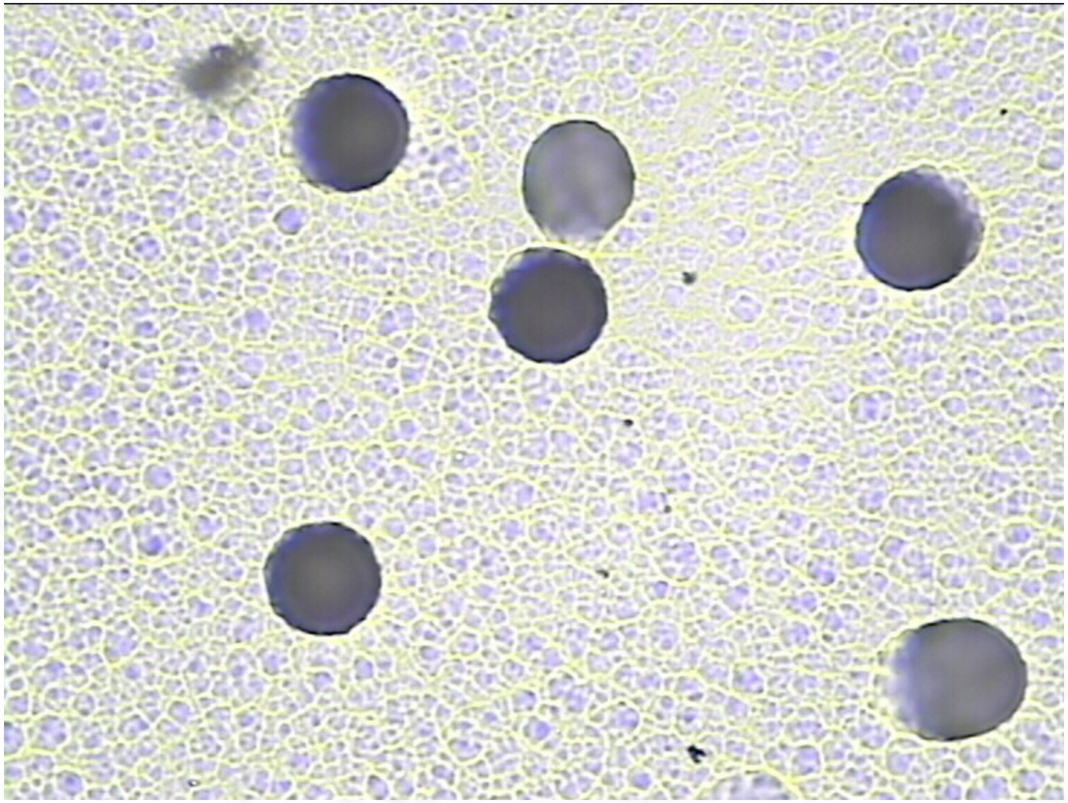
Some parameters of the exposure sites

Place	Altitude (a.m.s.l.) (m)	Mean Atmospheric Pressure (hPa)	Geographic latitudes and longitudes	Geomagnetic latitudes and longitudes
Darjeeling	2200	780	27.0º N, 88.3º E	17.6º N, 162.2º E
Ooty	2200	785	11.4º N, 76.7º E	2.9º N, 149.9º E
Hanle	4500	580	32.8º N, 75.9º E	24.2º N, 151.2º E

