Multi-nucleon transfer: a probe to investigate the reaction mechanism around Coulomb barrier

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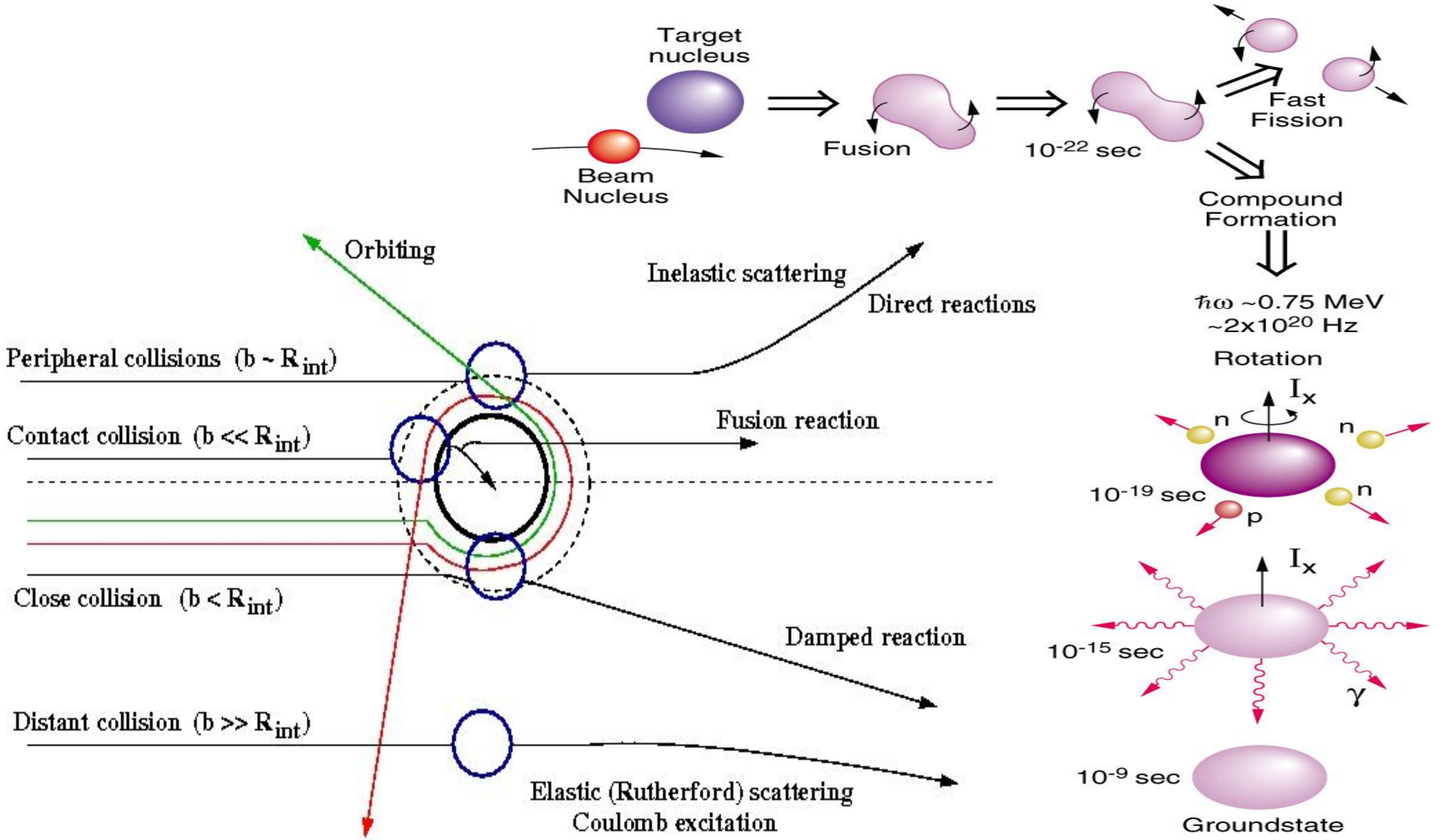
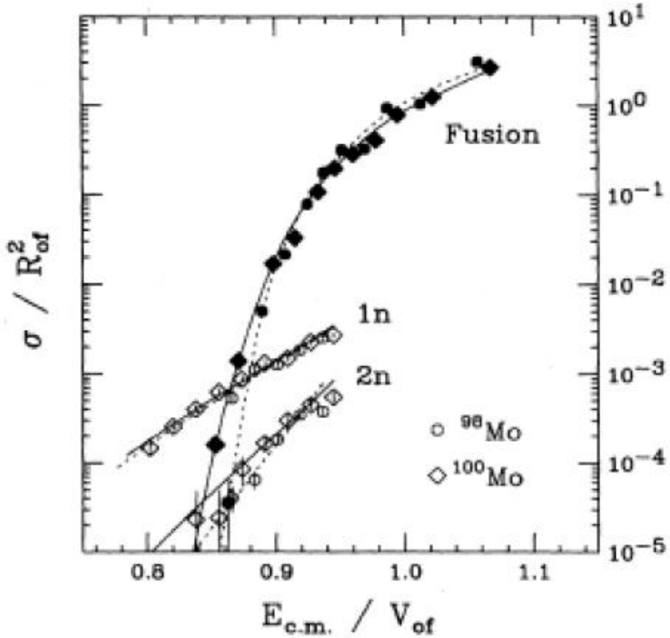
Future Plan with Radioactive ion beam' (FPRIB2012) at Saha Institute of Nuclear Physics from 16 -18, April, 2012

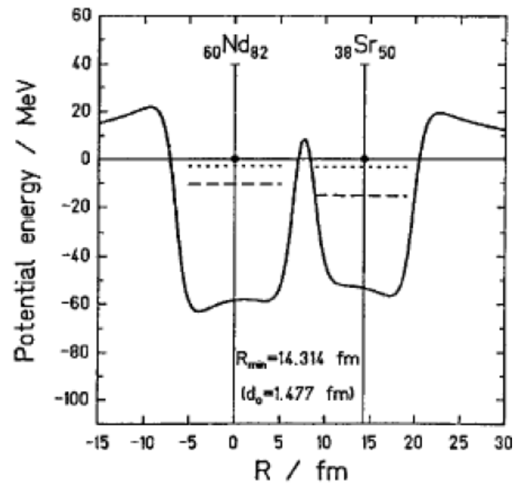
Nuclear Reaction



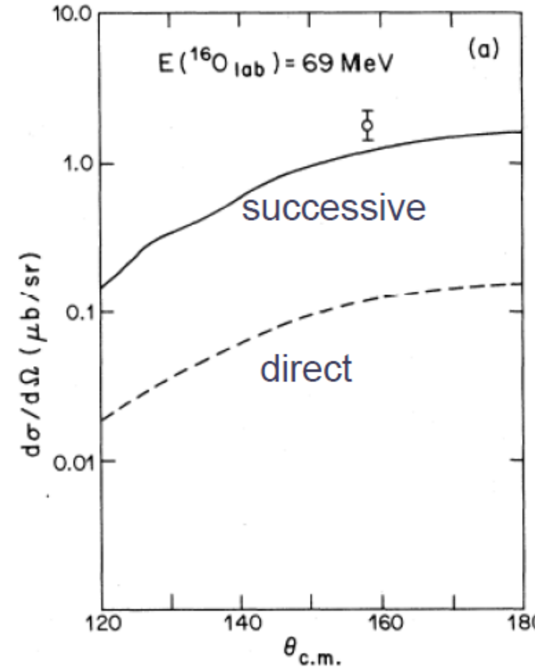
Multinucleon transfer reaction

Transfer & Fusion
in an overlapping
zone

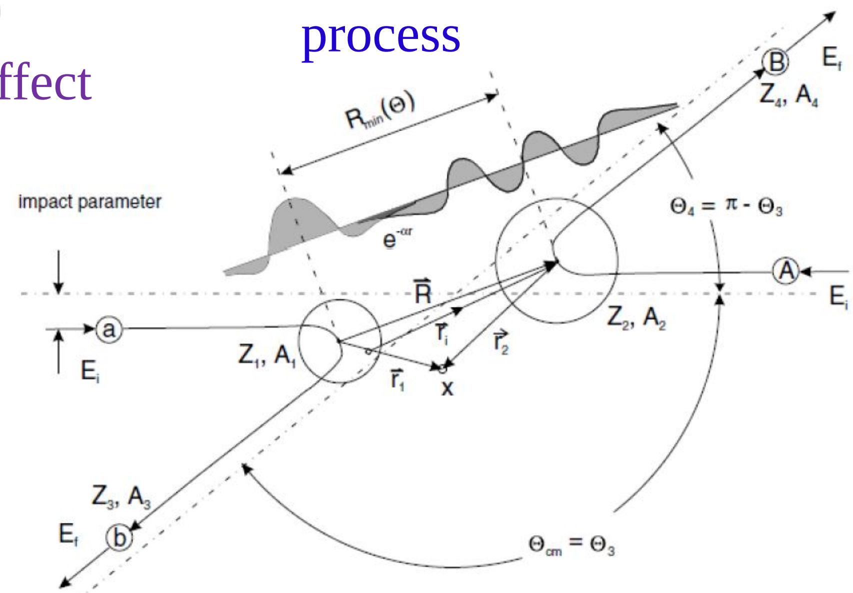




Tunneling effect



Single & multi step
process



Recent Interest:

Multi-neutron transfer will give access to very neutron-rich nuclei.

Spectroscopic tool for nuclei far off stability. Because of long range and the non-locality of the form factors

→ coupled reaction channels method is mandatory.

The role of the pairing interaction in states with low binding energy

→ information on the pairing interaction at low densities.

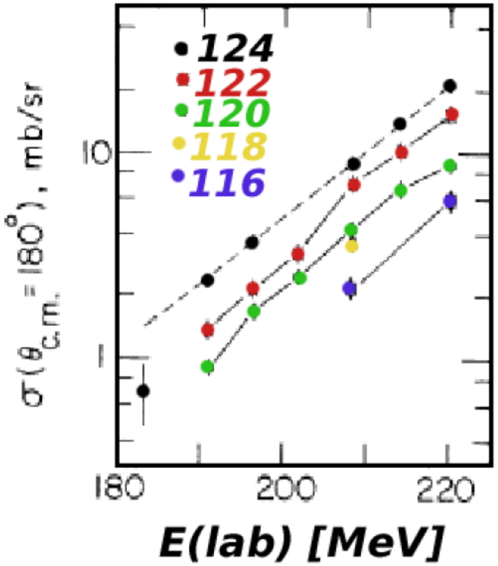
The effect of the continuum and the role of coupling to collective low-lying vibrations of the core in weakly bound systems need to be clarify.

In two-nucleon stripping

→stable targets & projectile with low binding energy of the nucleon pairs in exotic nuclei

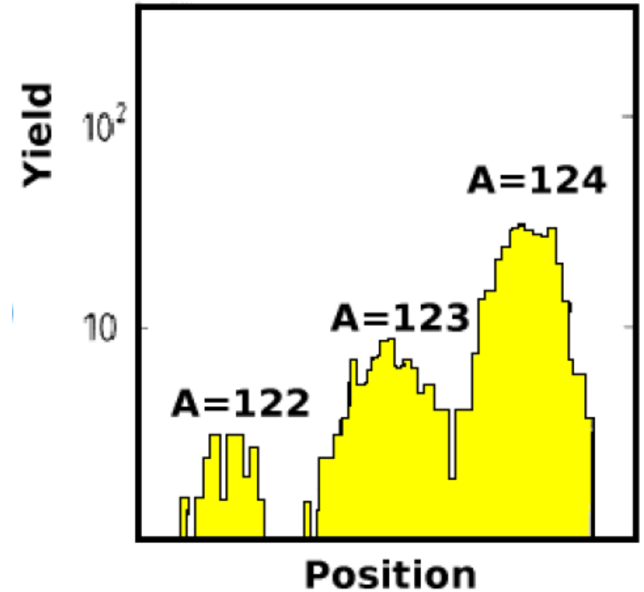
→ favour population of pairing states in the final nucleus close to the particle → matching condition

→These states are expected to have different and new collective properties. Some information on the predicted giant pairing vibrations .



