The role of isospin in Fusion-Evaporation reactions

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Outline

- Level density dependence on isospin
- Statistical model predictions for neutron-rich composite nuclei, showing that fusion-evaporation reactions are a powerful tool to study the level density of exotic nuclei
- Conclusions

SPES
exotic beams for science

Fusion-Evaporation reactions as a tool to study the level density of exotic nuclei

$$P(U_o, J_o, \varepsilon, l, U, J) \propto \rho(U,J)\,.\,T_l(\varepsilon)$$

$$\rho(U) = \frac{1}{12\sqrt{2}} \frac{1}{\sigma a^{1/4}} \frac{\exp[2\sqrt{a(U-\delta)}]}{(U-\delta)^{5/4}}.$$

$$\rho(U,J) = \frac{(2J+1)}{2\sigma^2} \exp\left[\frac{-\left(J+\frac{1}{2}\right)^2}{2\sigma^2}\right] \rho(U).$$

Pairing & Shell effects, Angular momentum

Isospin (?)

Isospin can affect two quantities: Level density parameter a
Symmetry Energy

Isospin effects on level density parameter *a*

S.I. Al-Quraishi et al. Phys. Rev. C 63, 065808 (2003)

$$\rho(U) = \frac{\sqrt{\pi}}{12} \frac{\exp(2\sqrt{aU})}{a^{1/4}U^{5/4}}$$

Best fit: 241 nuclei E_x up to 7 MeV 20<A<110 ENSDF

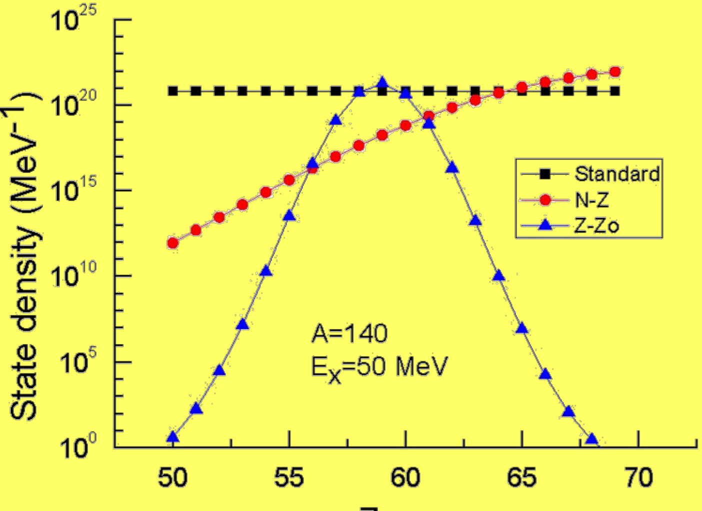
Form A: $a = \alpha_1 A$

Form B: $a = \alpha_2 A / \exp[\beta (N - Z)^2]$ → LD decreases with N-Z increase

Form C: $a = \alpha_3 A / \exp[\gamma (Z - Zo)^2]$ → Strong support from recent exp. findings and realistic LD calculations of nuclei far from the stability line

Better reproduction of data with Z-Zo dependence

If confirmed experimentally with RIB's this result would have strong implications in nuclear astrophysics: dramatic reduction of level density of exotic nuclei



SPES-SPIRAL2 offer the opportunity of a systematic study of these isospin effects

- **Observables: light particle multiplicities, energy spectra and Evaporation Residue yields.**

- **Reactions on ^{4}He target: CN with low angular momentum and relatively low Ex.**

