Study of fusion of n-rich nuclei: ^{50}Ti + ^{208}Pb and ^{9}Li + ^{70}Zn

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Fusion reactions with n-rich nuclei

- Determination of P_{CN} for a “cold” fusion reaction: ^{208}Pb (^{50}Ti, 2n) ^{256}Rf
- A pilot study of ^{9}Li + ^{70}Zn fusion (along with an attempt at studying a ‘halo’ nucleus fusion: ^{11}Li + ^{70}Zn)

Determination of P_{CN} for a “cold” fusion reaction: $^{208}Pb\ (^{50}Ti,\ 2n)\ ^{256}Rf$

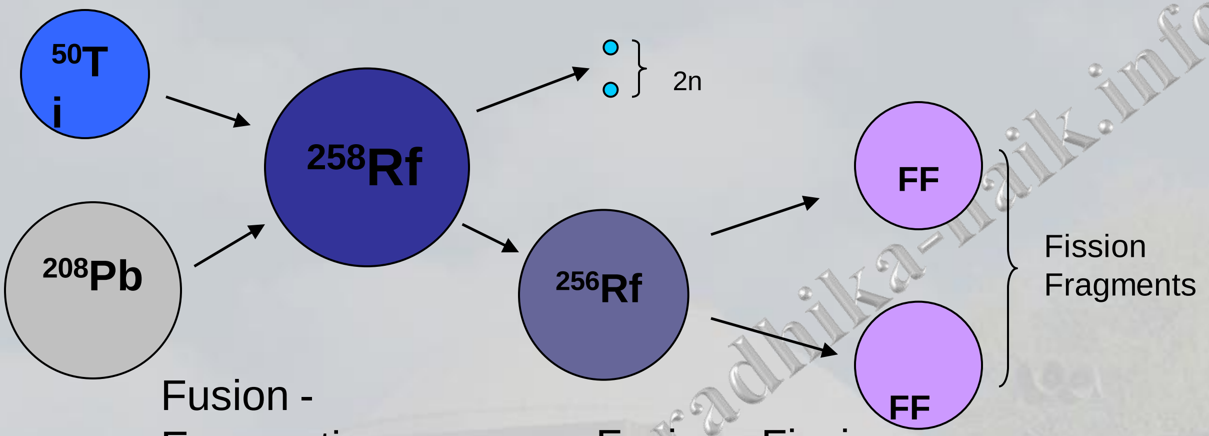
Two established ways of synthesizing new elements

- ‘Hot’ fusion involves an actinide target (Z=90 to 103) and a light projectile (Z=6 to 20).

  $E_{\text{compound nucleus}} \approx 50\text{-}60$ MeV.

- ‘Cold’ fusion which involves Pb or Bi target and a relatively heavier projectile, like Ti (Z=22).

  $E_{\text{compound nucleus}} \approx 10\text{-}15$ MeV.



^{50}Ti

^{208}Pb

^{258}Rf

2n

^{256}Rf

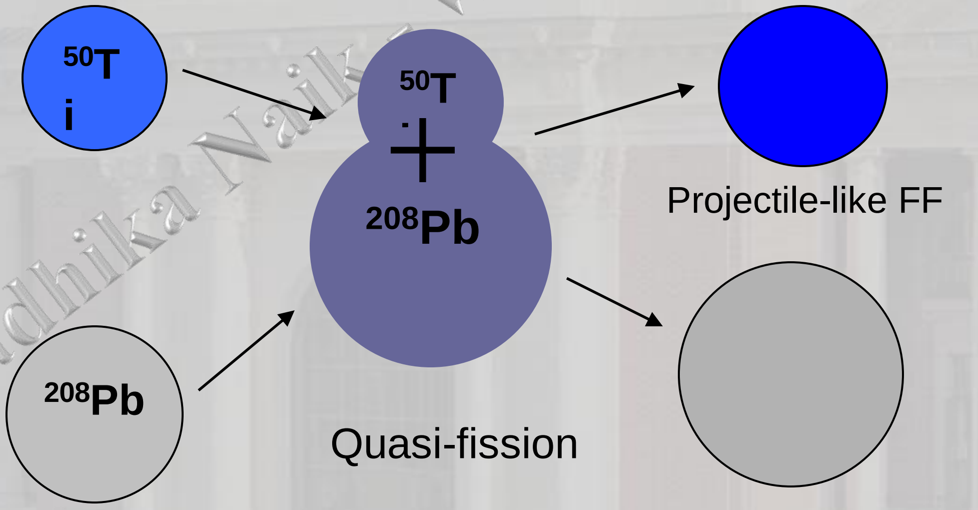
FF

FF

Fission Fragments

Fusion - Evaporation

Fusion - Fission



^{50}Ti

^{208}Pb

^{50}Ti + ^{208}Pb

Projectile-like FF

Quasi-fission

Target-like FF

- Cross section for producing a heavy nucleus in a heavy ion reaction is given by,

$$\sigma_{ER} = \sigma_c \times P_{CN} \times W_{sur}$$

where σ_C - Capture cross section
P_{CN} - Probability of formation of compound nucleus
W_{sur} - Survival probability of the excited nucleus

- In ‘cold’ fusion reactions, both the target and the projectile are of comparable mass (symmetric system). Therefore the Coulomb repulsion is significant and the chance of their coming together and forming a CN is a crucial factor. This makes the quantity P_{CN} more important for ‘cold’ fusion reactions.