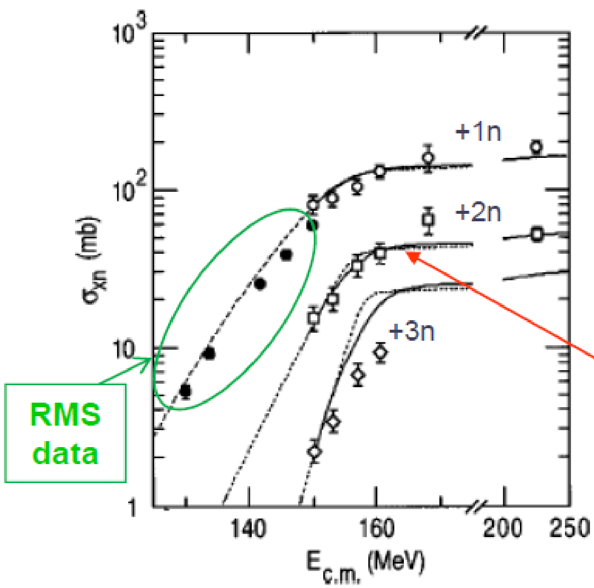
$$\alpha = \sqrt{\frac{2\mu B}{\hbar^2}}$$

$$\frac{P_{tr}}{\sin(\theta_{c.m.}/2)} \propto \exp(-2\alpha D)$$

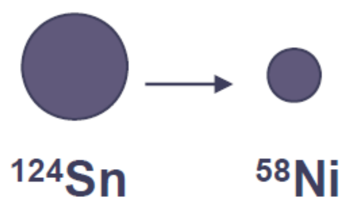


R.Betts et al., PRL59(1987)978

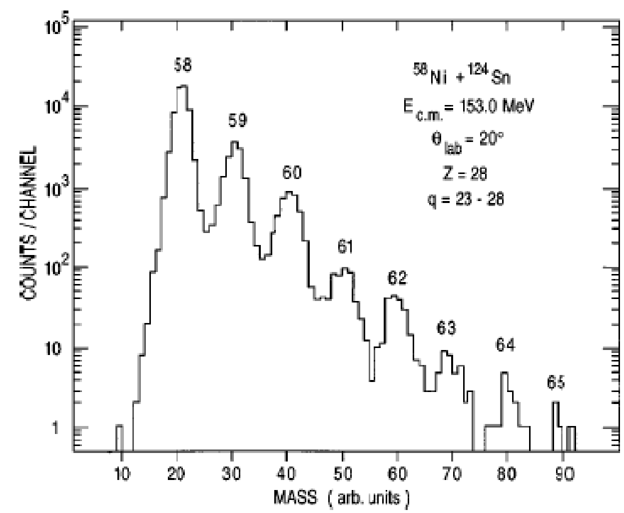
Successive & Pair transfer



H.Esbensen et al., PRC57(1998)2401



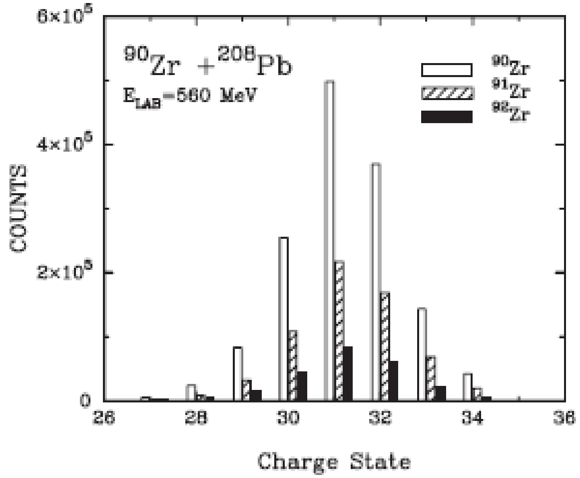
$$F_{2n}(r) = \alpha_{2n} V_0 \frac{d}{dr}\left[1 + \exp\left(\frac{r - R_0}{a_{2n}}\right)\right]^{-1}$$

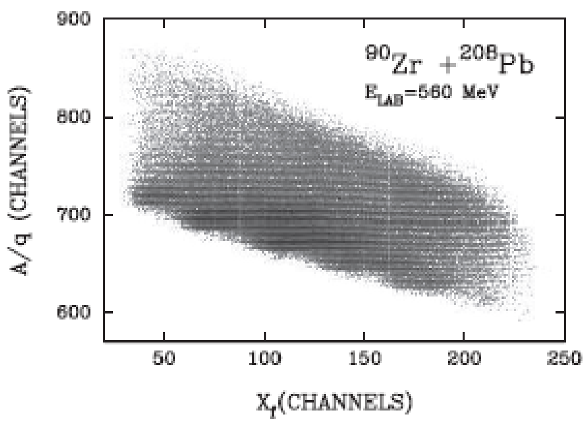


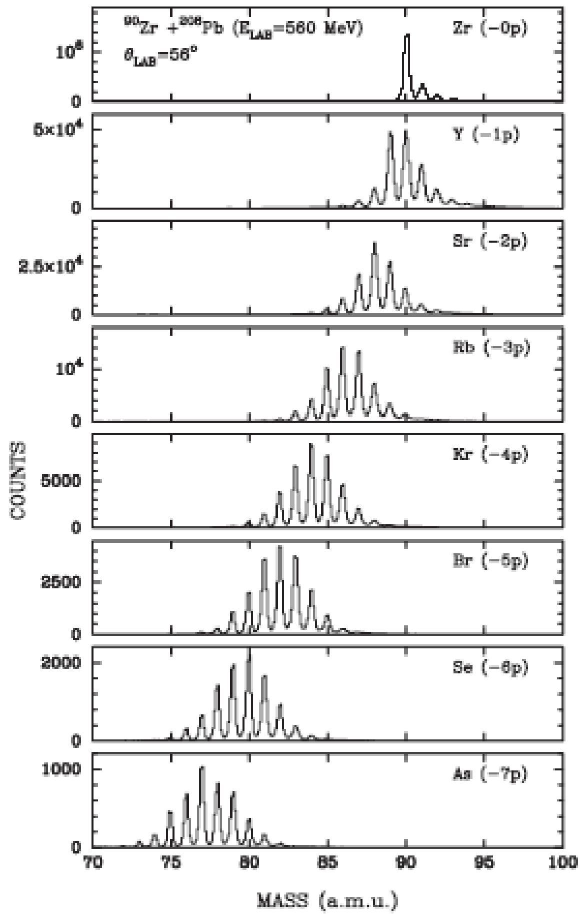
C.L.Jiang et al., PRC57(1998)2393

$^{90}Zr+^{208}Pb$

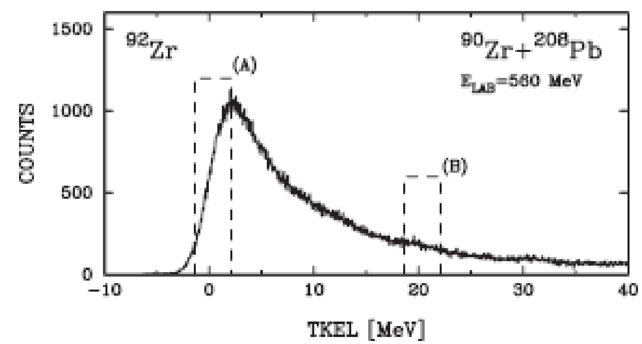
$E_{lab} = 560$ MeV

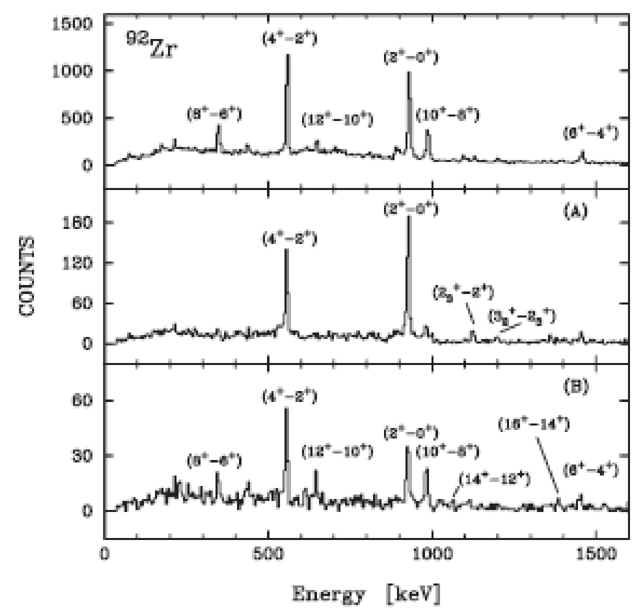






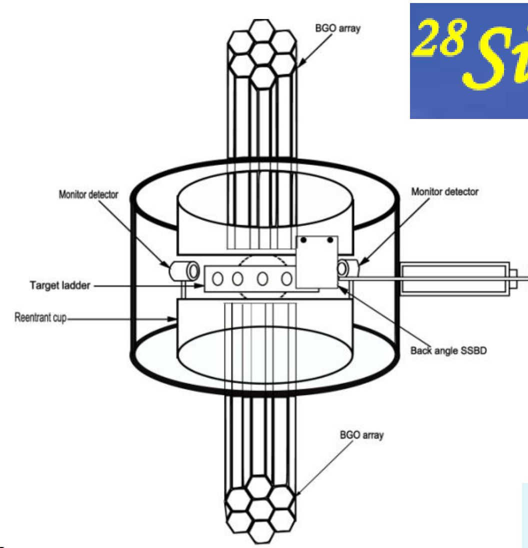
^{92}Zr





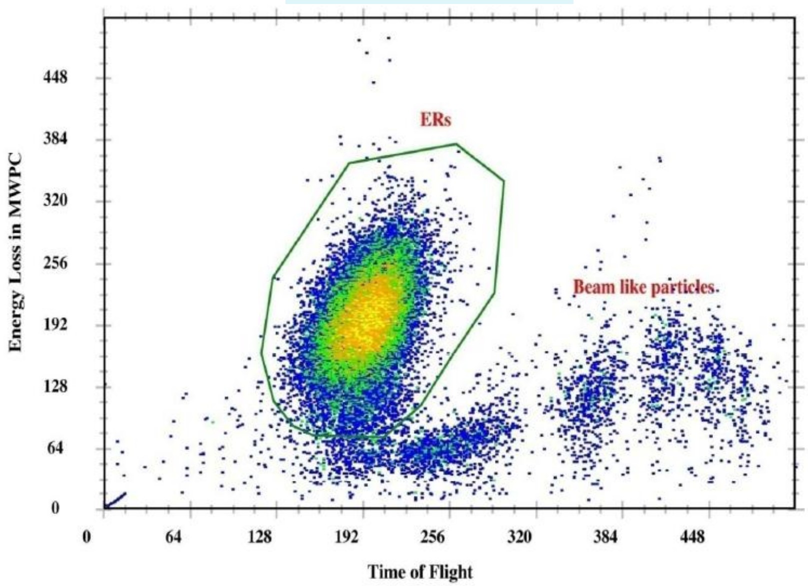
L. Corradi et al. J. Phys G 36 (2009) 113101

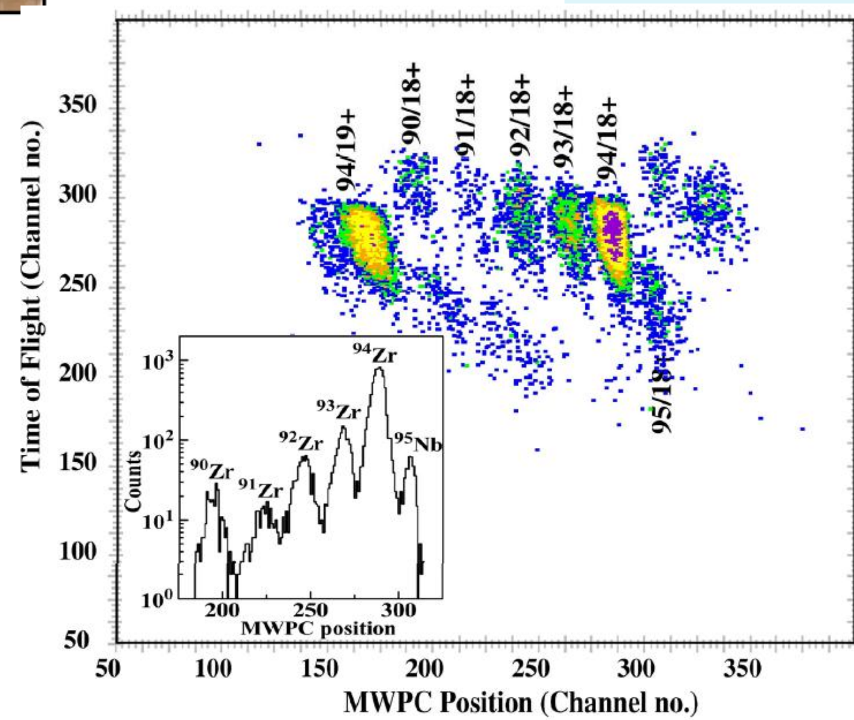
$^{28}Si + ^{90,94}Zr$



Transfer

Fusion

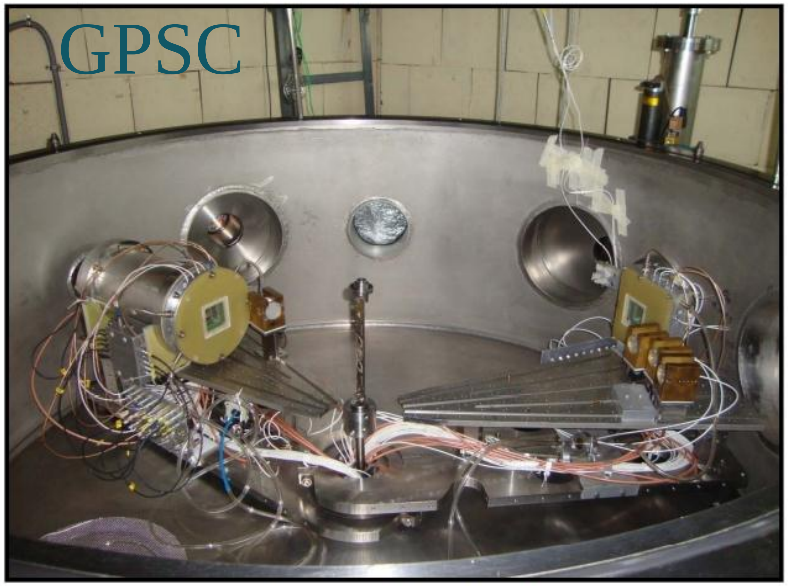




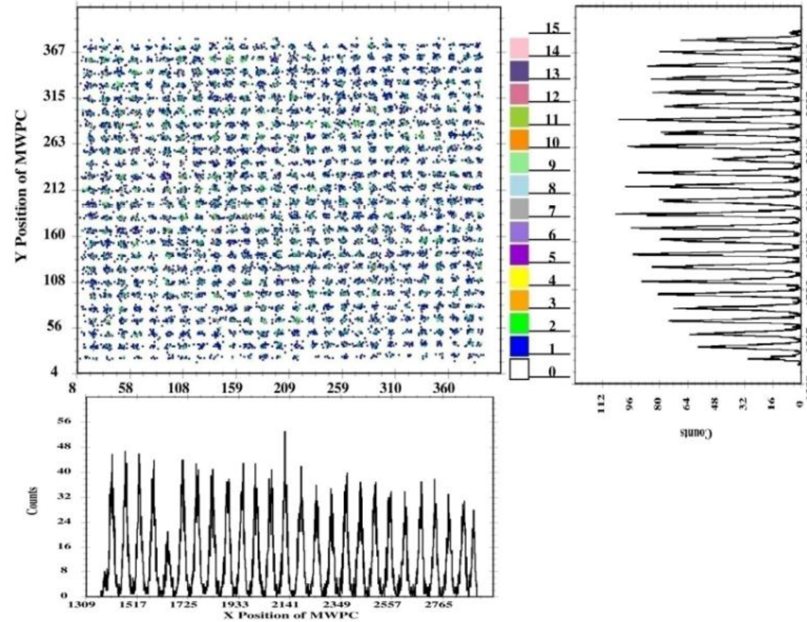
Sunil Kalkal et al. Phys. Rev. C81 (2010)044610