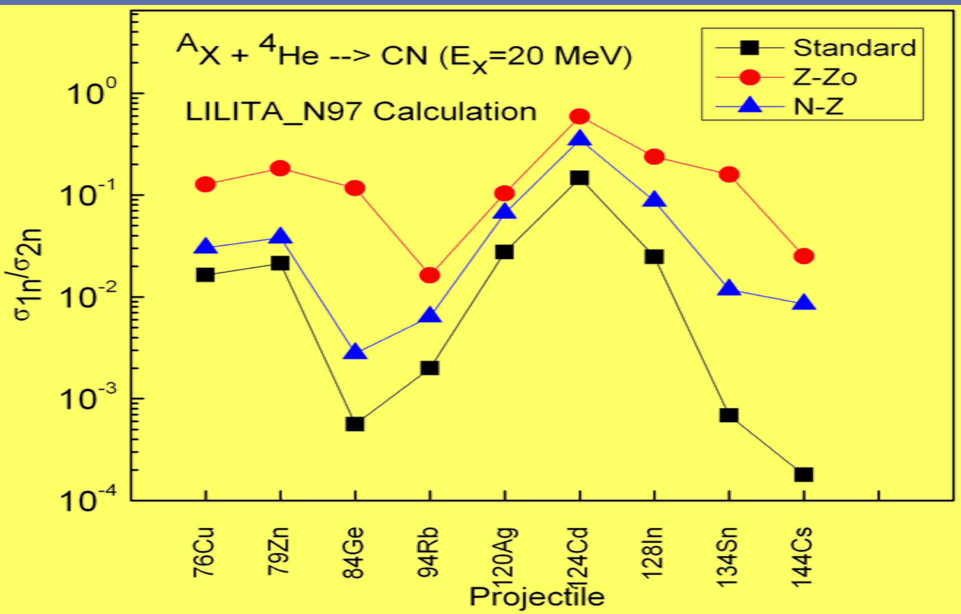
- **Possible beams:**

  ^{76}Cu, ^{79}Zn, ^{84}Ge, ^{94}Rb, ^{120}Ag, ^{124}Cd, ^{128}In, ^{134}Sn, ^{144}Cs

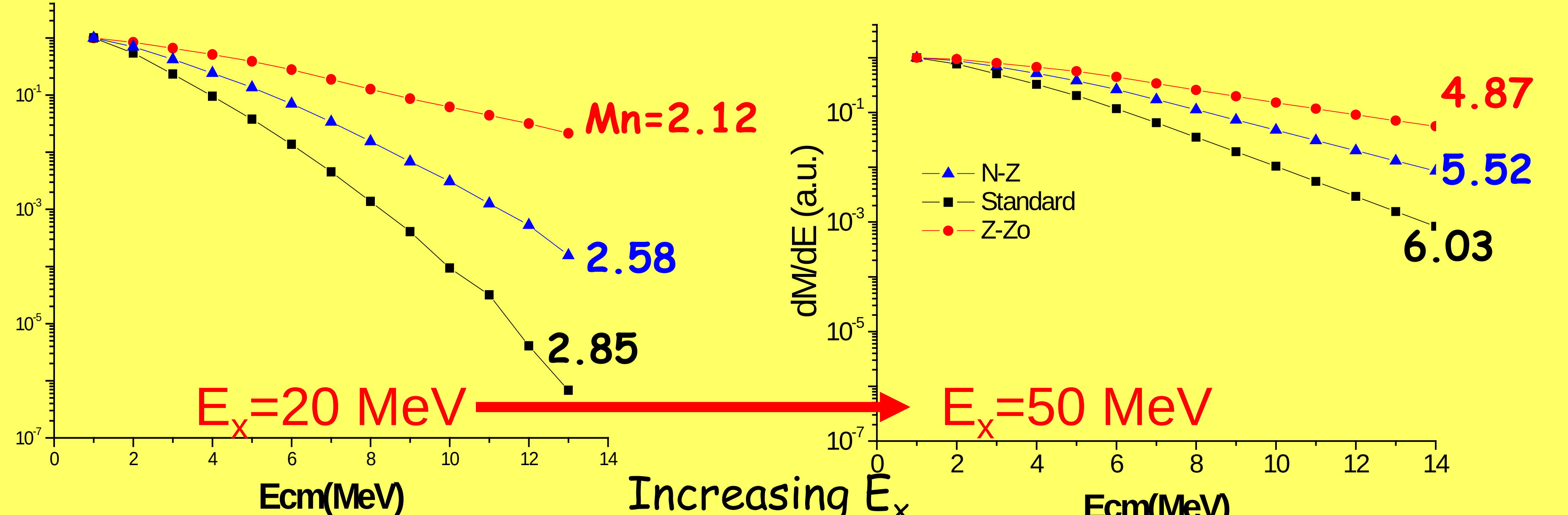
  $E_{lab} \sim 3 - 10$ MeV/A ; Ex $\sim 20 - 50$ MeV ; $\sigma_{FUS} \sim 0{,}2 - 1$ barn

Simulations with Lilita_N97 for these reactions, including isospin effects

SM predictions for n-rich nuclei



$^{134}Sn + ^{4}He$ Neutron Spectra normalized to the maximum to compare the shape



Symmetry Energy

$$E_{sym}(T)=b_{sym}(T)(N-Z)^2/A$$

Well known expression with temperature and isospin dependence

SM-Lilita_N97: $a(T)T^2=E_x^i-E_{sep}(T=0)-\varepsilon+(E_{sym}(T^i)-E_{sym}(T))$
energetic balance for each decay step