Important facts about ^{208}Pb(^{50}Ti,2n)^{256}Rf reaction from previous studies

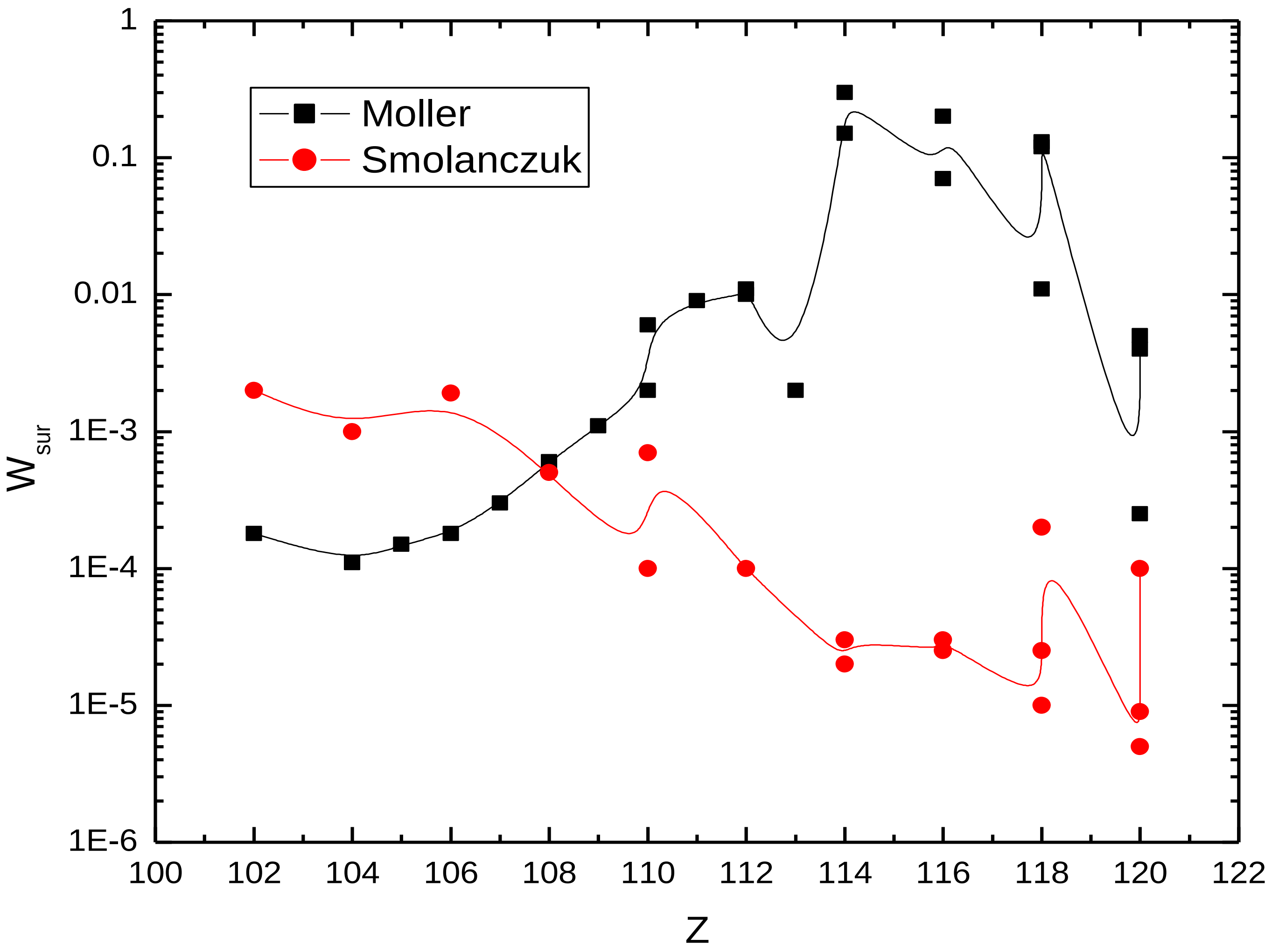
- This reaction produces a ‘cold’ Rf with higher W_{sur} and decaying by n-evaporation rather than by SF *(Ghiorso 1982).*
- The σ_{fus} can only be explained by the “extra push” theory of Swiatecki *(Clerc, Keller et al. 1984).*
- This system sometimes bypasses the complete fusion path and ‘quasi-fission’ takes place, making the calculation of σ_{fus} complicated *(Lützenkirchen, Kratz et al. 1986).*
- The values of σ_{EVR} for 1n, 2n and 3n excitations and of σ_c have been established *(Heßberger 1997, Clerc, Keller et al. 1984).*

Why the need to determine P_{CN}?

- The value of W_{sur} is based on Γ_n/Γ_f which in turn depends on the fission barrier of that reaction.

- Zubov *(Zubov, 1999)* calculated the W_{sur} using Γ_n/Γ_f given by both Smolańczuk and Möller methods.

- They differ by more than an order of magnitude for most of the heavy elements and show an opposite trend with increasing Z.


1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
W_{sur}
Moller
Smolanczuk
100
102
104
106
108
110
112
114
116
118
120
122
Z