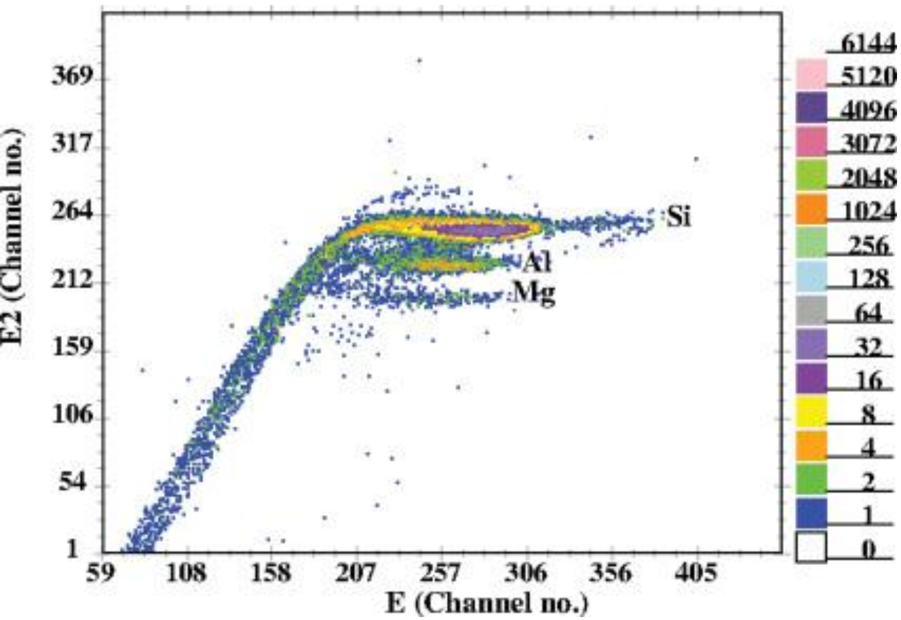
Sunil Kalkal et al. Phys. Rev. C83 (2011)054607

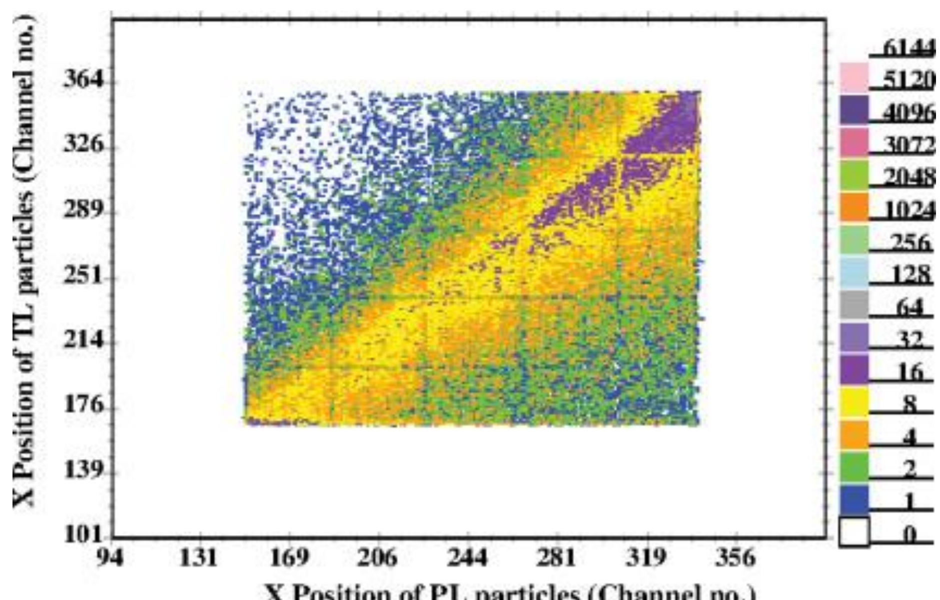
$^{28}Si + ^{90,94}Zr$



An inside view of the chamber.

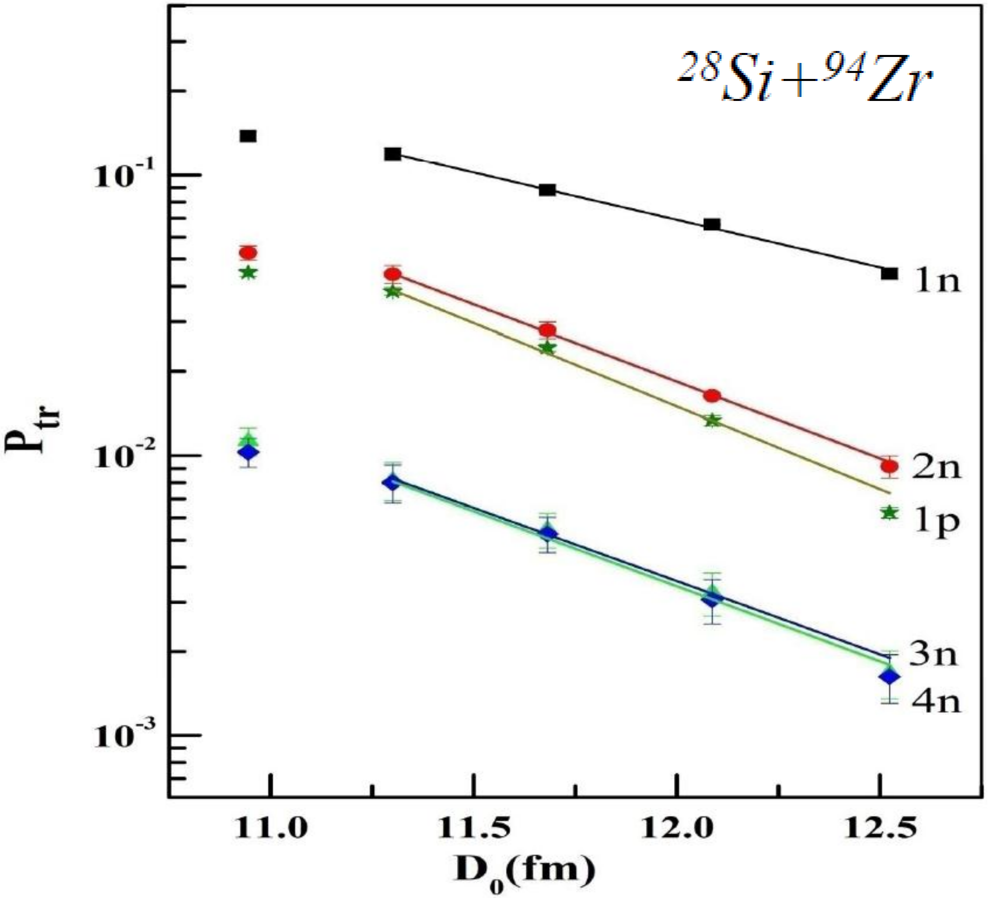






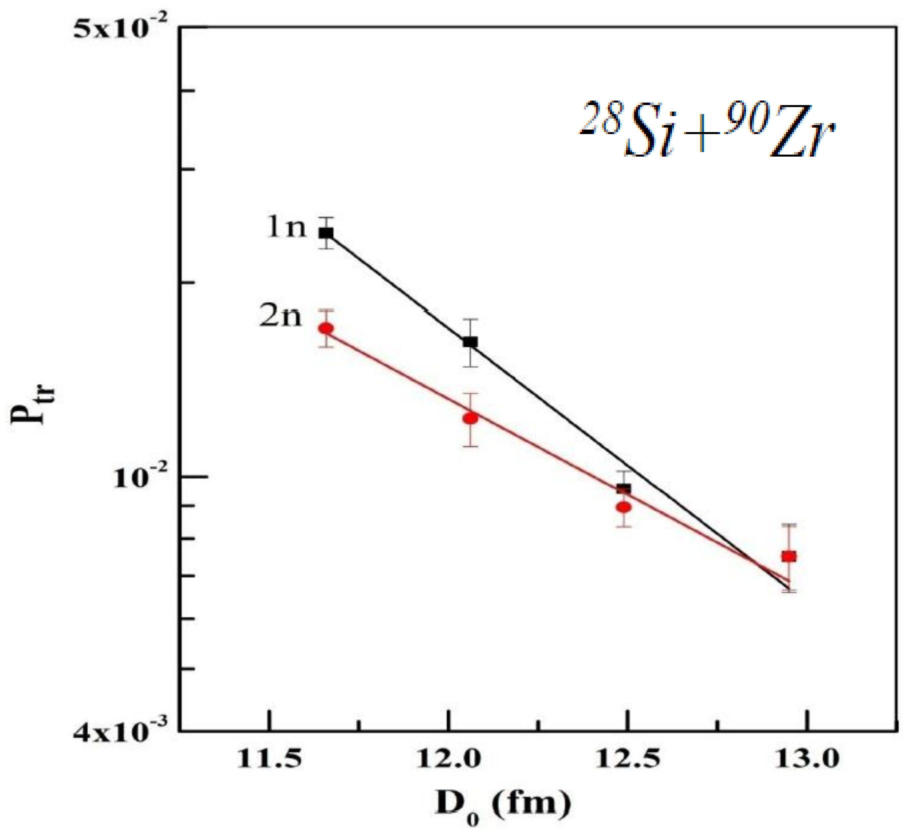
Sunil Kalkal et al. Phys. Rev. C85 (2012) 034606

Transfer Probability



$$P_{tr} = \frac{Y_{tr}}{Y_{qe}} \times \eta_m$$

$$D_0 = \frac{Z_P Z_T e^2}{2E_{c.m.}}\left(1 + \cos ec\,\frac{\theta_{c.m.}}{2}\right)$$

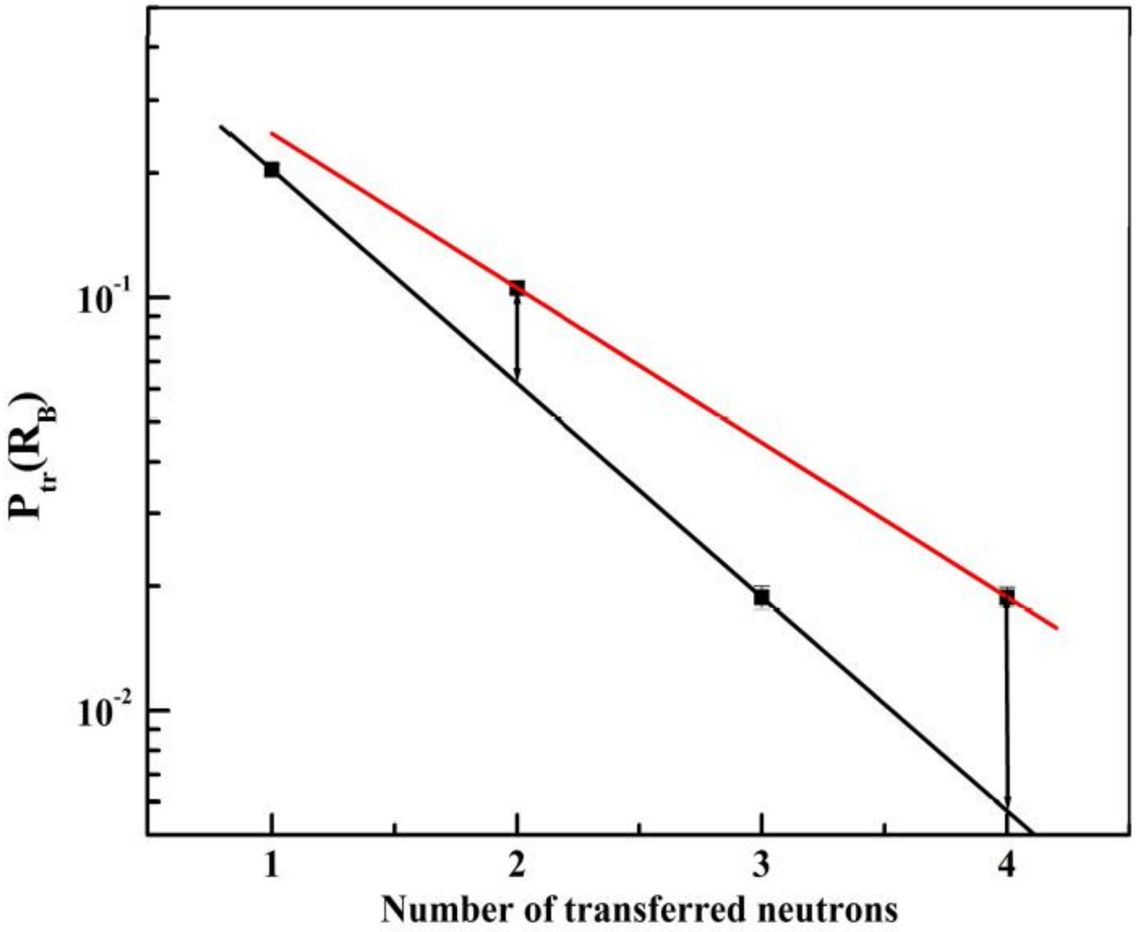


$$P_{tr}(D_0) = \frac{\pi}{\sigma^2}\frac{d\left|F_\beta(D_0)\right|^2}{dQ}\int_{-\infty}^{Q_{gs}} \exp\left[\frac{-(Q_\beta - Q_{opt})^2}{2\sigma^2}\right] dQ.$$