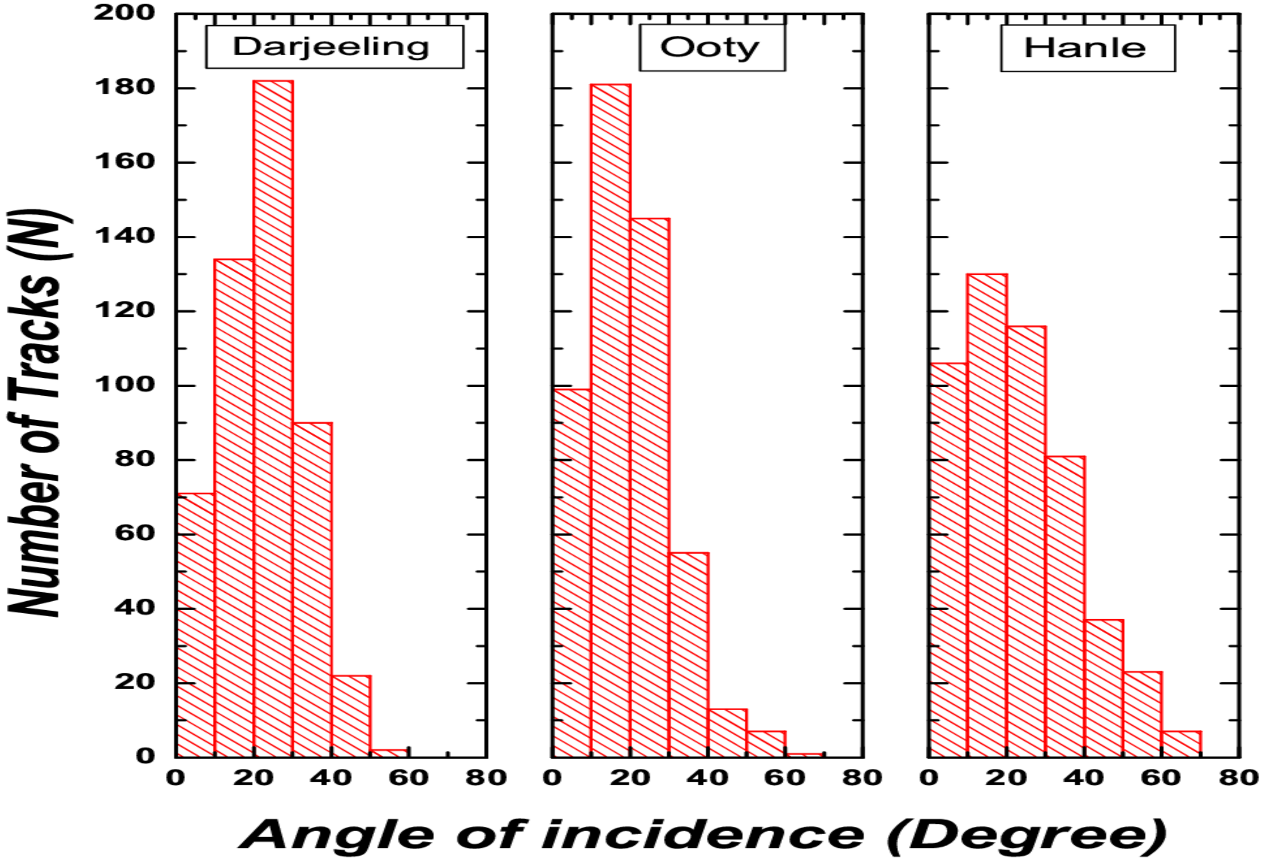
Bulk etch rates of CR-39 and PET

Place	Exposure Duration (Days)	V_B of CR-39 (µm/h)	V_B of PET (µm/h)
Darjeeling	532	11.7 ± 0.7	2.6 ± 0.15
Ooty	190	10.0 ± 0.6	2.2 ± 0.13
Hanle	320	11.5 ± 0.7	2.4 ± 0.13
Unexposed	-	1.4 ± 0.07	1.0 ± 0.05