Motivation behind the experiment

$$\sigma_{EVR} = \sigma_{C} * P_{CN} * W_{SUR}$$

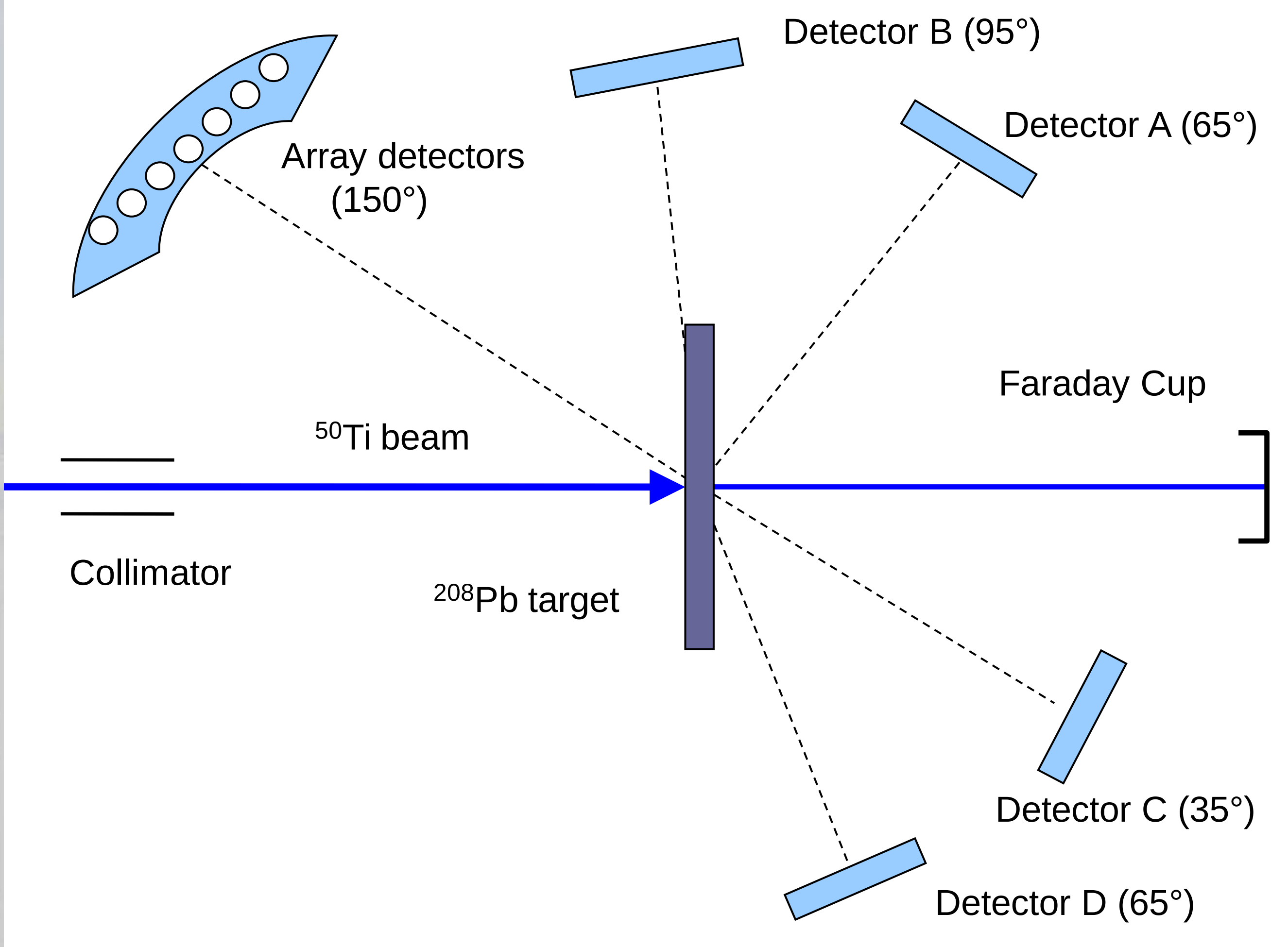
Determined by Heßberger *(Heßberger 1997)*

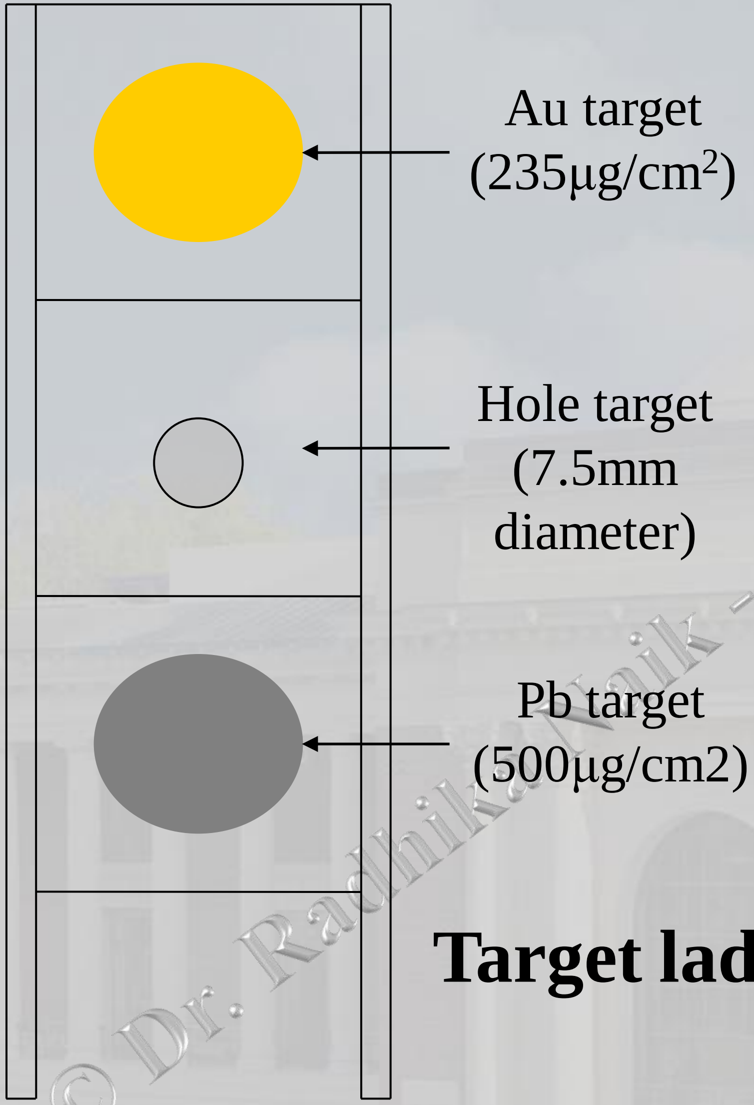
Determined by Clerc et al *(Clerc et al. 1984)*

We are trying to find the value of this quantity

Need to decide which method, Smolańczuk or Möller, is the correct one for determination of W_{SUR}.