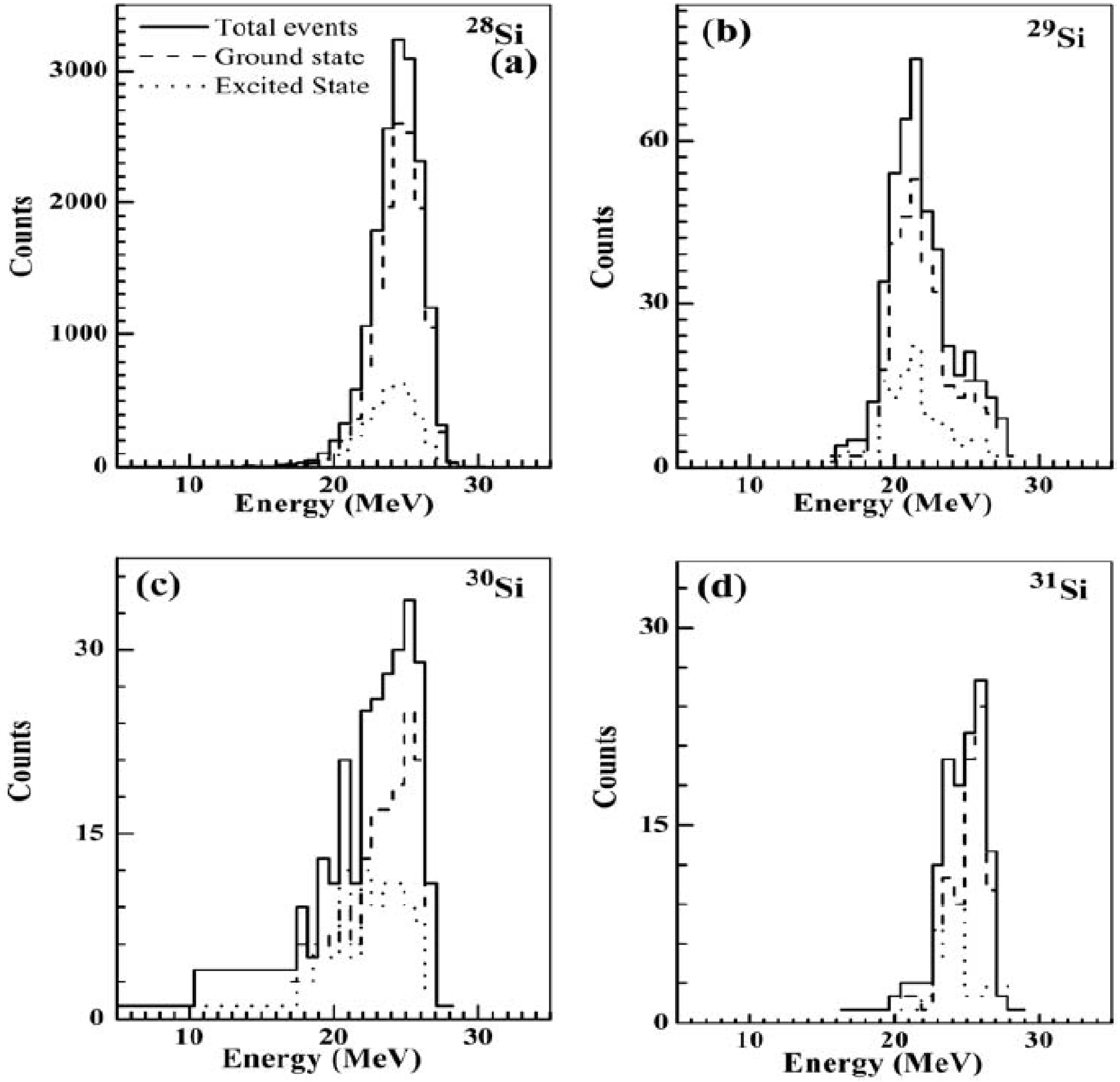
$$\sigma = \sqrt{\frac{\alpha\hbar^2\ddot{r}}{2}} \qquad Q_{opt} = \left(\frac{Z_P^f Z_T^f}{Z_P^i Z_T^i} - 1\right) E_{c.m.}$$

Sunil Kalkal et al. Phys. Rev. C83 (2011)054607

Odd - Even Effect !!



$^{28}Si+^{90}Zr$



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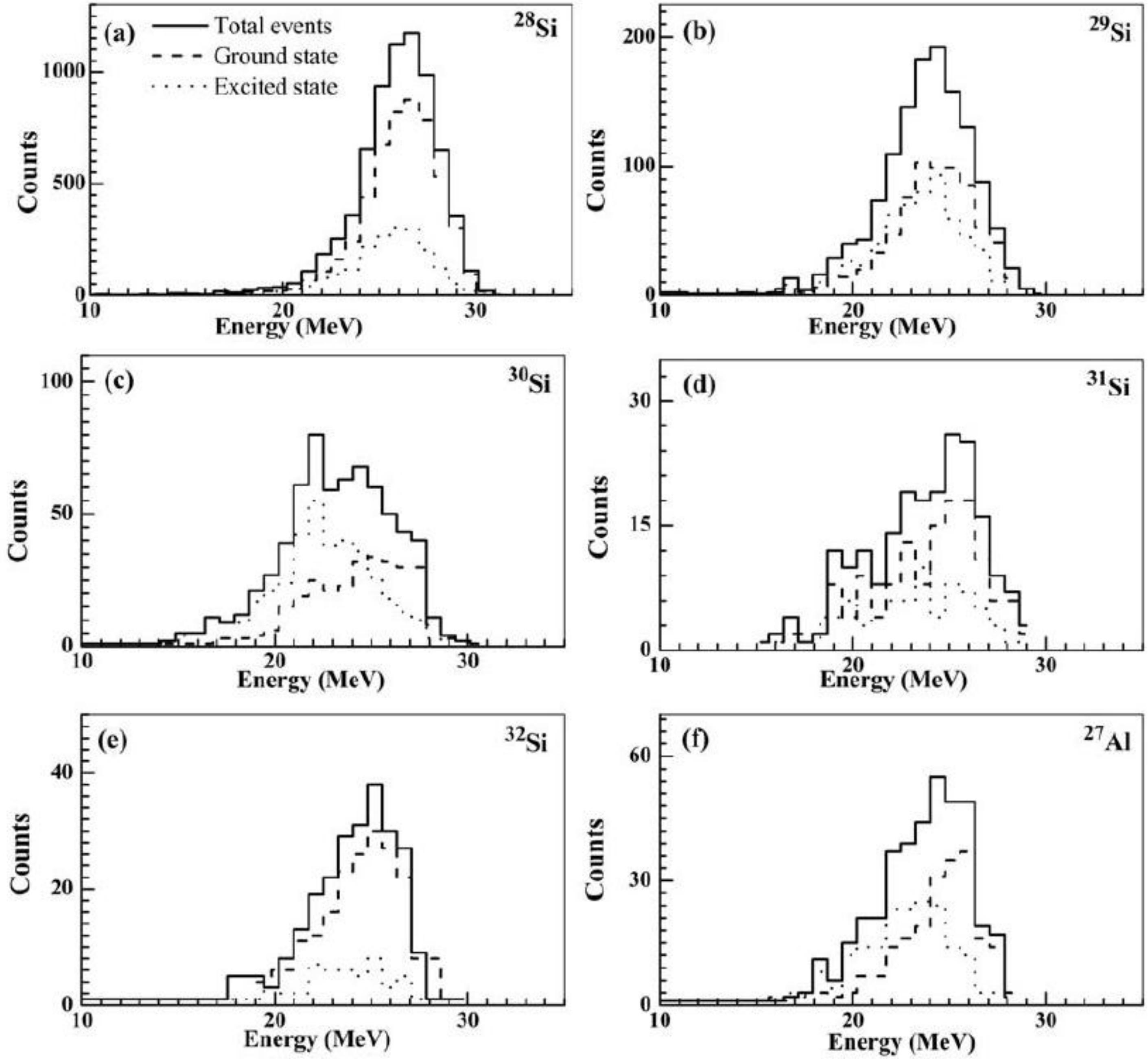
$^{28}Si+^{94}Zr$



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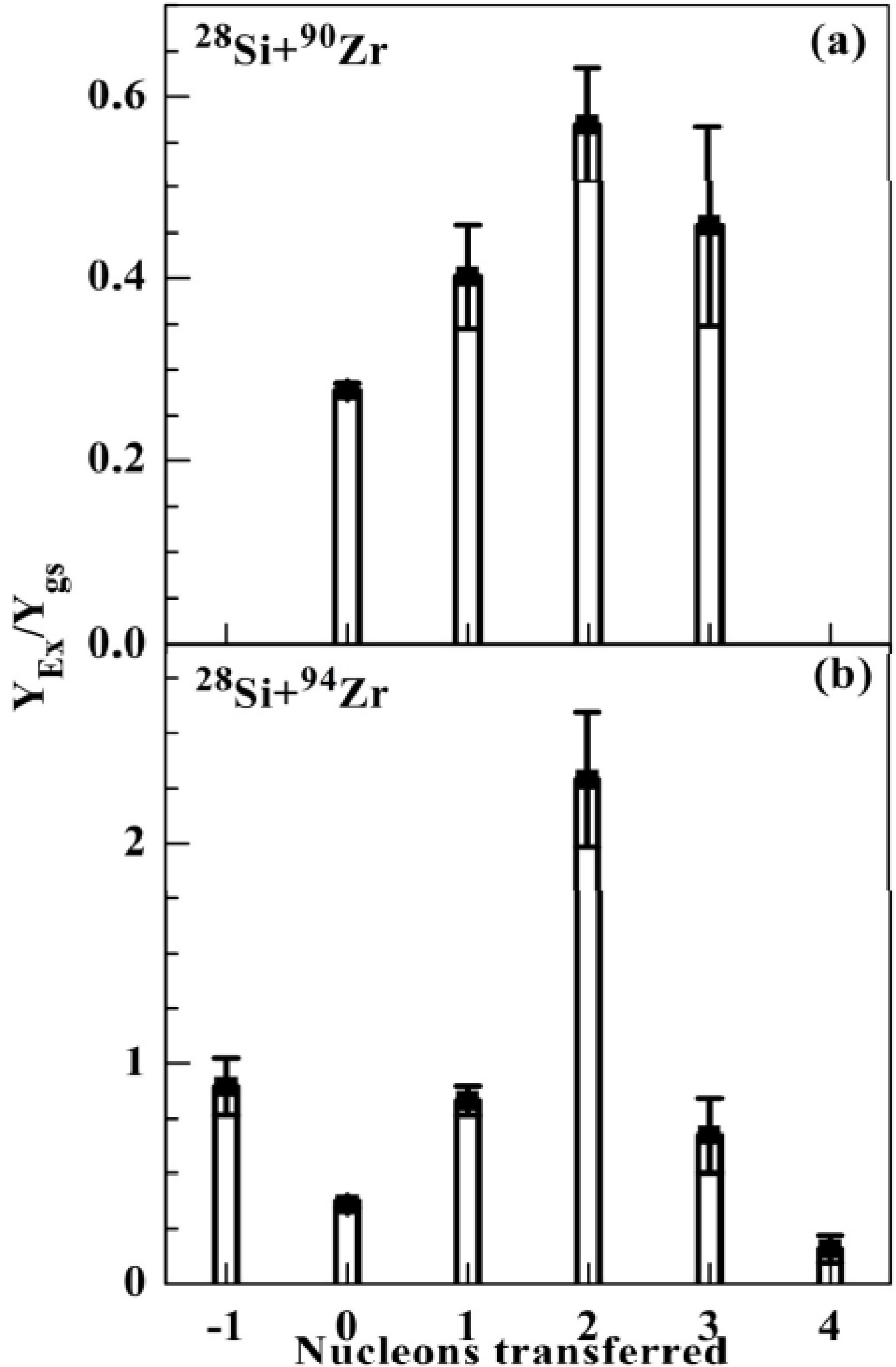
Ratio of Excited state to the Ground State Transfer evens



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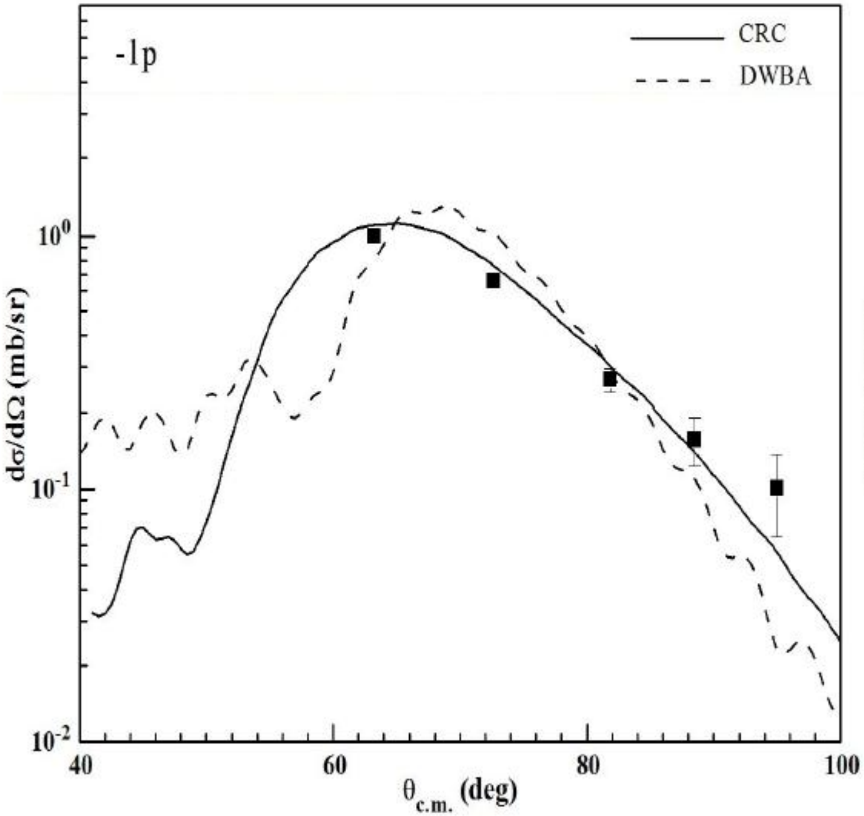
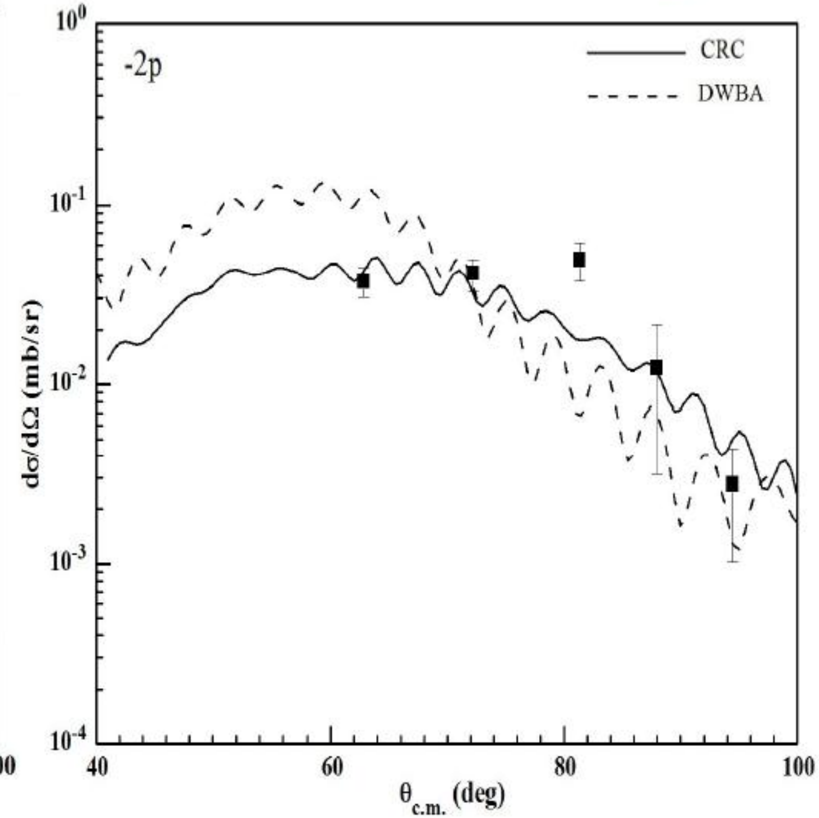
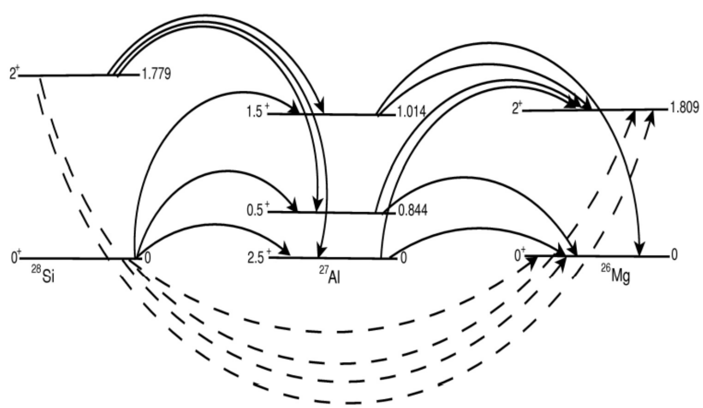