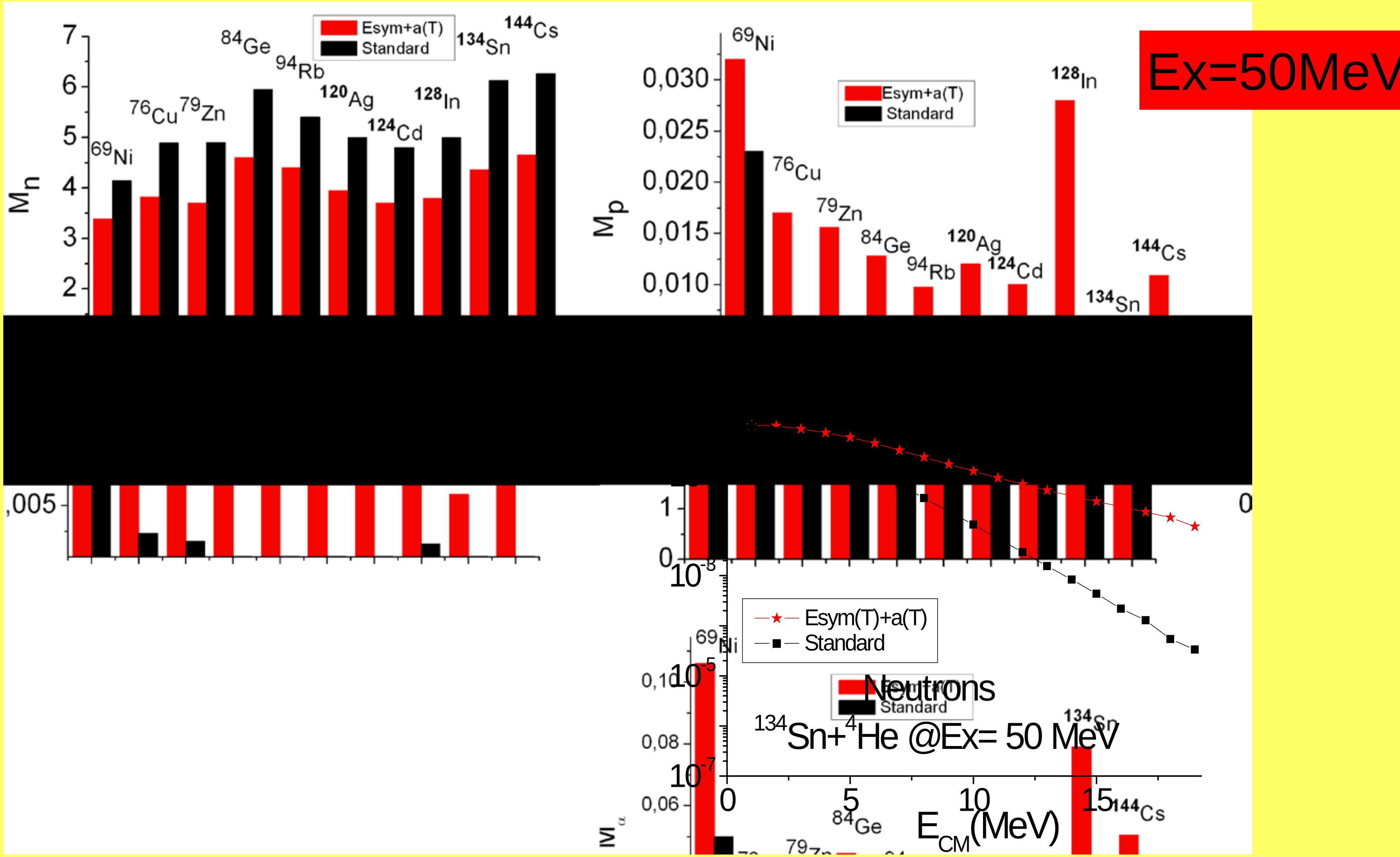
a(T) and E_{sym}(T) from P. Donati et al. Phys. Rev. Lett. 72, 2835 (1994)
Framework: Dynamical Shell Model
Hartree-Fock and Coupling single particle states to surface vibrations

Increasing T

Decrease of the nucleon effective mass m* → decrease of a(T)