Experimental setup



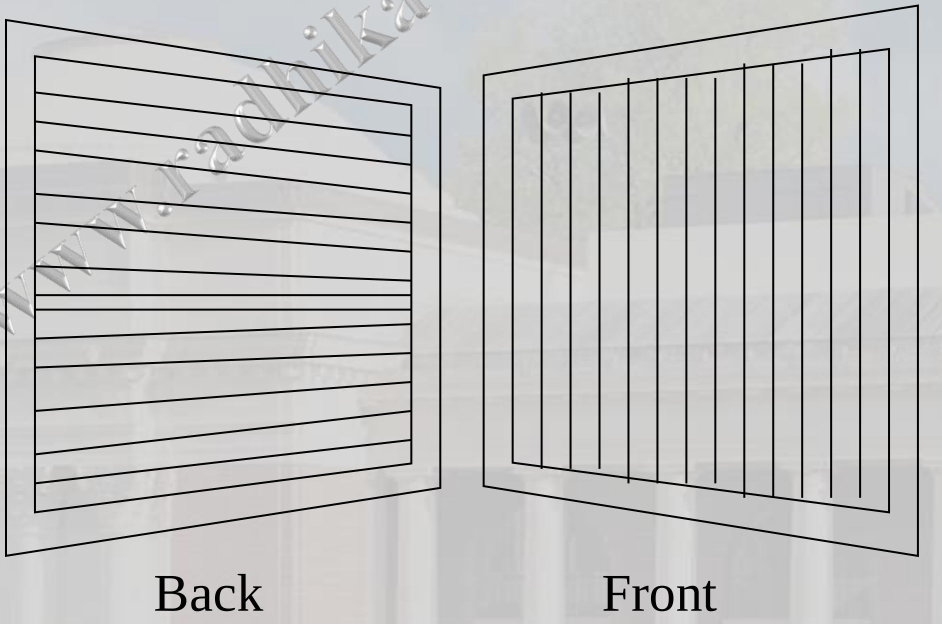

Au target
(235μg/cm^2)

Hole target
(7.5mm
diameter)

Pb target
(500μg/cm2)

Target ladder

Double sided strip detector (DSSD)



Details of the experiment run

- The ^{50}Ti beam was used at 5 different beam energies bracketing the maximum of excitation function, from 253 to 230 MeV.
- A potential of +10,000V was applied to the target ladder to prevent detector damage due to δ–electron bombardment.
- The experiment was begun with the calibration runs done with the SF source ^{252}Cf and with the impingement of ^{50}Ti beam on ^{197}Au target.
- First run with ^{50}Ti beam on ^{208}Pb target was performed in 'singles' mode and rest of the runs were performed as 'coincidence' runs.
- The target ladder as well as the detectors were moved through some angle intermittently from their original position to get a better angular distribution.

Data analysis

- The solid angles subtended by each detector at the centre of the target ladder were calculated using the formula,

$$Solid\ \ angle\ (\Omega) = \frac{A}{4\pi\ r^{2}}$$

- Energy loss due to beam passing through the half-thickness of the target was calculated using SRIM and UPAK softwares.

Pulse height defect (PHD)

- Heavily ionizing particles produce high density of electron-hole pairs which nullify the local charge created and therefore the ‘rise time’ of pulse is longer than usual.
- During this delay, electrons and holes get a chance to recombine making the collected charge less than created charge, shortening the ‘pulse height’.
- This is the Pulse Height Defect (PHD) which results in non-linear response of the detectors with increasing energy.
- PHD makes the calibration of detectors necessary. The Schmitt-Kiker-Williams (SKW) Calibration Method is widely used for this purpose.

SKW Energy Calibration

$a = 24.0203 / (P_L - P_H)$

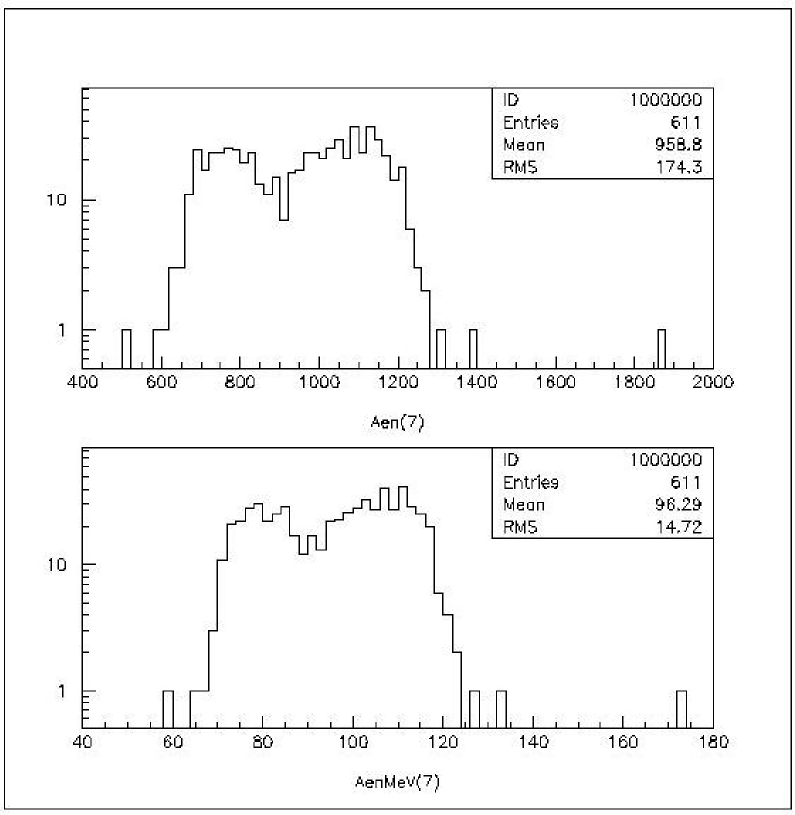
$a' = 0.03574 / (P_L - P_H)$

$b = 89.6083 – a * P_L$

$b' = 0.1370 – a' * P_L$

P_L – Pulse height for light fragment peak

P_H - Pulse height for heavy fragment peak



$$\mathbf{E_{(MeV)} = [a+(a'*M_{(amu)})]*P+[b+(b'*M_{(amu)})]}$$

Time Calibration

- Time (ns) = 0.72 * l_{cm} * $\sqrt{A/E}$

where l_{cm} – Distance of detector from target ladder
E – Energy of elastically scattered particle
A – Mass of the beam particle (50 amu)

- Calibration coefficient = $\dfrac{\text{Expected time (ns)}}{\text{Centroid channel \#}}$

Data analysis (contd.)