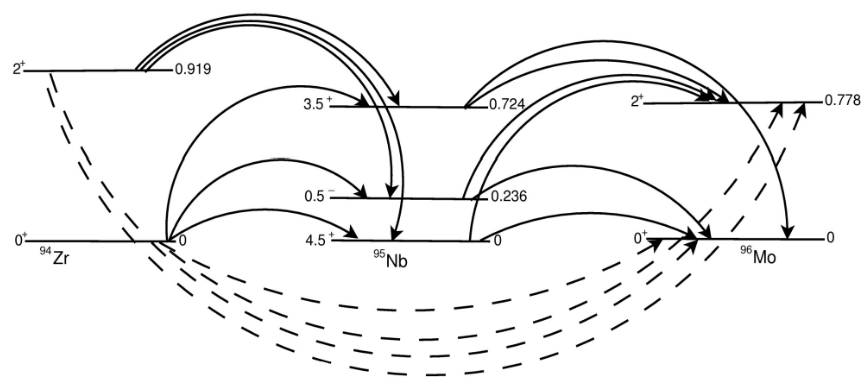


$^{28}Si+^{94}Zr$

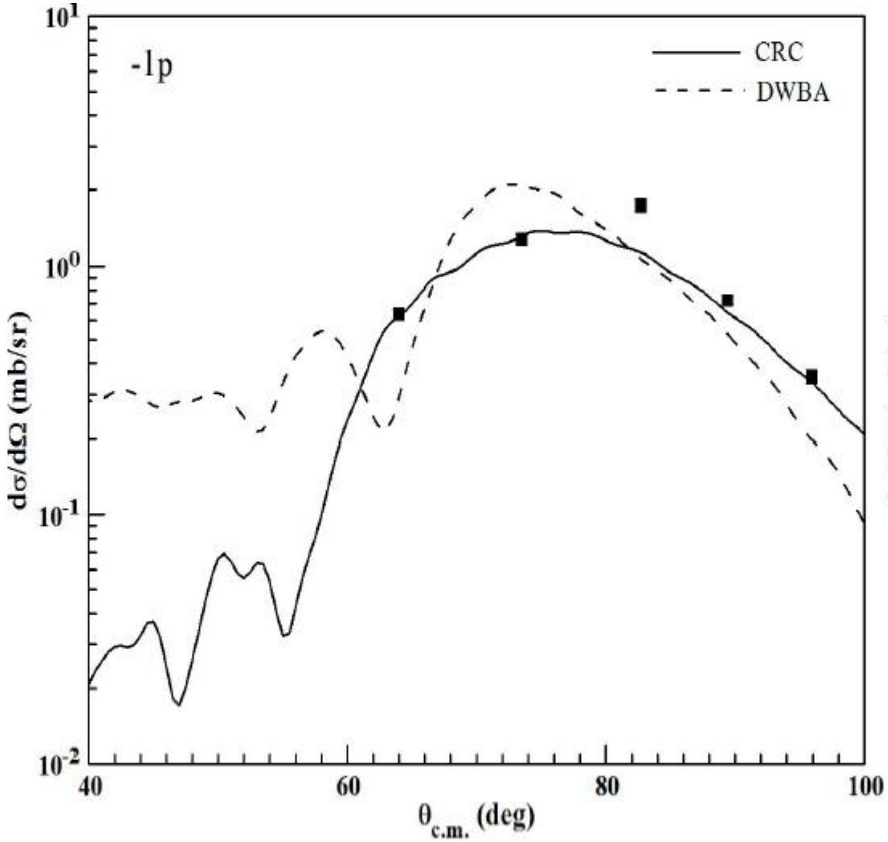
Coupling Scheme for CRC Calculations

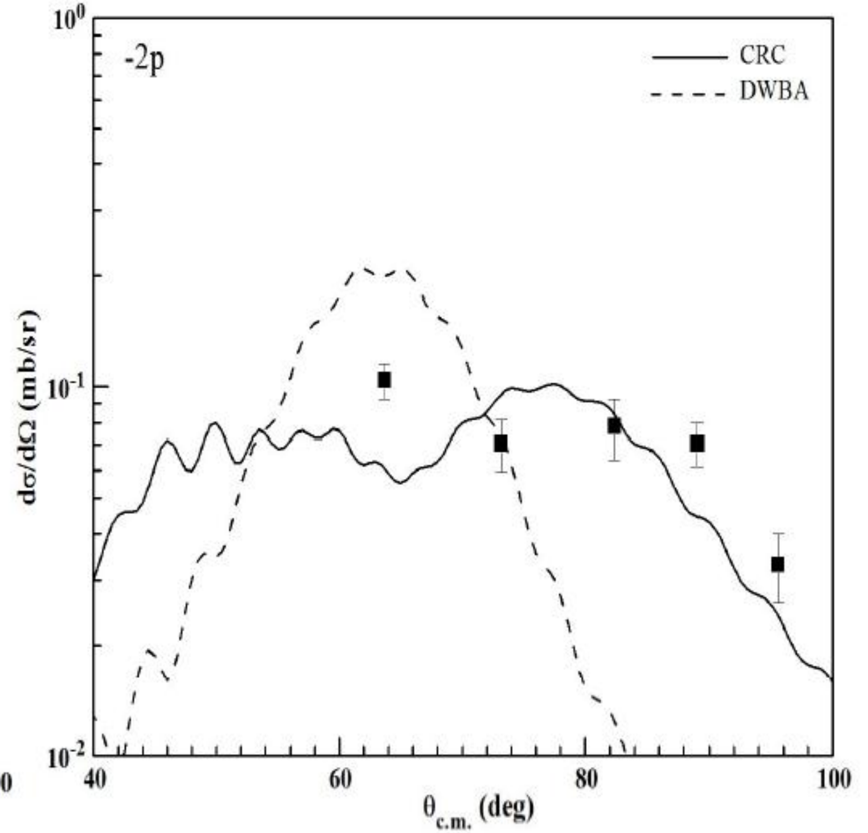


A schematic of the couplings of the projectile-like nuclei.



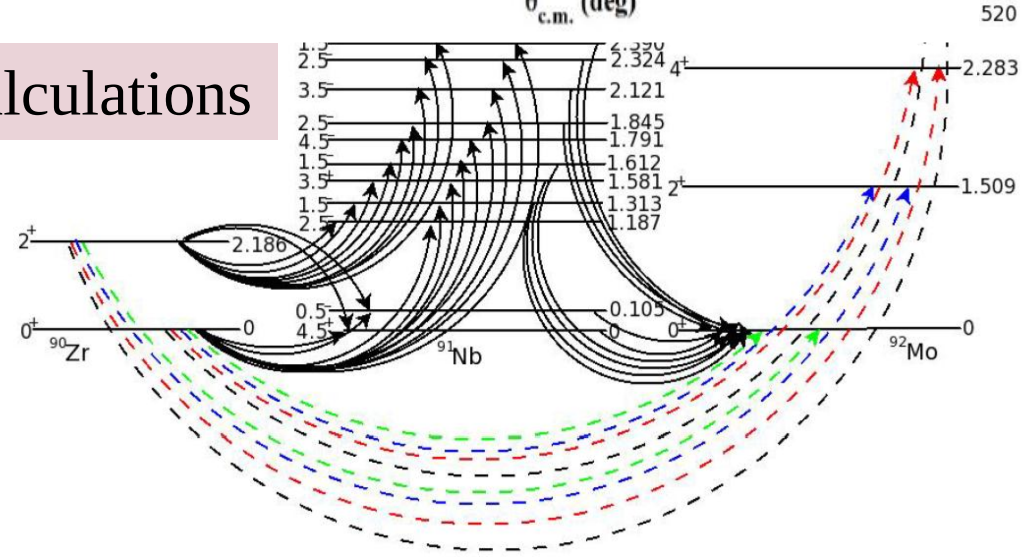
A schematic of the couplings of the target-like nuclei.





Coupling Scheme for CRC Calculations

$^{28}Si+^{90}Zr$



A schematic of the couplings of the target-like nuclei.

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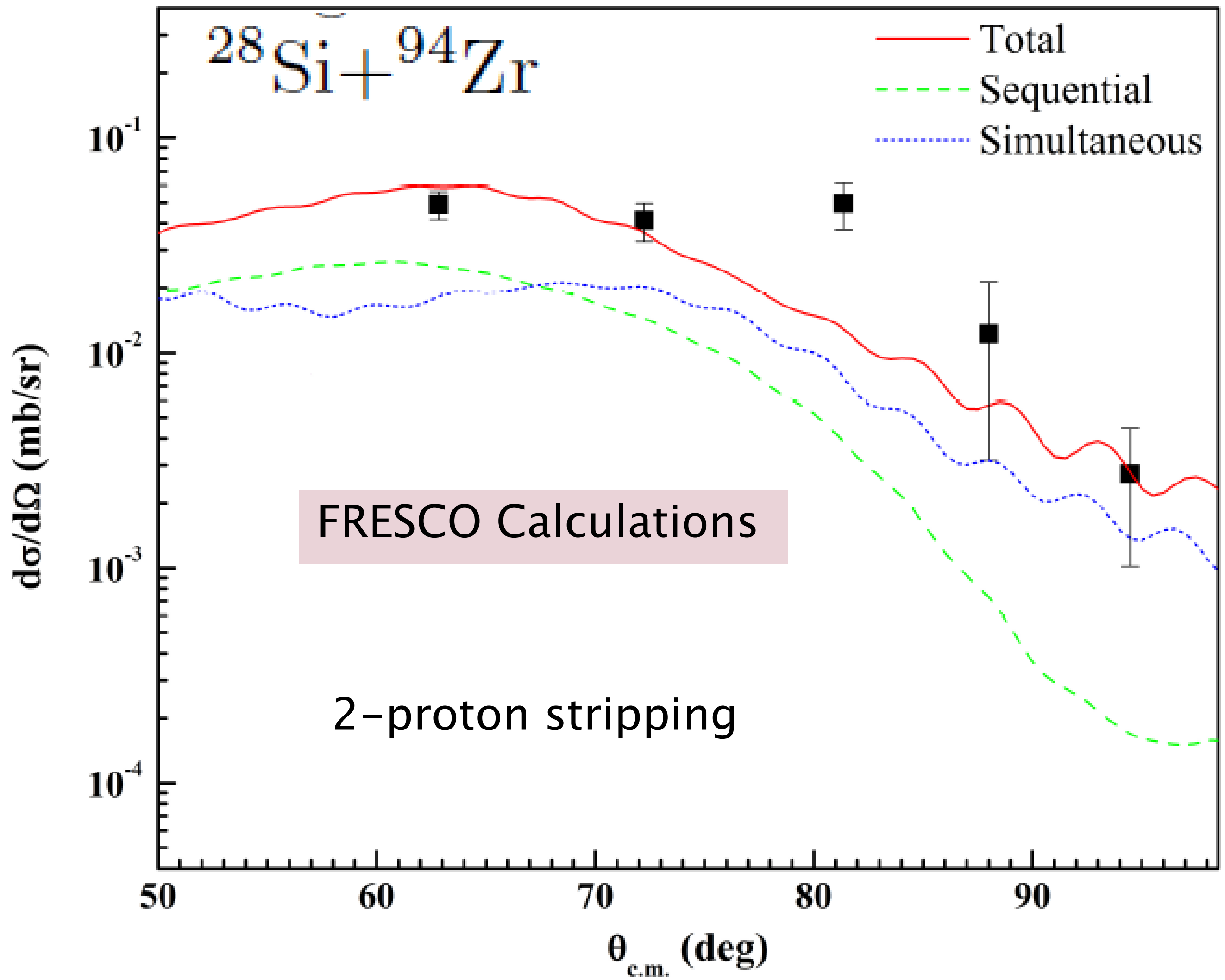