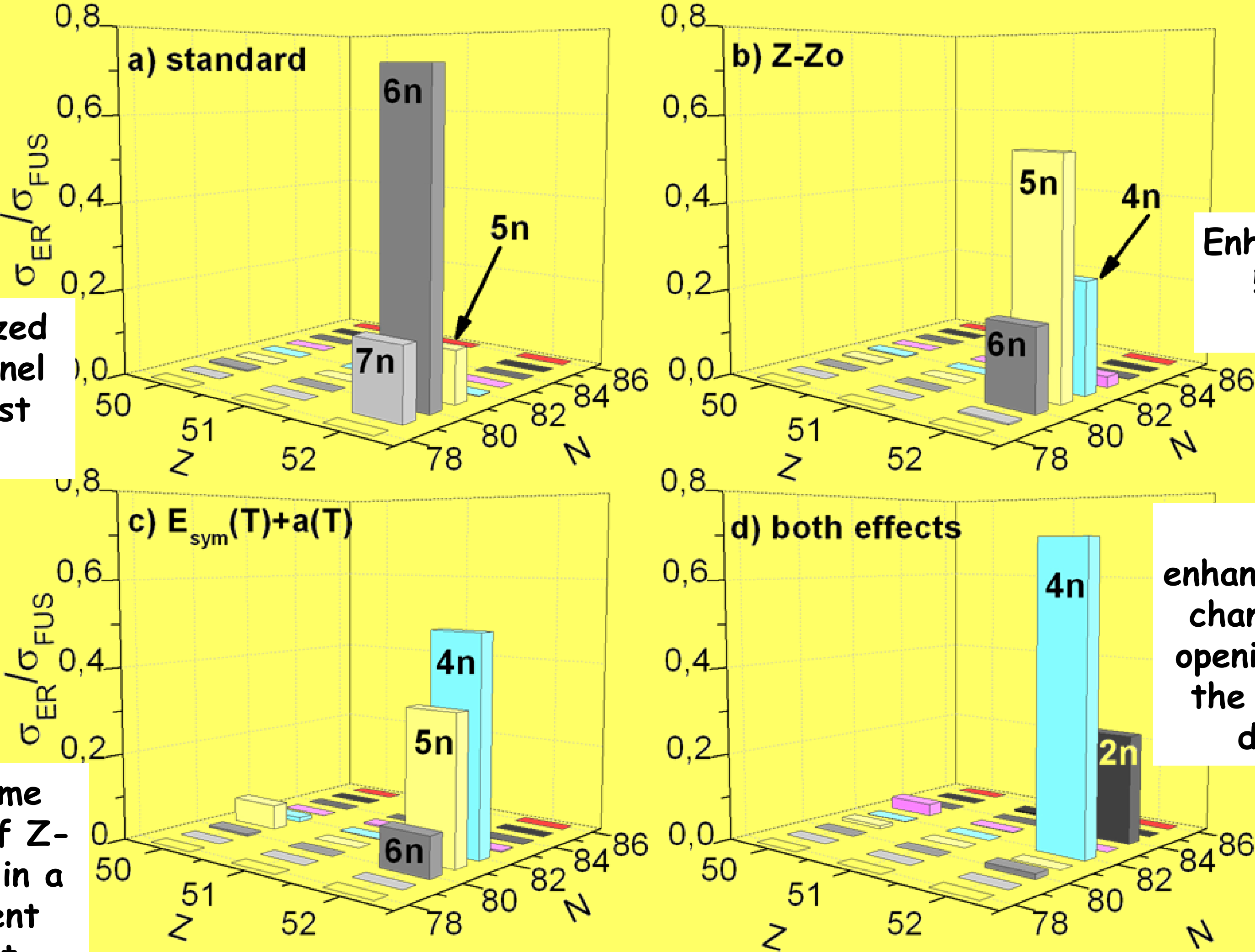
Increase of E_{sym}(T)→ increase of nuclear mass, decrease of BE

SM predictions for exotic nuclei (RIB's + 4He)



lcp channels are open including Esym(T)+a(T) effects

Calculations with isospin effects for $^{134}Sn+^{4}He$ @Ex=50MeV



Characterized by 6n channel as the most intense

Enhancement of 5n and 4n channel.

The same effect of Z-Zo, but in a different extent

Strong enhancement of 4n channel and the opening of 2n, all the other being depressed

Measurements and expected rates

Measurements require decay channel selection: γ-rays (AGATA or GALILEO) in coincidence with neutrons (NEDA).

	Euroball-DIAMANT	AGATA-NEDA	AGATA-NEDA
	STABLE BEAM “1 week”	$^{134}Sn+^{4}He$	$^{132}Sn+^{4}He$
		E_{LAB}~10 MeV/A	E_{LAB}~10 MeV/A
Φ(pps)	$1*10^{9}$	$5*10^{5}$	$3*10^{7}$
ε_{LP}	60%	40%	40%
ε_{γ}	10%	≥10%	≥ 10%
σ_{ch}	1 mb	200 mb	200 mb
Relative rates	1	≥ 0.06	≥ 4.5