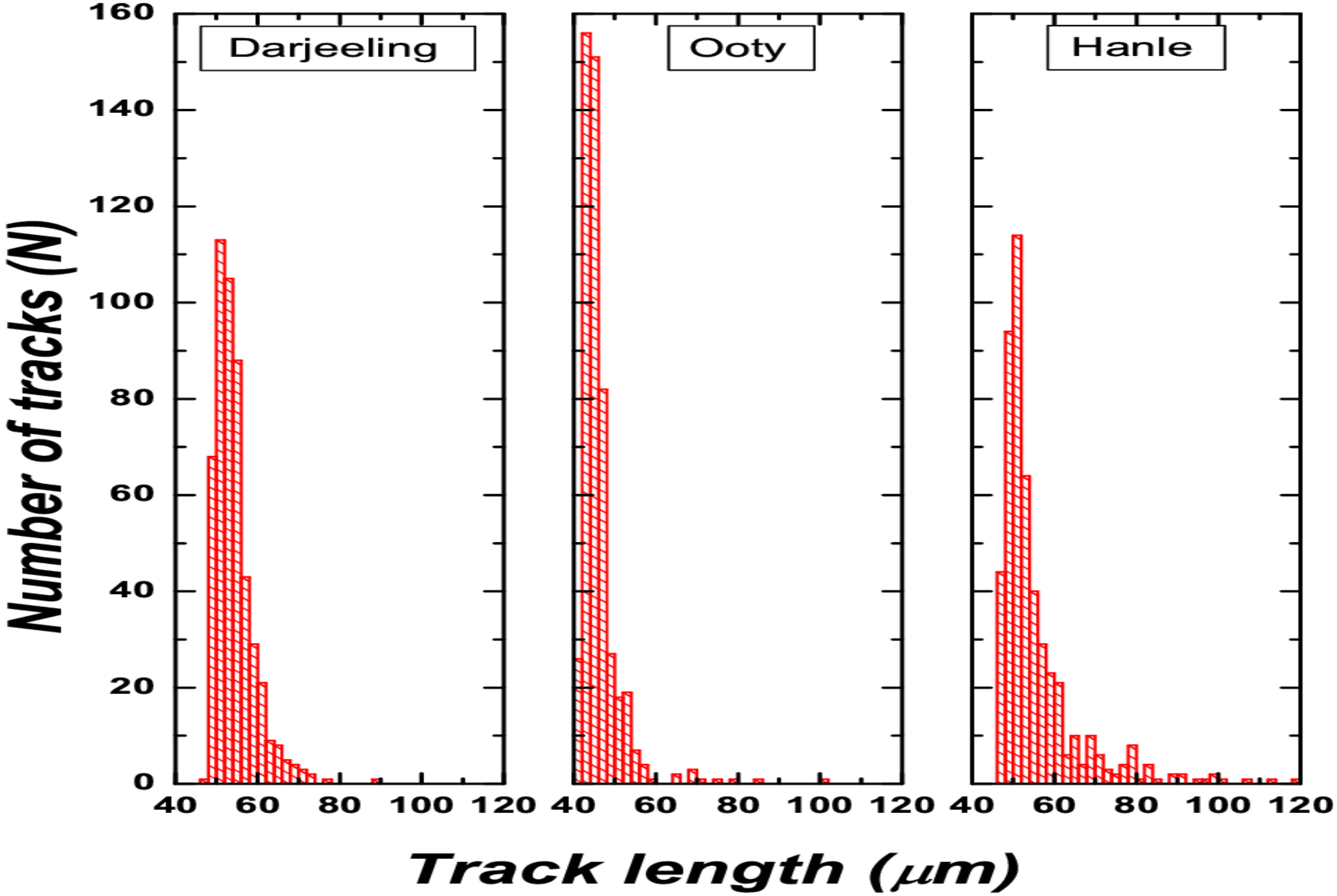
Tracks on CR-39 at Darjeeling