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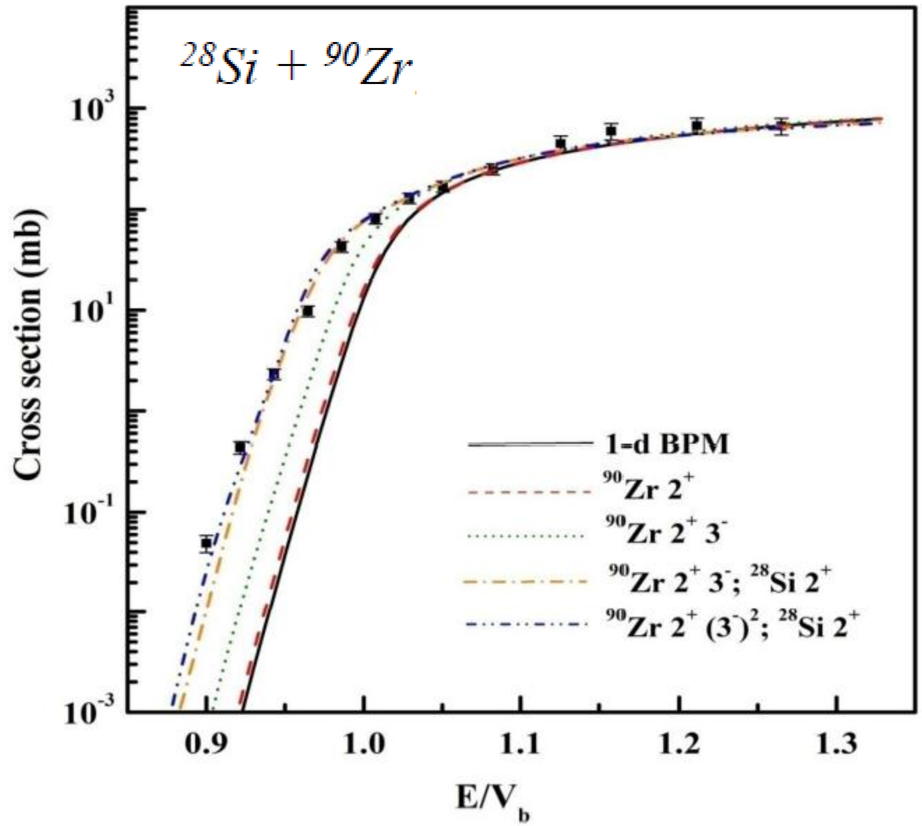
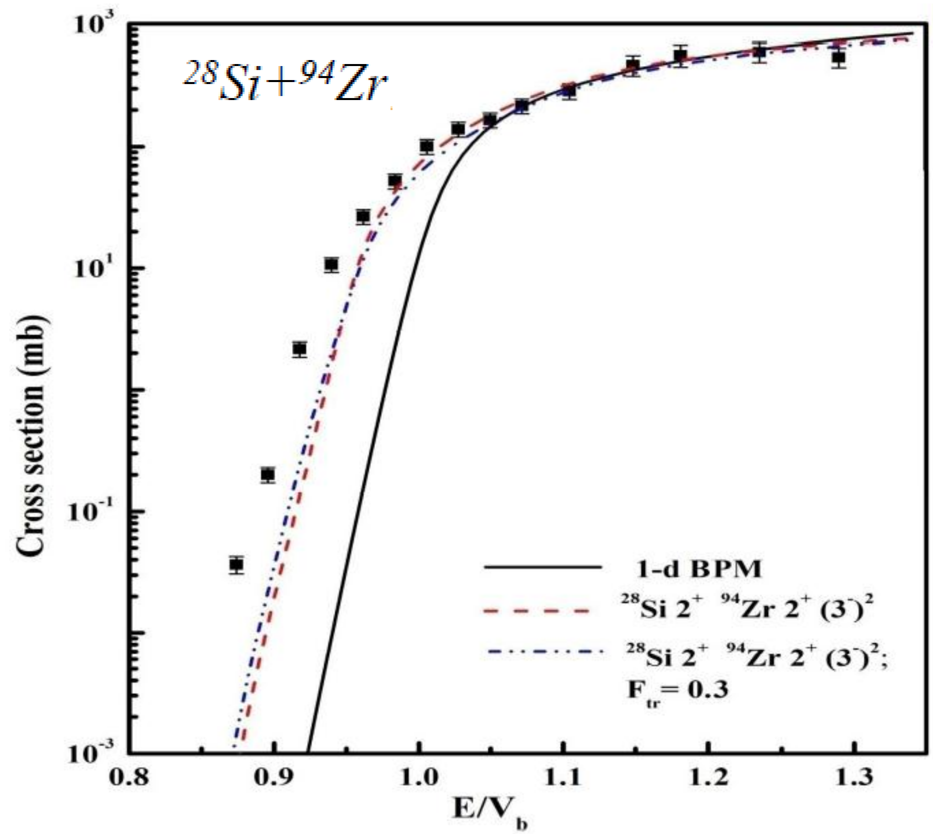
FUSION EXCITATION FUNCTIONS



Sunil Kalkal et al. Phys. Rev. C81 (2010)044610

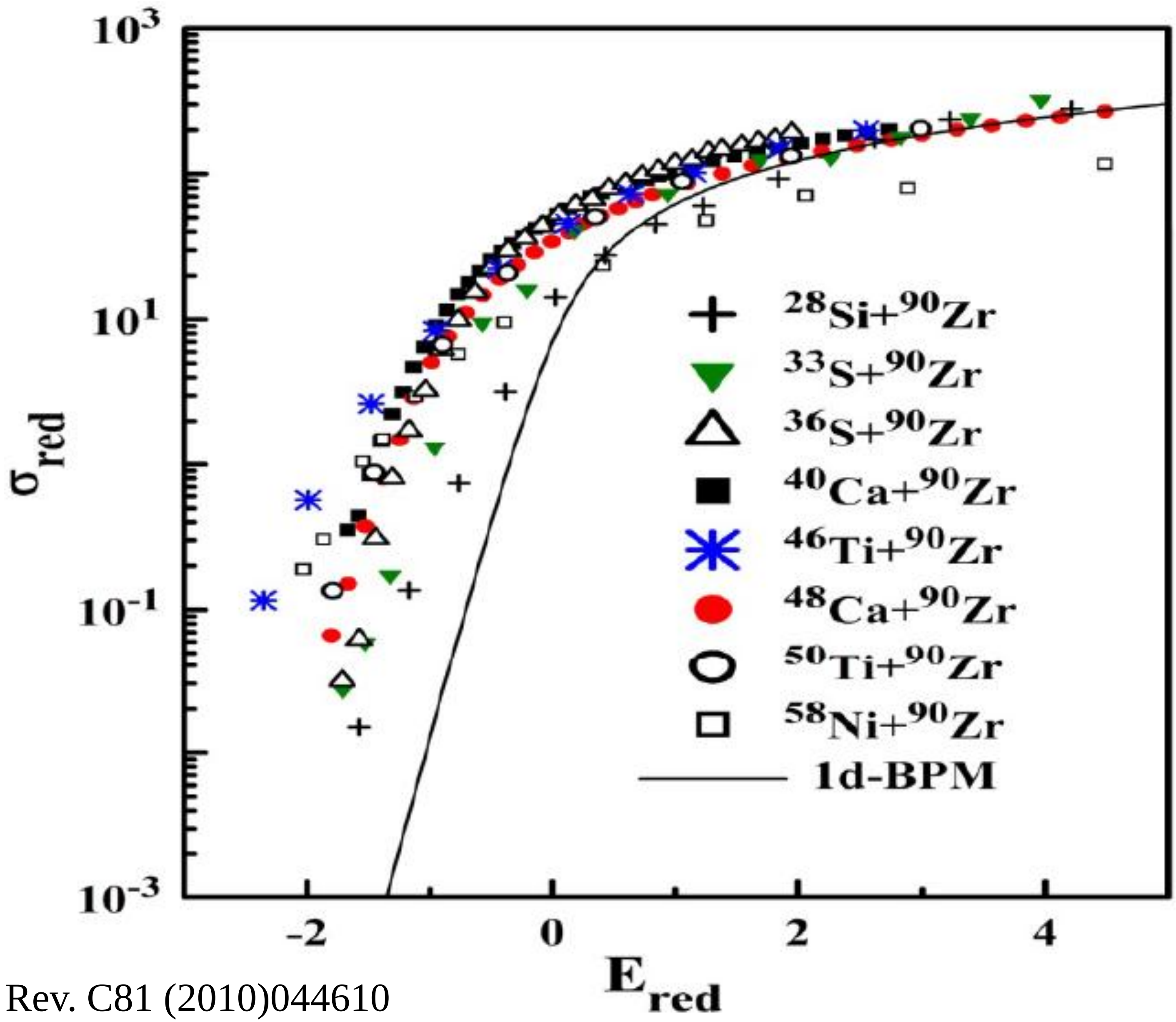


Wong's formula

$$\sigma_{fus} = \frac{R_b^2 \hbar\omega}{2E c.m.} \ln[1 + \exp\{\frac{2\pi}{\hbar\omega}(E_{c.m.} - V_b)\}]$$

$$\sigma_{red} = 2\sigma_{fus} E_{c.m.} \Big/ R_b^2 \hbar\omega$$

$$E_{red} = (E_{c.m.} - V_b) \big/ \hbar\omega.$$



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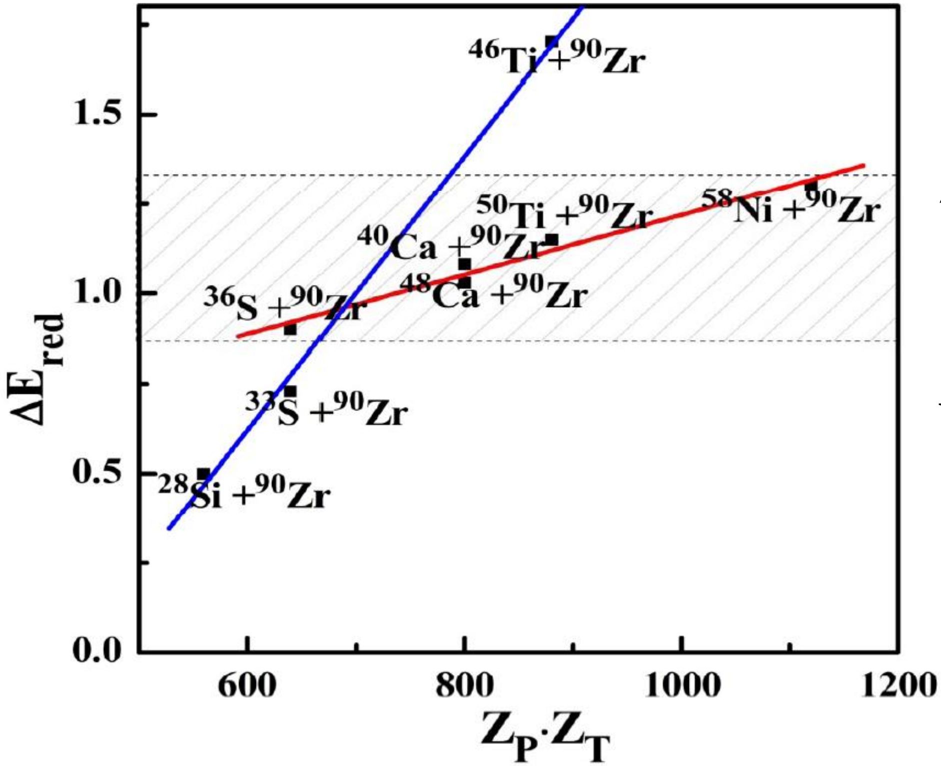
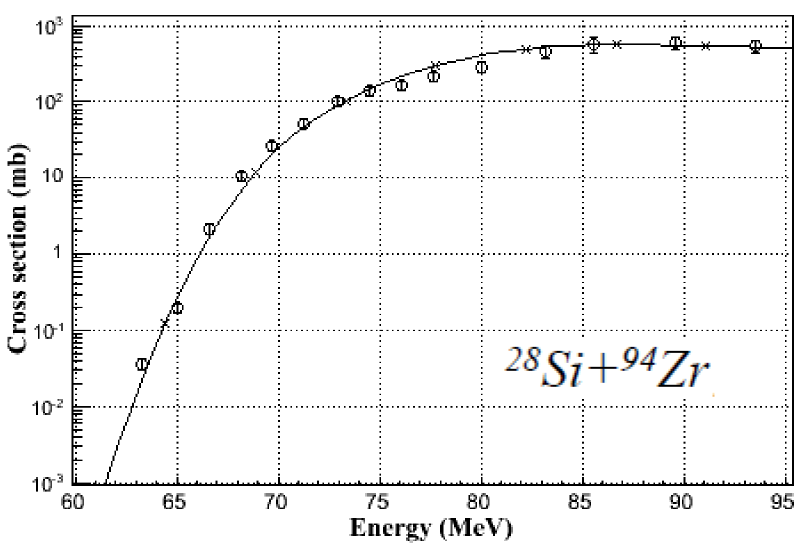


ΔE_{red} : difference in the value of E_{red} correspond to the cross section (~ 0.1mb) for various system



Multi Nucleon coupling effect on fusion channel: (Zagrebev model)

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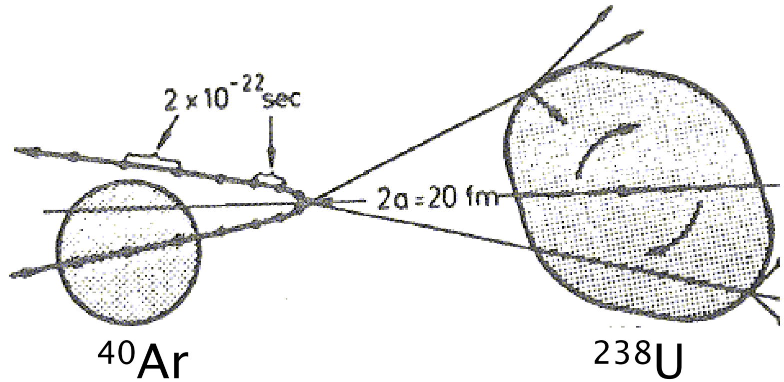
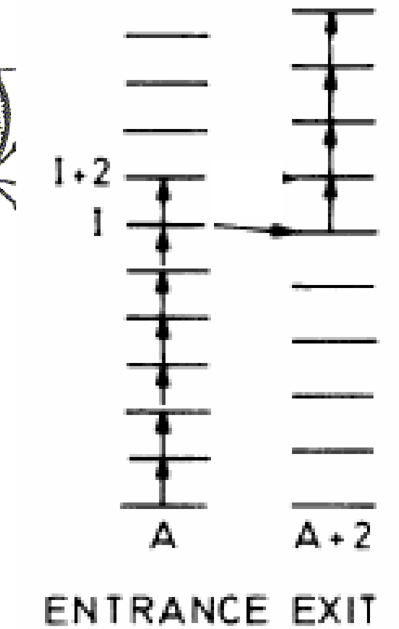
Diabolic pair transfer at higher angular momentum states

Pair transfer as a function of spin

Nuclear Josephson Effects:

Enhanced transfer of nucleon pairs between two superfluid heavy nuclei in a cold reaction correspond to a super-current.