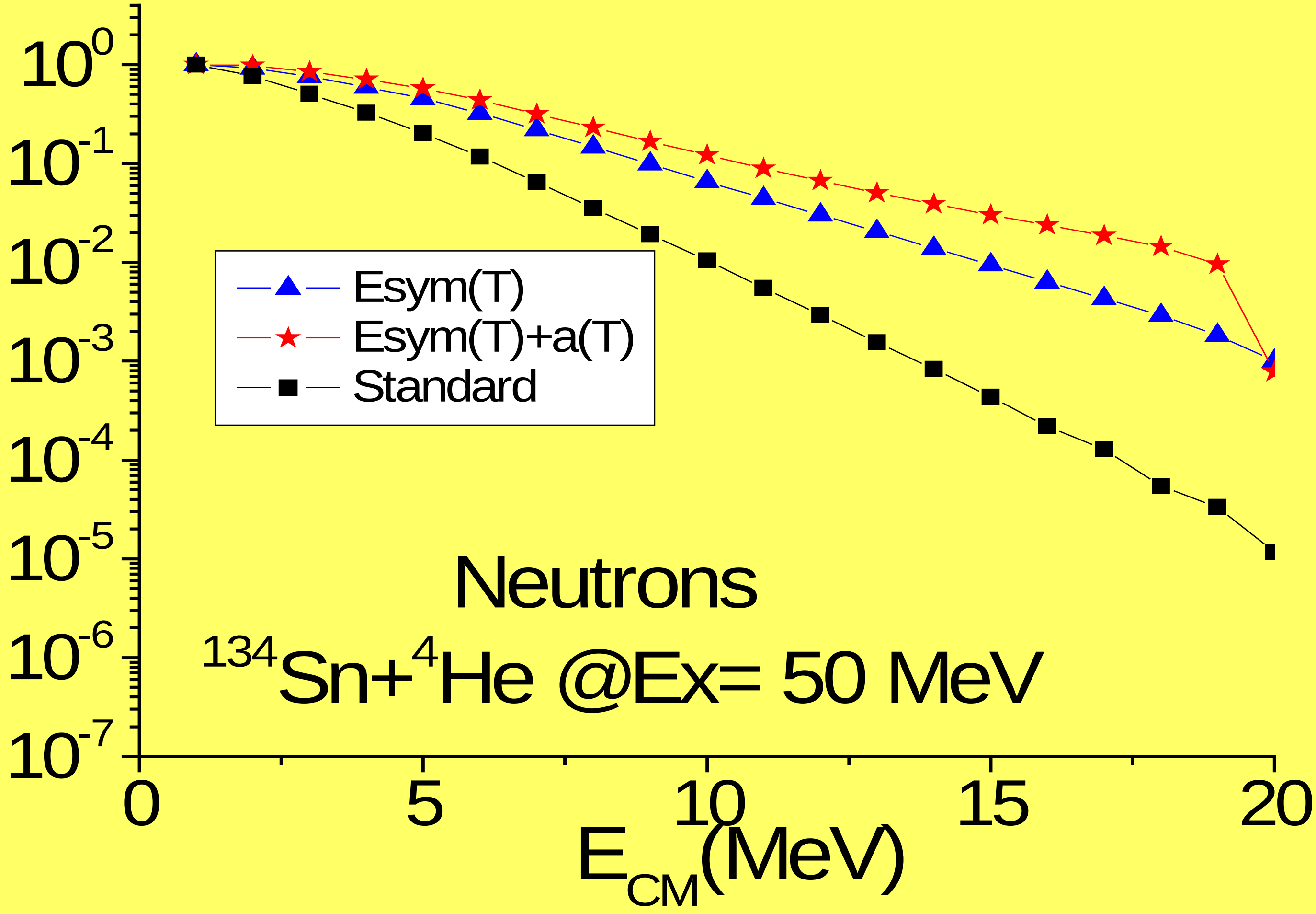
Conclusions

● Level density of exotic nuclei can be strongly affected by the isospin degree of freedom, through the level density parameter *a* and the symmetry energy.

● Statistical model calculations show that evaporative light particles and evaporation residues are a good probe to study the level density of the exotic nuclei, that will be produced by SPES and SPIRAL2 facilities.