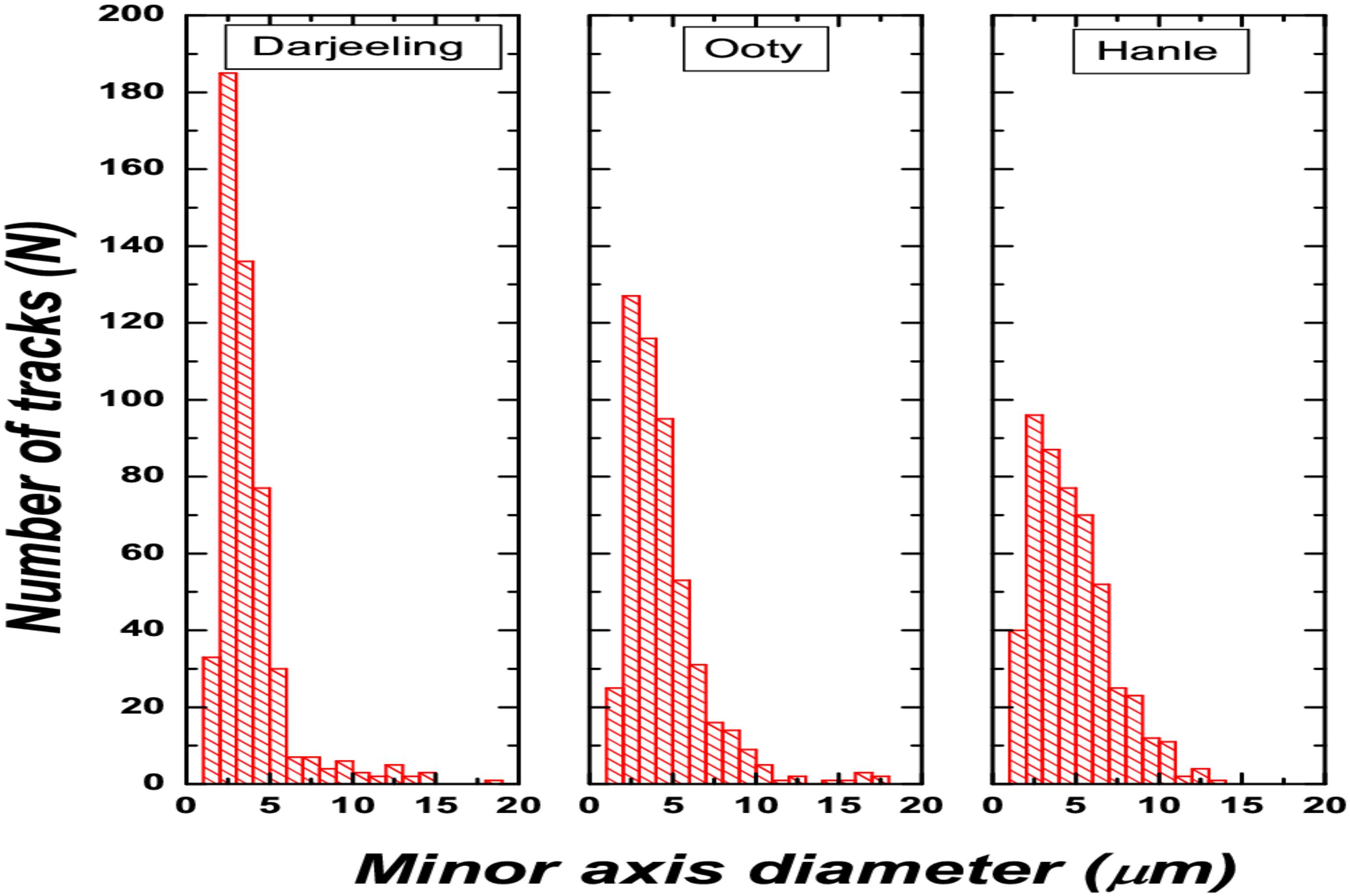
Distribution of angle of incidence of tracks on CR-39