Spectroscopic quantities

$$\left\langle A+2, I \left| \left(a^+ a^+\right)_{\ell=0} \right| A, I \right\rangle$$

$$\left\langle I+2, A \left\| \hat{Q} \right\| I, A \right\rangle \approx \sqrt{B(E2; I \to I+2}$$

Intrinsic quantities

$$\left\langle \Phi \left| \left(a^+ a^+\right)_{\ell=0} \right| \Phi \right\rangle \qquad \left\langle \Phi \left| \hat{Q} \right| \Phi \right\rangle$$

Parameters Δ $\qquad \beta$

$$\left\langle A+2, I \left| \left(a^+ a^+\right)_{\ell=0} \right| A, I \right\rangle$$

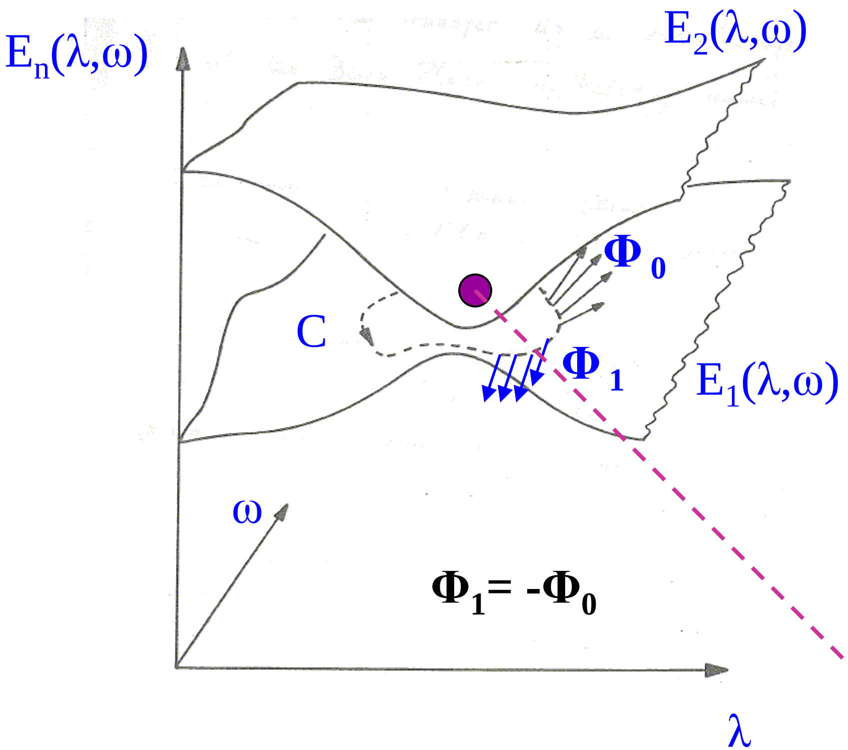
pair transfer amplitude

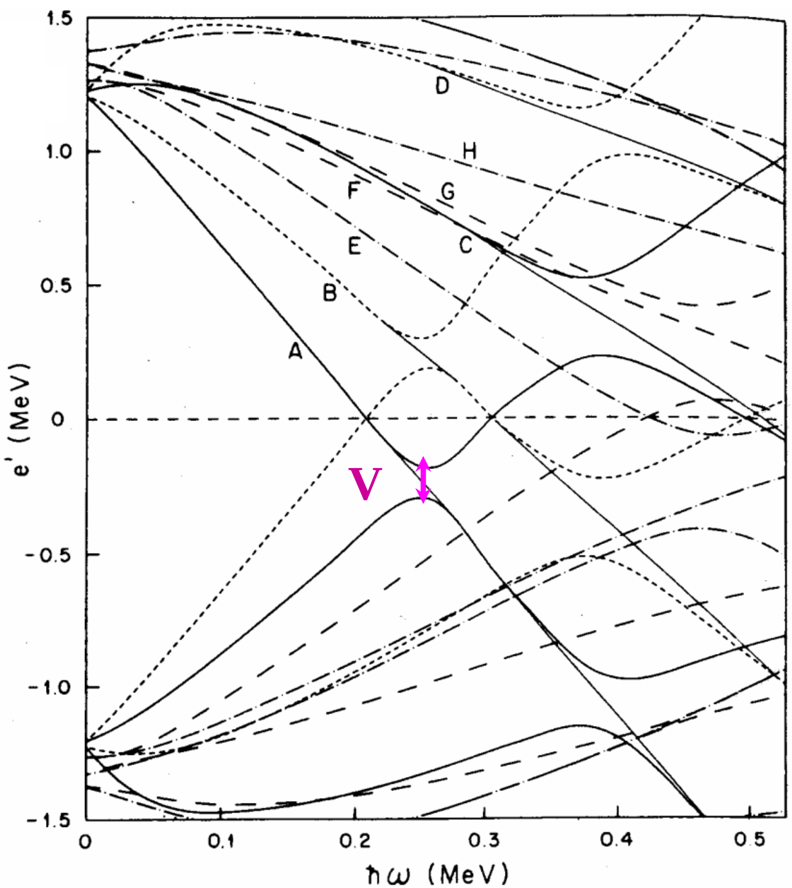
Berry's Phase, Diabolic Pair Transfer

Berry's phase is a simple mathematical fact. Berry considers a Hamiltonian, which depends on external parameters $\vec{R} = (x, y, z \ldots)$

*Examples: (a) Nilsson Model **R=β***

*(b) Cranked Shell Model **R=(λ,Δ,ω)***

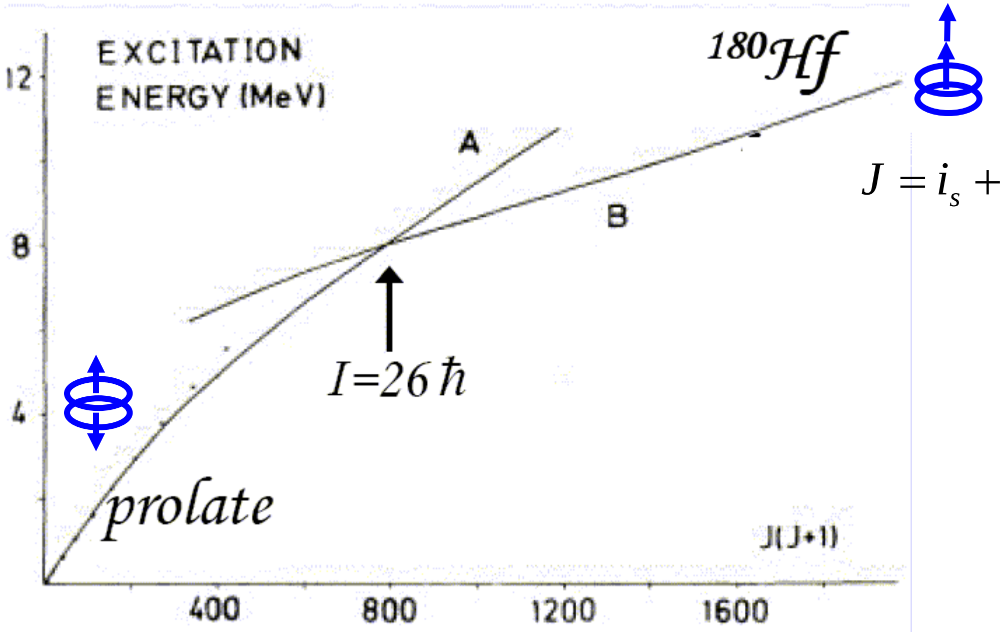




chemical potential λ, angular velocity ω, pairing gap Δ

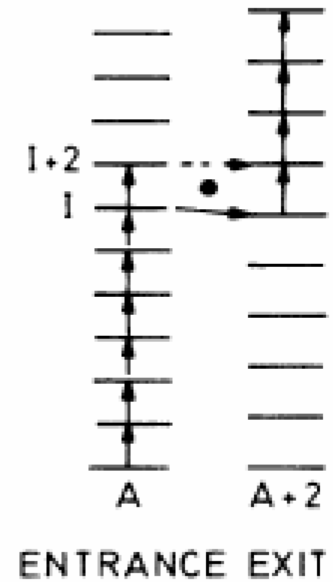
A diabolical point, where two energy surfaces touch and a closed path on the lower surface encircling this point

Berry's Phase and the Backbending Effect



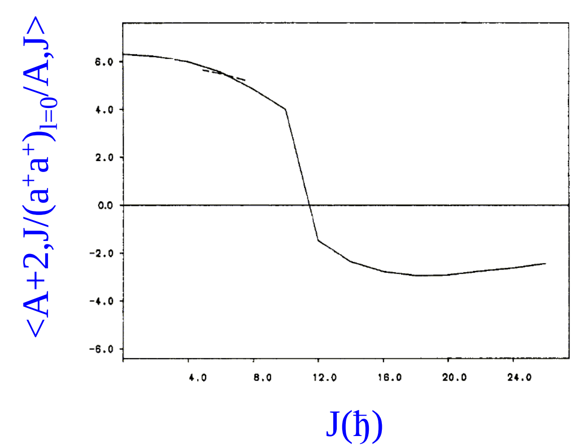
$$J = i_s + \Im\omega_s \quad \omega_s < \omega_g$$

$$J = \Im\omega_g$$



Two different paths around a diabolic point

The oscillating behavior of the pair transfer matrix element has a close ***analogy to*** *the oscillating behavior of the* ***electric current in Superconducting Quantum Interference Devices as a function of the magnetic field****, the DC-Josephson effect*

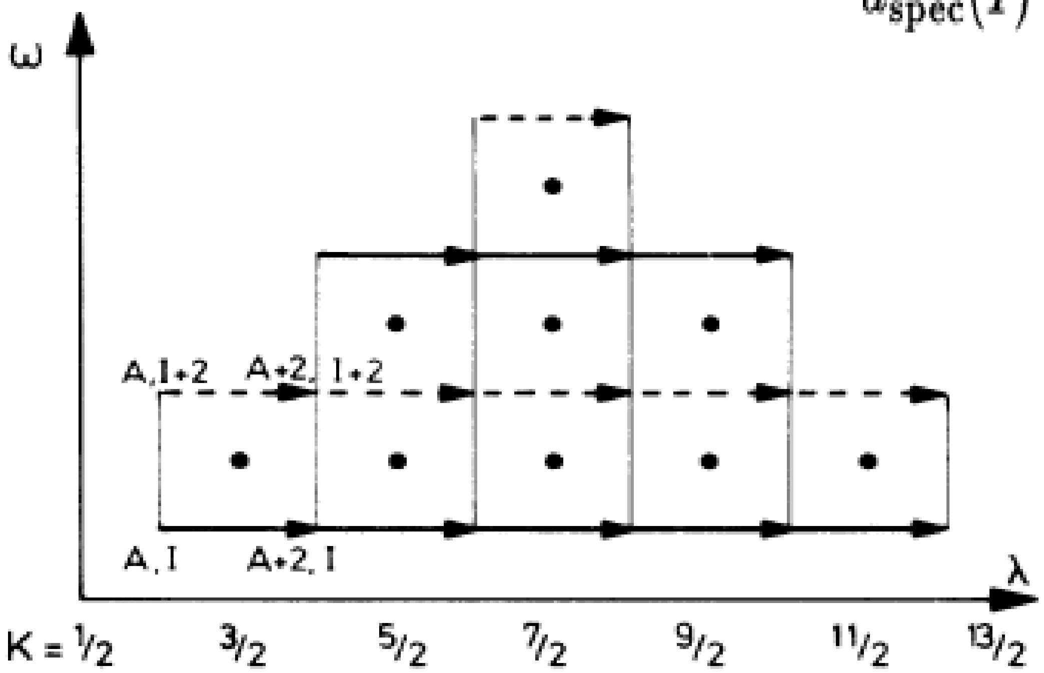


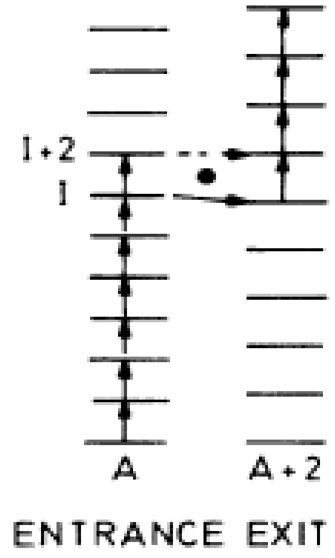
Berry's Phase in Nuclear Physics

- ❖ *open problem for experimentalist*

Pair transfer matrix

$$a_{\text{spec}}(I) = \langle A+2, I | (a^{\dagger}a^{\dagger})_{L=0} | A, I \rangle$$