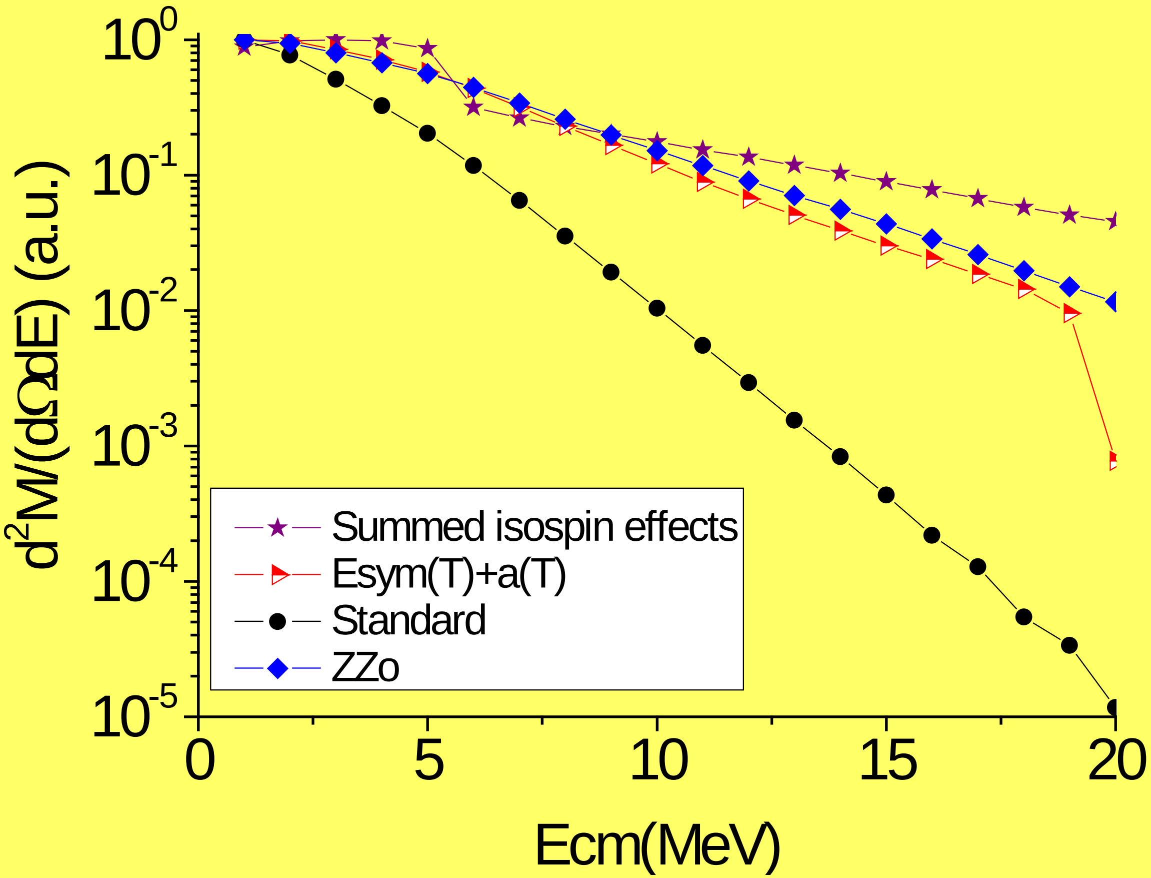
Backup transparencies

Symmetry Energy is the main effect with respect to the a(T)



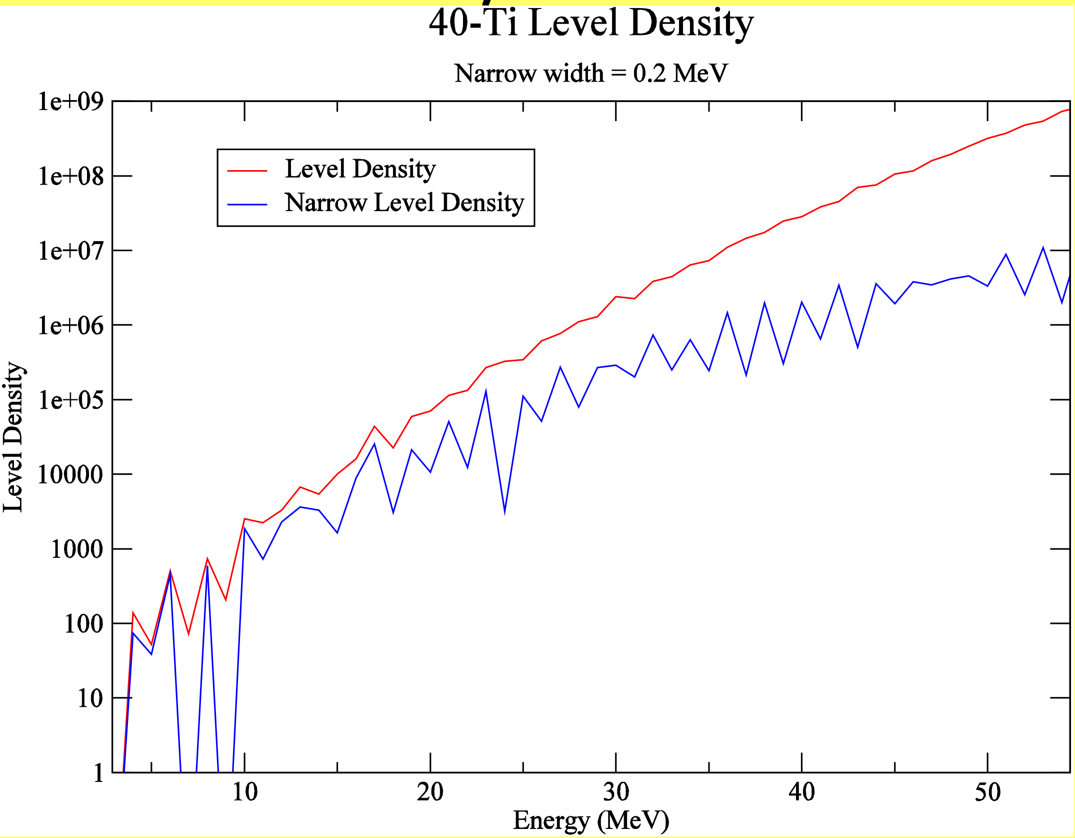
But they have to be treated in a consistent way according the model predictions