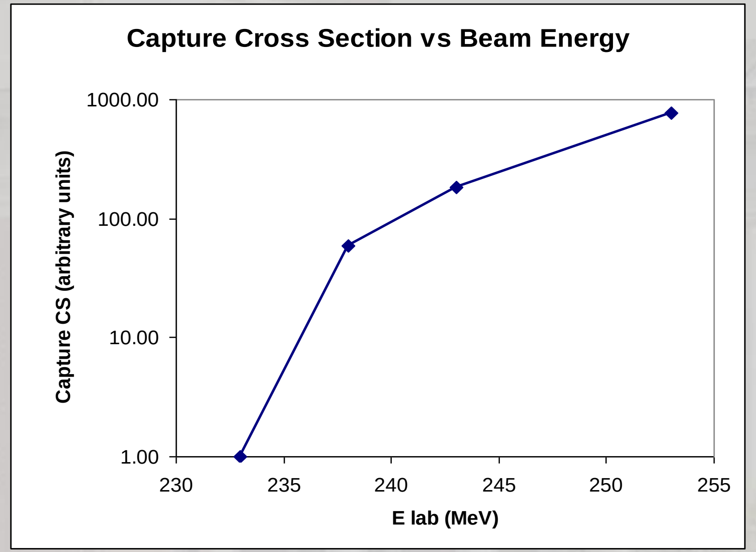
- Various parameters calculated or noted from the data, to be used in further data analysis were
  - Grazing angle (θ_{gr}) of the reaction
  - Fission fragment energy (E_{FF}) and folding angle (θ_{fld})
  - Expected elastic scattering cross section (σ_{elas}) and energy of scattered fragments (E_{elas})
  - Beam scalar for each run

Capture cross section

$$\sigma_c = \frac{Number\ of\ \ fission\ events}{\begin{pmatrix} Number\ \ of\ total\ \ particles\ in\ the\ run \\ \times Number\ of\ \ atoms\ in\ the\ target \end{pmatrix}} \times Various\ correction\ \ factors$$

$$(beam\ \ flux)\times(duration\ of\ \ run) = (beam\ scalar)\times\left(3\times10^{9}\right)$$

- E_{FF}'s and θ_{fld} were used for performing cuts on the E_1 vs E_2 spectra of ‘coincidence’ detectors to get the number of fission fragments.
- Due to large particle flux in beam one scalar was recorded for every $3x10^9$ particles hitting the Faraday Cup.
- The correction factors involved solid angle and detector acceptance correction, dead time in data acquisition etc.



Future work in analysis

- Calculating the σ_C considering the correction factors and in proper units of mbarns.
- Calculating the masses of products from energy-time correlation and check if they can be understood by the accepted Physics of the reaction.
- Fitting the angular distribution of σ_C to calculated values and determining the contribution of Quasi-fission process to σ_C.
- Determination of $\sigma_{\text{complete fusion}} = P_{CN}$ and therefore of W_{sur} using the equation $\sigma_{EVR} = \sigma_C * P_{CN} * W_{SUR}$

A pilot study of ^{9}Li + ^{70}Zn fusion

(along with an attempt at studying a ‘halo’ nucleus fusion: ^{11}Li + ^{70}Zn)

Why the ^{9}Li + ^{70}Zn system?

- The nuclear structure and reactions of ^{9}Li are of interest because
  - It is the core nucleus of 2n ‘halo’ nucleus ^{11}Li and therefore is important in understanding of ^{11}Li.
  - ^{9}Li is itself a very n-rich (N/Z=2) nucleus with a neutron skin.
  - It is well characterized with a simple Shell Model structure, which is helpful in modeling its interactions.

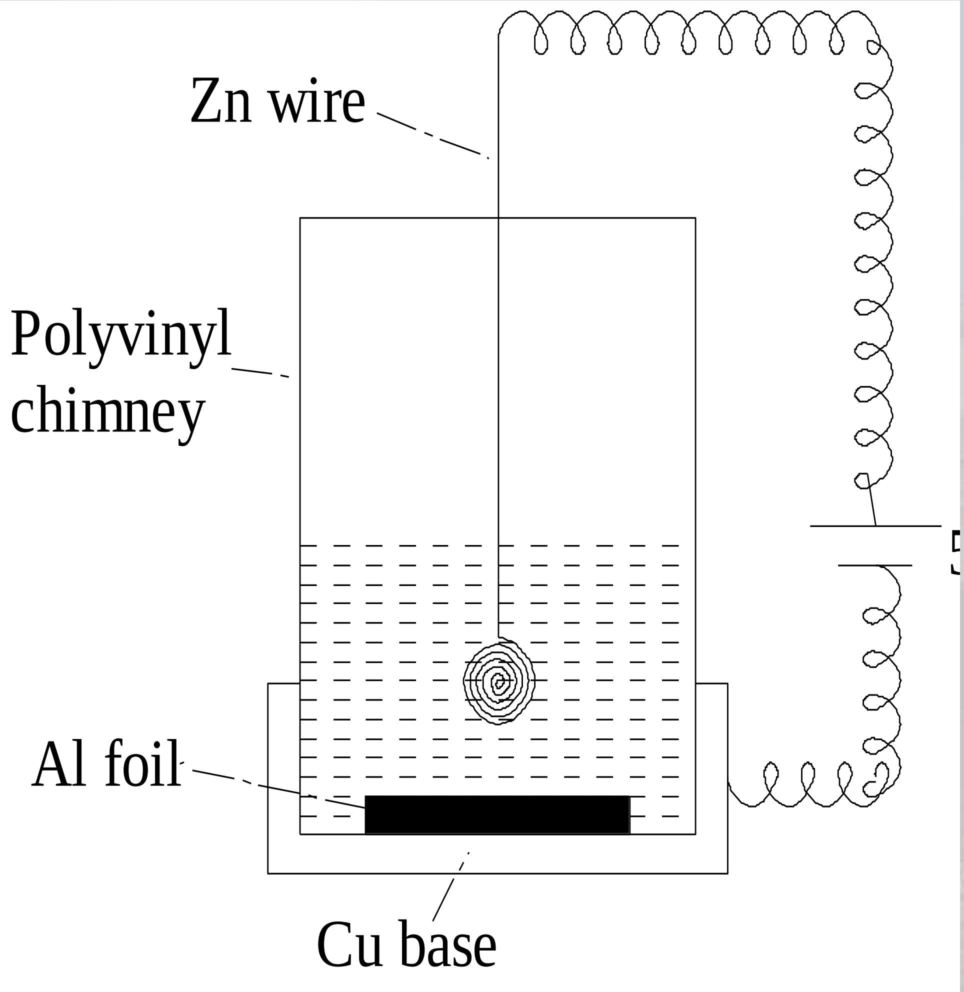
- Fusion of ^{9}Li has been studied at RIKEN
  - with Si at 11.2-15.2 A MeV but no information on σ_{fus} or analysis is available.
  - with ^{209}Bi at 36 MeV but σ_{fus} was not measured.