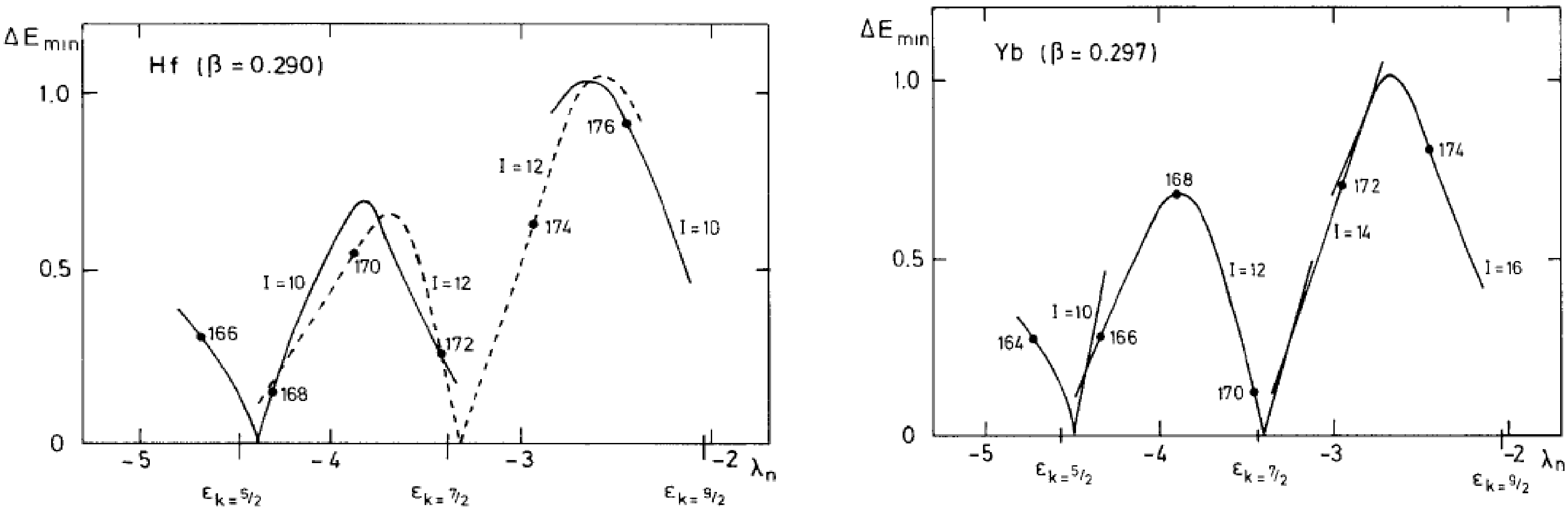




Full horizontal arrow indicates pair transfer matrix elements with positive sign and dashed arrows indicate those with negative sign . K quantum number for j=13/2 is shown.

Possible Systems:

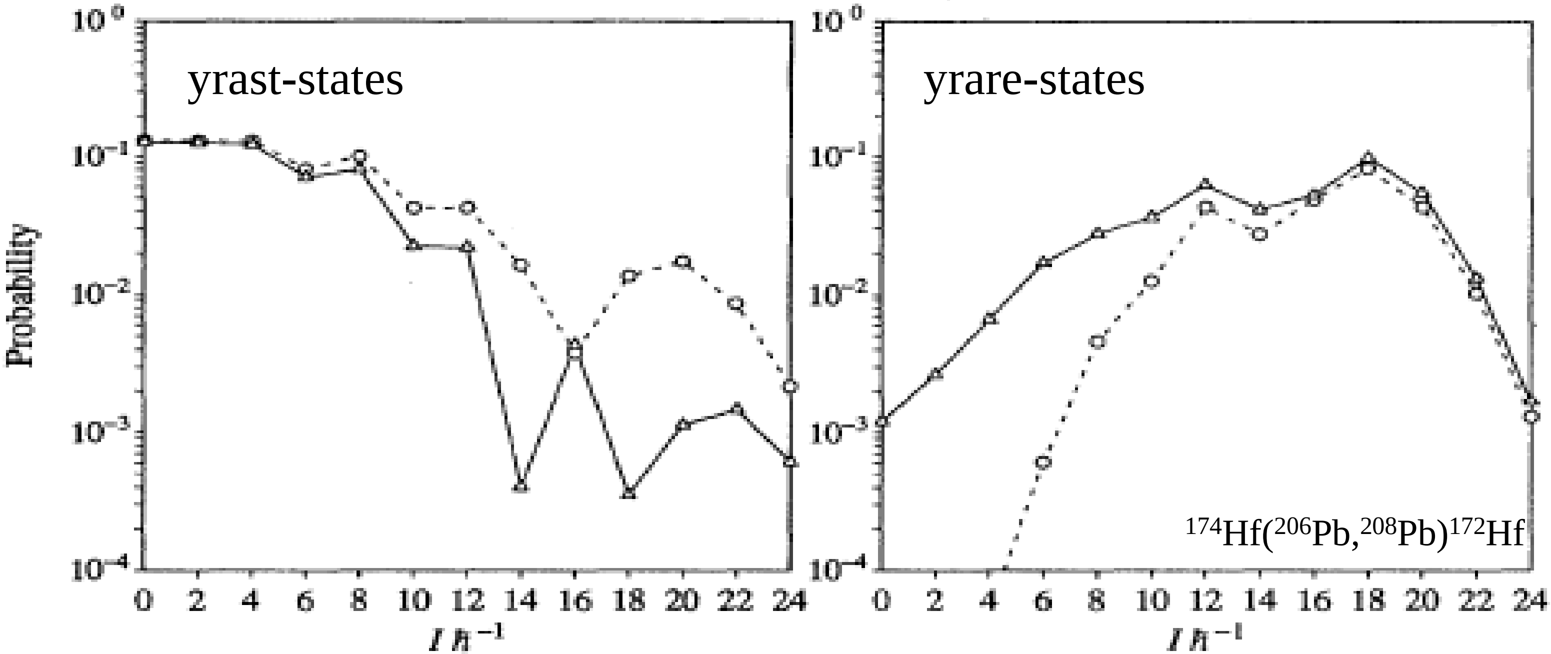
^{172,174}Yb on ^{206}Pb
^{174,176}Hf on ^{206}Pb



The Hf and Yb-chain : The interaction strength in the level crossing between the ground state band and the s-band characterized by the minimal distance between the yrast band and the first excited band $\Delta E_{min.}$ Connected lines correspond to minimal distances for the angular momenta I= 10-16ħ. Full dot symbols indicate the even mass Yb-isotopes. The position of the deformed single-particle energies of the ν $i_{13/2}$ levels for the nucleus ^{166}Yb and ^{170}Hf are given on the abscissa.

Y. Sun et al, Z. Phys. A339 (1991) 51

2n-transfer probability as a function of spin



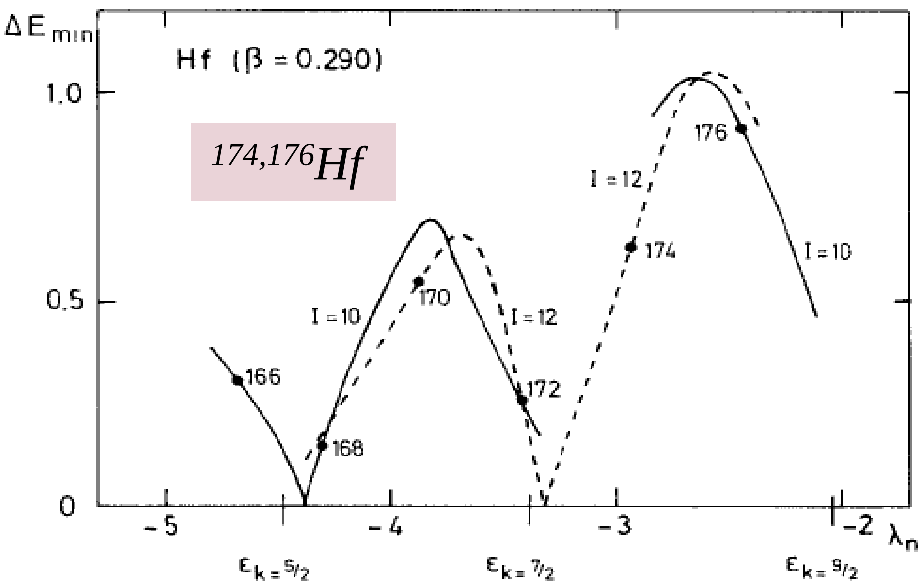
The calculation show the diabolic effect for ^{206}Pb on ^{174}Hf. This calculation assumes ^{174}Hf transfers to ^{172}Hf. The symbol o's are non diabolic case and Δ's are diabolic cases.

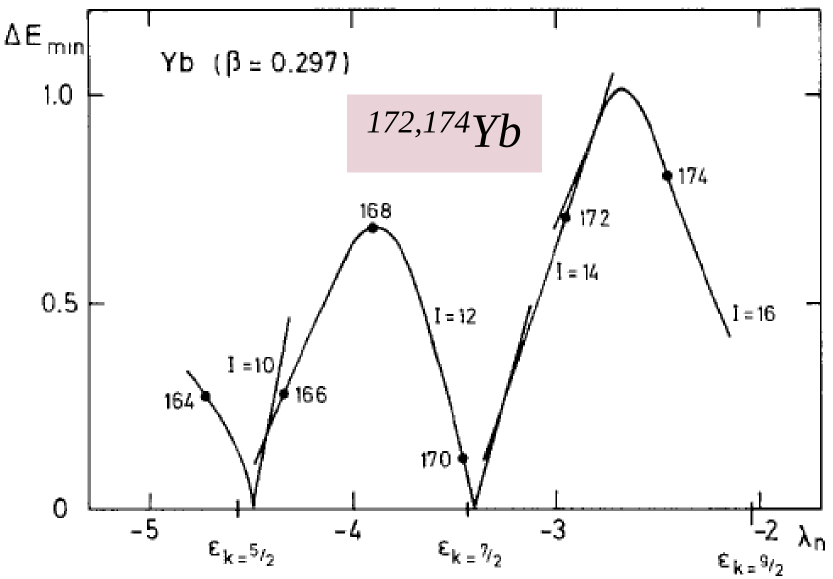
L F Canto et al PRC 47,2836(1993).

Diabolic pair transfer at higher angular momentum states by using heavy-ion induced reaction

Berry Phase in Nuclear Physics

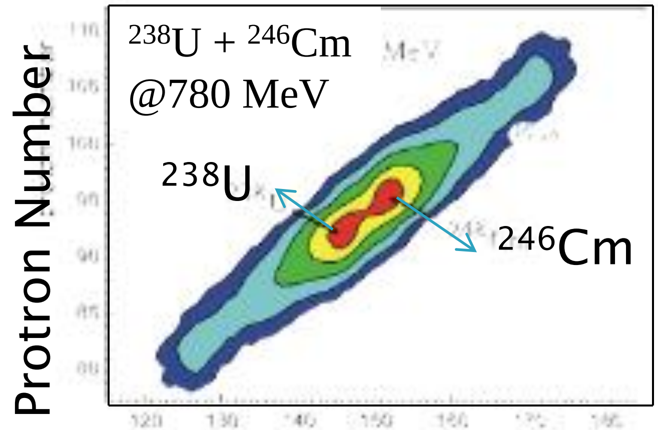
Nuclear Josephson Effects

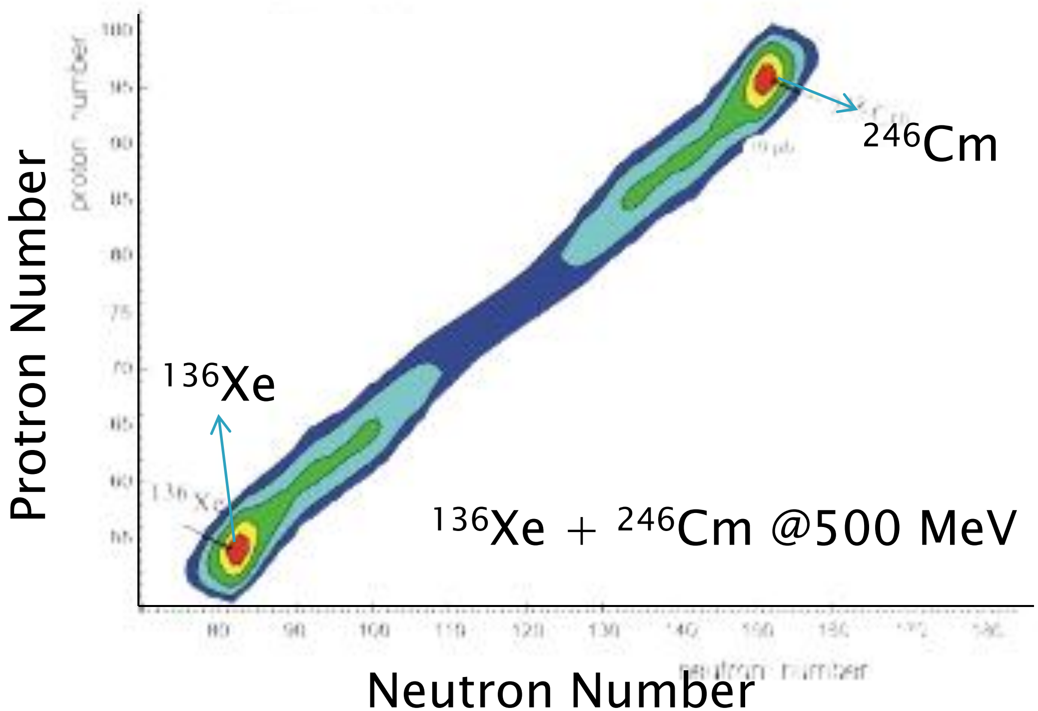




Y. Sun et al, Z. Phys. A339 (1991) 51

Multi-nucleon transfer: Production of Super-Heavy





Summary

- *Strong correlation between the transfer and fusion reactions.*
- *Sequential transfer of nucleons is an important mechanism of transfer in multi nucleon transfer reactions at above barrier energies.*
- *Indication of cold pair transfer at sub-barrier energies.*
- *Odd-even staggering is observed in multi neutron transfer case for* $^{28}Si+^{90,94}Zr$ *systems.*
- *The ratio of excited to ground state transfer is much more in* $^{28}Si+^{94}Zr$ *as compared to* $^{28}Si+^{90}Zr$*.*

Collaboration (Transfer + Fusion)

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THANKS