Neutron Spectrum in CM
$^{134}Sn+^{4}He$ @ Ex = 50 MeV



Z-Zo physics from Grimes

Resonances with Γ>0.2 MeV are considered not compound nucleus states (the life-time is less than the time need to the particle to cross the nucleus), therefore they are not take into account when the total number of level density is valuated. INCREASING OF INSTABILITY



A	B.E. (related to Z-Zo)	Uc
20	8	30.3
20	6	17.04
20	4	7.59
20	2	1.9
200	8	303
200	6	170
200	4	75.8
200	2	19

Assuming single particle in 1-Body potential → Calculate LD and Γ of each level at different Ex

Exp. Findings [Grimes2008]

Pal et al. a for 69At and 70Ge

The normal assumption a=$\alpha * A$ of ^{70}Ge 1.3% greater, but a fit to tabulated LD of 3%. In fact for ^{70}Ge Z-Zo=1, while for ^{69}At is 2→ a would be lowered of an additional amount. Al-Quraishi predicts this results

Zhuravlev et al. a for

(p,n) on different target ^{116}Sn, ^{118}Sn, ^{122}Sn and ^{124}Sn, the values of LD of corresponding Sb isotopes: the traditional model predicts that the *a* values increase with A, but the exp. results show the *a* decreases. And the dependence on Z-Zo is in agreement with Al-Quraishi.

Isospin physics N-Z from Al-Quraishi

$T_z = (N-Z)/2$

$T_{min} = T_z$

$T_{min} \leq T \leq A/2$

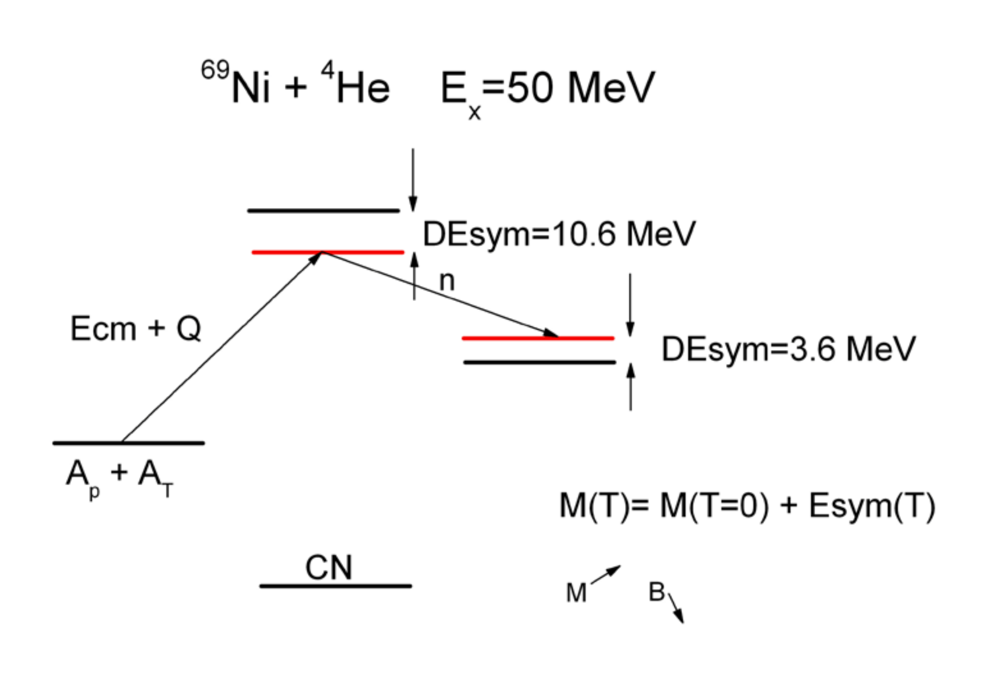
Possible states |Tmin,-Tmin,…,0,+Tmin>…|A/2,-A/2,…,0,…,+A/2>

Strong experimental dimostration of A=14 isobars, A=2 possible nuclei, B-decay and reaction process etc. [Bohr-Mottelson, Krane]

Increasing the difference between neutrons and protons the number of available isospin values decrease, due to the enhancement of lower value of T_{min}, while the maximum is fixed.

E_{sym} effect on the energy spectrum

During the cascade the Esym assumes a value around 3 MeV, it reduces the Ex and the emission probability of lp.
The reduction of emission probability is produced by a decrease of exponential argument of LD, that produce more similar values of probability at the high energy side of the spectrum, but the total light particle multiplicity decrease!!!



$$a(T) = a(T=0)\frac{m_{\omega}(T)}{m_{\omega}(T=0)}$$

The effective mass

Mean field theory provides a correct sequence of single-particle level, but fails in reproducing the observed LD

T [0,3MeV] → a~A/8
T>5 MeV→ a=A/15

In the Fermi gas model the symmetry energy can be written as a sum of kinetic and potential contributions.