Why ^{9}Li + ^{70}Zn system? (contd.)

- ^{70}Zn was chosen as the target because
  - It is a n-rich nucleus and hence the reaction would give insight into the fusion of a very n-rich nucleus (N/Z=2) with a n-rich nucleus (N/Z=1.33).
  - The predicted evaporation residues (As and Ge) are easy to detect by radiochemical procedures.

Preparing Zn targets by electroplating

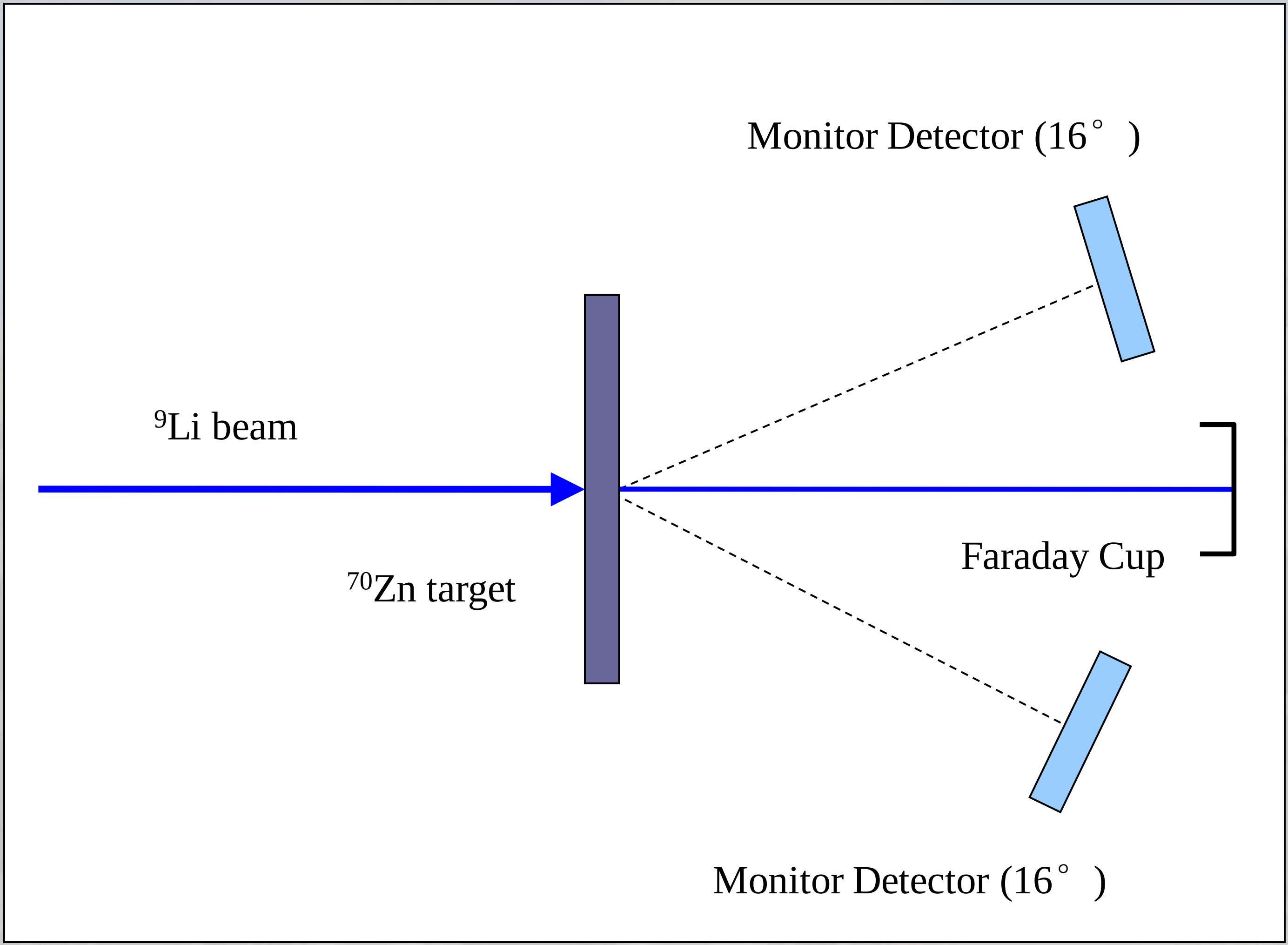
- Target area density ~ 0.8 - 1.1mg/cm^2
- Electrolyte : $ZnSO_4.7H_2O$, $Al_2(SO_4)_3.18H_2O$, NH_4Cl
- Zn wire : anode
  Al backing foil (0.54- 0.71 mg/cm^2): cathode



Extraction of As and Ge from the irradiated target and their separation

- Irradiated target was dissolved in HCl, 1 ml each of the As and Ge standard carriers were added to it.
- AsI_3 and GeI_4 were formed with Hydriodic Acid (HI) added.
- They were then extracted with Chloroform ($CHCl_3$), AsI_3 first and then GeI_4.
- H_2S passed through them, As_2S_3 and GeS_2 formed, filtered, dried and counted.
- Average yields were 63% and 22% for As and Ge, respectively.