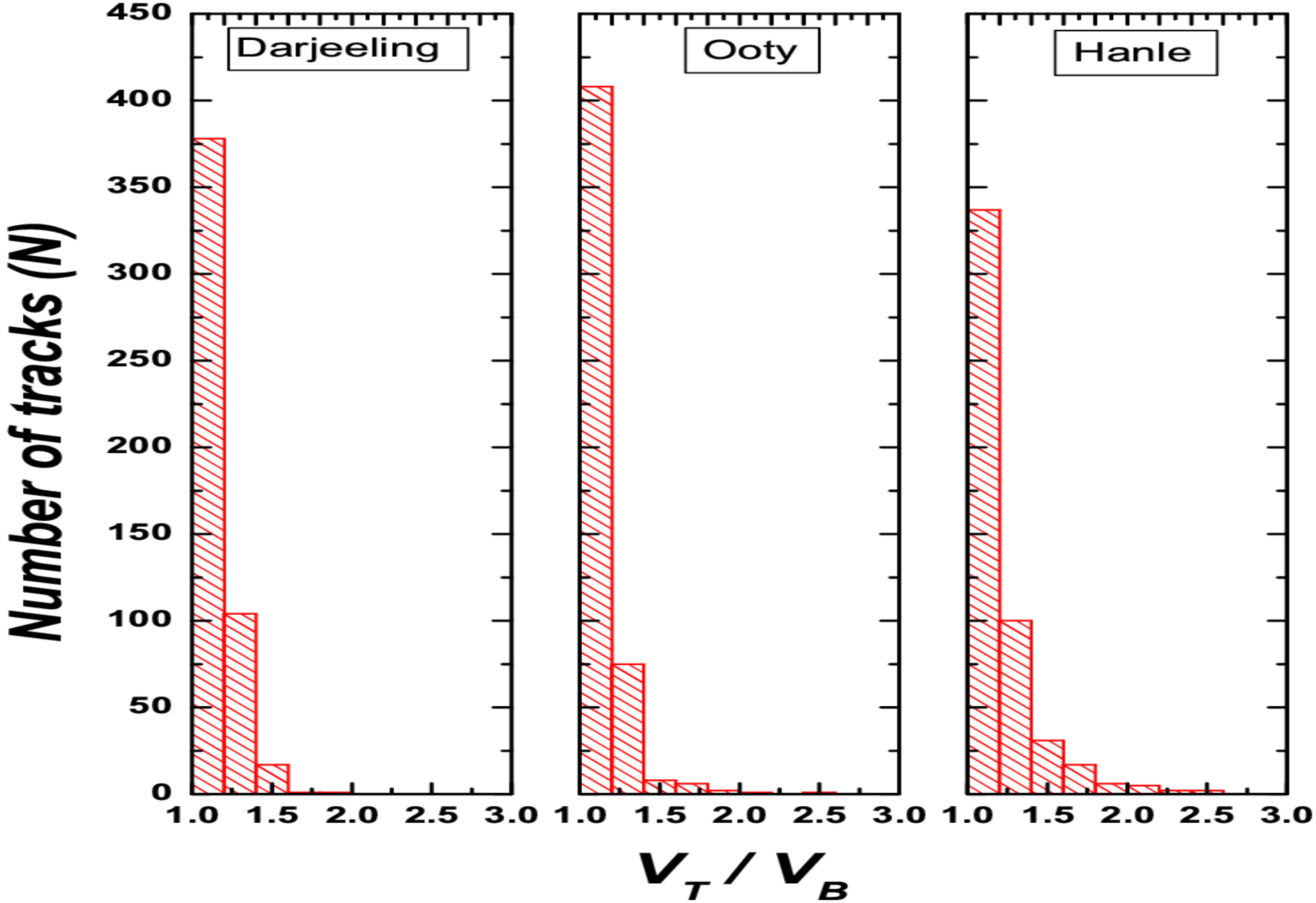
Distribution of minor axis diameter of tracks on CR-39 (Etching duration 4 h)



Distribution of minor axis diameter of tracks on CR-39
(Etching duration 4 h)



Distribution of V_T/ V_B values of the tracks recorded on CR-39

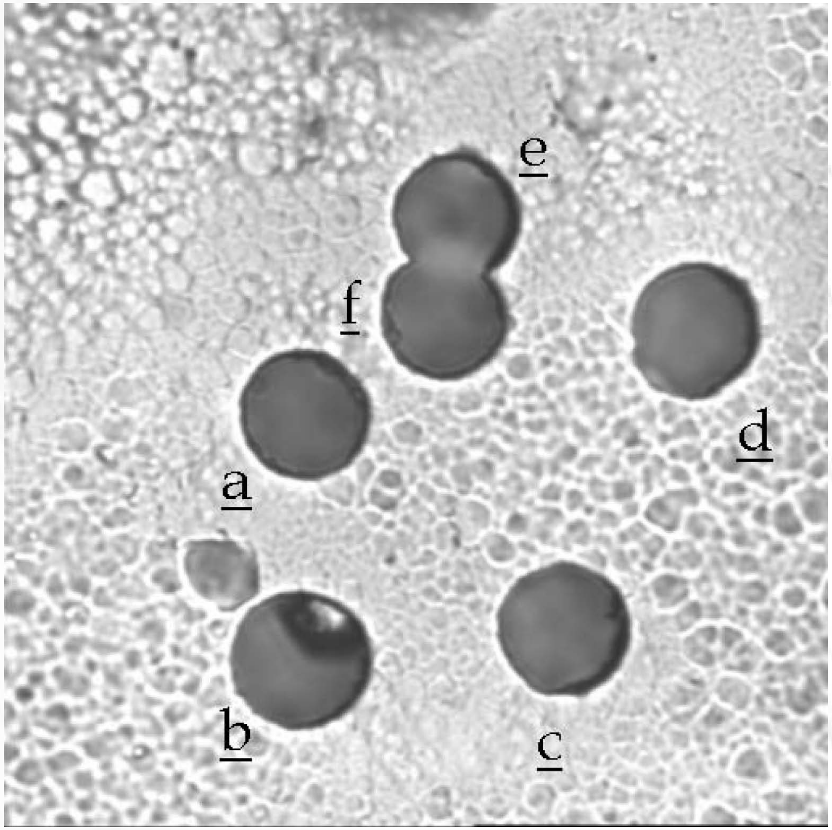


Flux recorded on CR-39 and PET

Place	Flux on CR-39 ($cm^{-2}\ s^{-1}\ sr^{-1}$)	Flux on PET ($cm^{-2}\ s^{-1}\ sr^{-1}$)
Darjeeling	6.0×10^{-4}	$< 1.0 \times 10^{-11}$
Ooty	1.3×10^{-4}	$< 4.1 \times 10^{-11}$
Hanle	4.6×10^{-4}	$< 2.4 \times 10^{-11}$

Unusual event on PET at Darjeeling

- Probability of six particles impinging one after another ~2.35 X 10^{-13}
- We therefore favor the conclusion that six tracks comprise a single event
- Charge of the particle corresponding to each of the six unusual tracks lies between Z = 18 to Z = 30
- If the six fragments indeed emanated from a single vertex, the parent particle would have Z ≥ 144
- Energy of particles ~ 1 MeV/n. This gives Z/β ~ 500



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Publications and patent

- Characterization and calibration of a SSNTD for heavy-ion detection and strangelet search in cosmic rays _ D. Bhowmik, S. Dey, **A. Maulik,** Sibaji Raha, S. Saha, Swapan K. Saha, D. Syam.
  Nuclear Instrum. and Meth. B 269 (2011) 197-201

- Calibration of a solid state nuclear track detector (SSNTD) with high detection threshold to search for rare events in cosmic rays _ S. Dey, D. Gupta, **A. Maulik**, Sibaji Raha, Swapan K. Saha, D. Syam, J. Pakarinen, D. Voulot, F. Wenander. ***Astroparticle Physics 34 (2011) 805 -808***

- Particle identification with polyethylene terephthalate (PET) detector with high detection threshold__S. Dey, **A. Maulik**, Sibaji Raha, Swapan K. Saha, D. Syam. ***Nuclear Instrum. and Meth. B 336 (2014) 163 -166***

- Observation of a rare cosmic ray event at mountain altitute___Basudhara Basu, Sibaji Raha, Swapan K. Saha, Sukumar Biswas, Sandhya Dey, **Atanu Maulik**, Amal Mazumdar, Satyajit Saha, Debapriyo Syam. . ***Astroparticle Physics 61 (2015) 88 - 92***

- Determination of the detection threshold for Polyethylene Terephthalate (PET) Nuclear Track Detector (NTD**)** __S. Dey, **A. Maulik**, Sibaji Raha, Swapan K. Saha, D. Syam. ***Nuclear Instrum. and Meth. B 370 (2016) 63 -66***

Indian patent application [No. 1473/KOL/2011] titled “A novel solid state nuclear track detector for charged particles” filed on 18 Nov. 2011

Thank you