Experimental setup at TRIUMF



Experiment setup details

- The experiment was done in Aug-Sept 2005 and May-June 2006.
- ^{9}Li beam was produced by striking a Ta metal target with proton beams at 50-85 μA, which was then mass-separated and accelerated.
- The runs with ^{9}Li beam were done at 7 different energies from 11.5 to 15.4 MeV.
- A shield of 5% boron-loaded paraffin was used to protect from delayed neutrons emitted from ^{9}Li.
- The Faraday Cup as well as two Si detectors at $^{+}$/-16.2° w.r.t. beam (measuring elastically scattered nuclei) were used to monitor the beam intensity.

Experiment run details

- Target irradiated for 1-3 days, then γ-counted for 1 day, As and Ge were separated chemically and then β-counting was done on the precipitates.
- Efficiency of Ge γ-detector was ~80% of NaI and the Low Background β-counter was ~53% efficient.
- The spectra obtained from both counting were analyzed using DECHAOS software.
- The β-decay of As and Ge samples was followed for several days to establish the identity of the isotope being detected.

Calculation of cross sections

- The production cross section (σ_{prod}) was calculated using the formula,

$$\sigma_{prod} = \frac{A}{n\phi\left(1 - e^{-\lambda t_i}\right)\left(e^{-\lambda t_d}\right)}$$

where, A – Activity

n - # of target atoms

Φ – Beam flux

λ – Decay constant

t_i – Duration of irradiation

t_d – Time after EOB when counting was started

- The σ_{prod} was calculated based on both β and γ counting, and then averaged over both.

Calculation of cross sections (contd.)

- The corrections applied for the calculation of production cross section (σ_{prod}) were
  - Chemical yields of As and Ge.
  - Branching ratios of isotopes involved, if any.
  - Efficiencies of the two detectors.
- The fusion cross section (σ_{fus}) was calculated after correcting σ_{prod} for unobserved products. This correction was ratio of σ_{fus}/ $\sigma_{As\text{-}76}$ as computed by PACE4.13 and HIVAP codes.

Fitting data with Wong formula

- The Wong formula represents the fusion barrier as a parabola and in a semi classical expression, gives fusion cross section as,

$$\sigma_W = \frac{\hbar\omega_B R^2{}_B}{2E} \ln\left\{1 + \exp\left[\frac{2\pi}{\hbar\omega_B}\left(E - V_B\right)\right]\right\}$$

where V_B - height of fusion barrier (MeV)

R_B - fusion radius (fm)

$\hbar\omega_B$ – barrier curvature (MeV)

- We fit data by fixing value of V_B=12.5MeV and varying R_B and $\hbar\omega_B$. This gave R_B=12.1+/-1.0fm, a value substantially larger than simple touching radius (7.44fm).

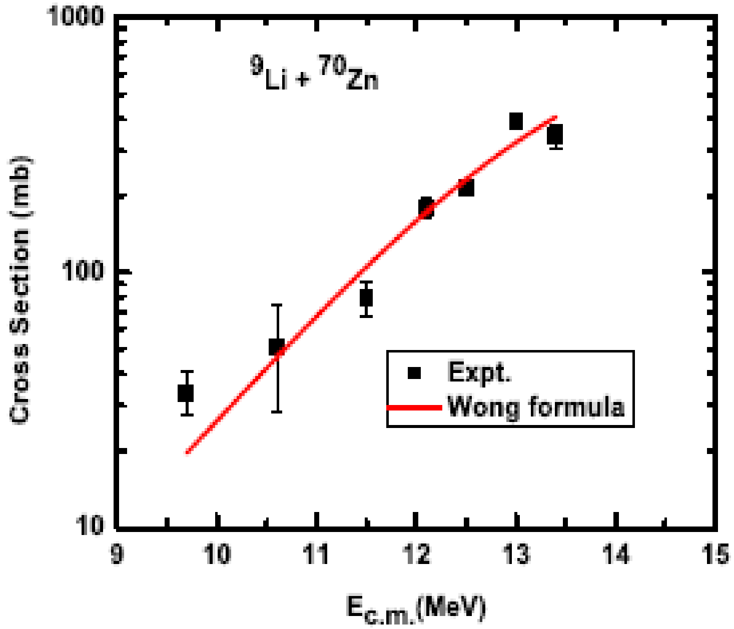


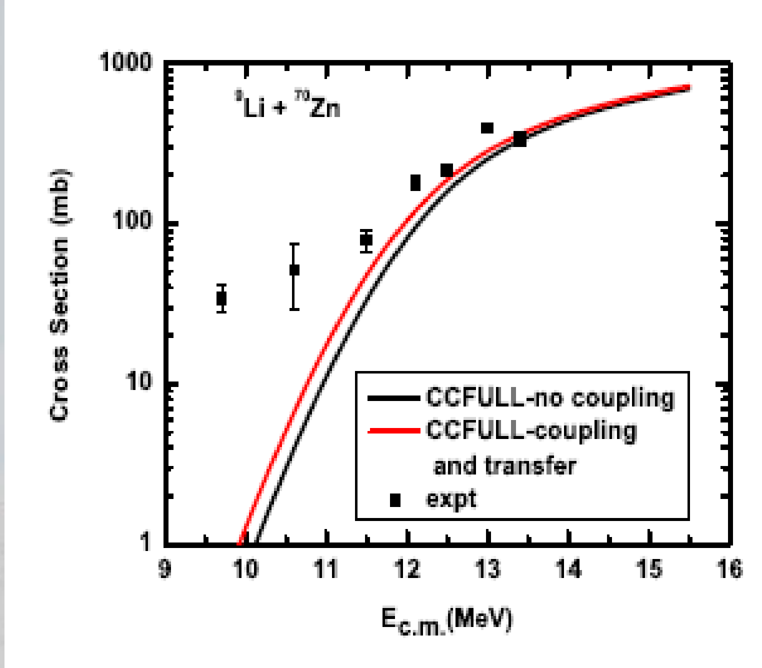
FIG. 2: The measured fusion excitation function for the ^{9}Li + ^{70}Zn reaction. The line is the result of fitting the data with the Wong one-dimensional barrier penetration model with $V_B = 12.5$ MeV, $R_B = 12.1 \pm 1.0$ fm and $\hbar\omega = 5.7 \pm 0.8$ MeV

Reasons to expect a large R_B

- Following factors make us expect such a large value for the fusion radius (R_B)
  - ^{9}Li has a neutron skin of thickness 0.48fm.
  - Density distribution of ^{9}Li shows a significant tail with ρ=10-^{4} nucleon/fm^{3} at 6.5fm.
  - It is described in the Shell Model as combination of ^{4}He, ^{3}H and 2n.
  - The Q value for 2n transfer (^{9}Li + ^{70}Zn → ^{7}Li + ^{72}Zn) is large (+8.612MeV)

- Hence this large R_B value presumably reflects interaction of large tails of ^{9}Li density distribution with that of ^{70}Zn.

Sub-barrier enhancement in σ_{fus}



- There is a sub-barrier fusion enhancement with ^{9}Li which cannot be explained by the Coupled Channel calculations.
- This fact will complicate the explanation of the sub-barrier fusion enhancement seen in ^{11}Li fusion.
- The view that enhancement is due to the 2 ‘halo’ neutrons might not be true anymore as the ^{9}Li core itself shows enhancement.

Conclusions

- Fusion excitation function shows a large sub-barrier enhancement, not accounted for by current CC calculations.

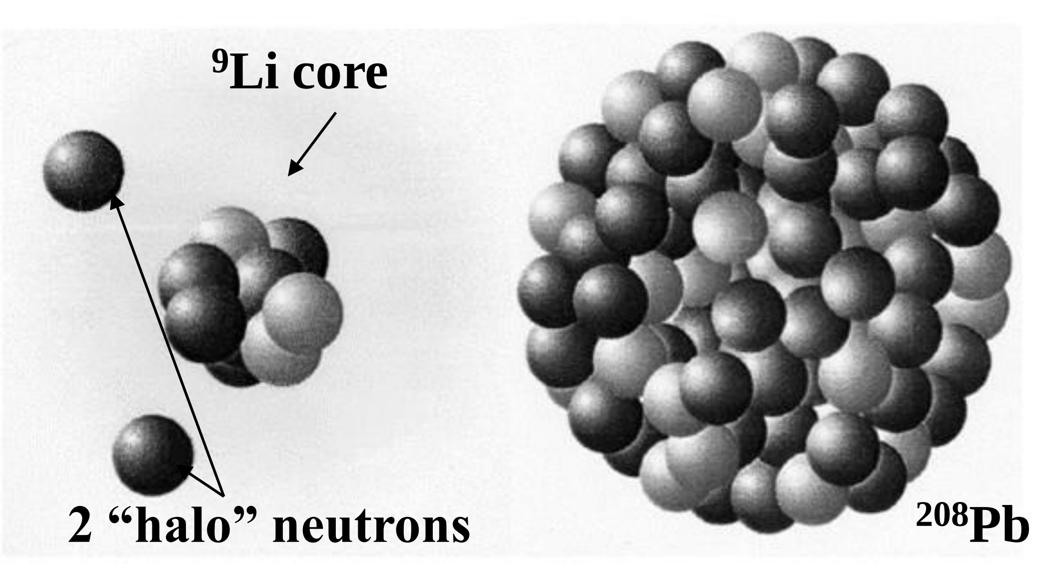
- The large fusion radius R_B=12.1fm, deduced from data-fitting by Wong formula, may be due to the neutron skin and extended neutron density distribution.

- Analysis of ^{11}Li fusion enhancement will need to take into account the sub-barrier fusion enhancement due to ^{9}Li core.

Fusion of Halo Nucleus: ^{11}Li + ^{70}Zn

- Some of the n-rich nuclei, especially the lighter ones, tend to show a peculiar nuclear structure and hence are called ‘Halo nuclei’.

- The ^{11}Li nucleus is ^{9}Li core with two halo neutrons and has a radius which is almost equal to that of ^{208}Pb.



Fusion with Halo nuclei

Theoretical contradictions	Experimental contradictions
•Enhancement near or sub-barrier due to lower Coulomb barrier and Soft Dipole Mode	•Enhancement : ^{11}Be (Munich) : ^{6}He (Dubna)
•Lowering above barrier due to breakup of nucleus into ‘core’ and separated ‘halo nucleons’	•Lowering : ^{11}Be (RIKEN) : ^{6}He (Kolata et. al.)

Attempt at ^{11}Li + ^{70}Zn fusion

- Three irradiations were done, two at 17.5 MeV and one at 16.5 MeV.

- Average on-target beam intensities were 680 (2005) and 740 particles/s (2006).

- Detection of EVR’s, even with radiochemical techniques, is very difficult.

- Available beams of ^{11}Li are not sufficiently intense to do fusion studies.

Thank you

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