While the kinetic energy scales as 1/m*, where m* is the effective mass, the potential contribution does not depend on m*.

In the framework of the dynamical shell model a reduction of the nuclear effective mass with temperature is expected, implying an increase of the symmetry energy. At the same time, this implies a decrease of the level density parameter *a* proportional to m*

$$Esym(T)=bsym(T)(N-Z)^2/A$$

If T increases also Esym increases

Esym=(Esym)pot + (Esym)kin

Independent on T (→ (Esym)pot)

Take into account the energy transferred as vibrational states (→ (Esym)kin)

The increase of Esym→ increase of nuclear Mass Ξ decrease of BE

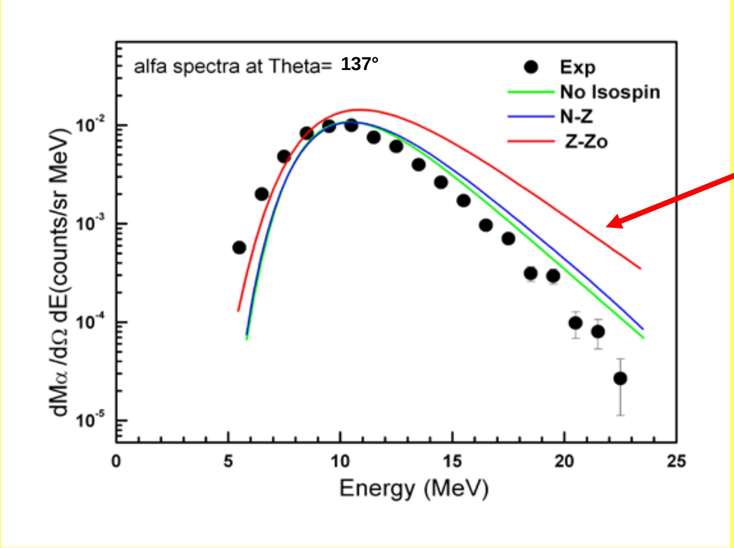
Effective mass

The H-F is a static approximation of many-body problem→ the presence of a mean field defines a surface that can vibrate. These vibrations renormalize the mean-field properties producing a total effect that increases the level density around the Fermi energy and it can be seen as an increase of effective mass with respect to experimental one. The energy parameter modifies only the nuclei with low lying energy at T=1-3 MeV, and doesn't affect the single particle level of T>5MeV, that have lower effective mass (~m_k=0.6 0.7 m) according the observation of a~A/15.

Effects of "a" decrease

If a decrease there is an increase of T ($Ex=aT^2$)
This produce an enhancement of the high energy side of the spectrum, but not an increase of the emission probability of lp.
In fact have to be taken into account that a decrease of "a" produce a reduction of the light particle emission probability as can be deduced from LD of residual nucleus

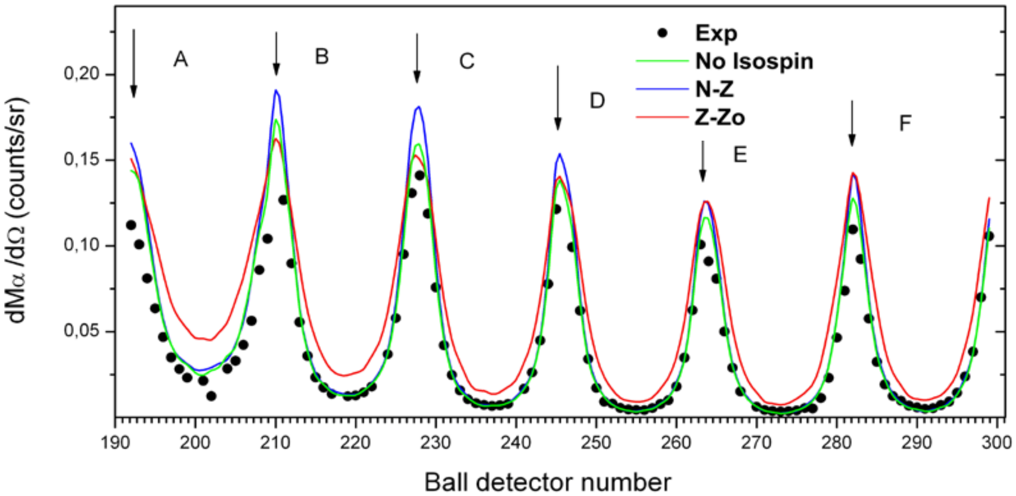
$$\rho(U) = \frac{1}{12\sqrt{2}} \frac{1}{\sigma a^{1/4}} \frac{\exp[2\sqrt{a(U-\delta)}]}{(U-\delta)^{5/4}}.$$



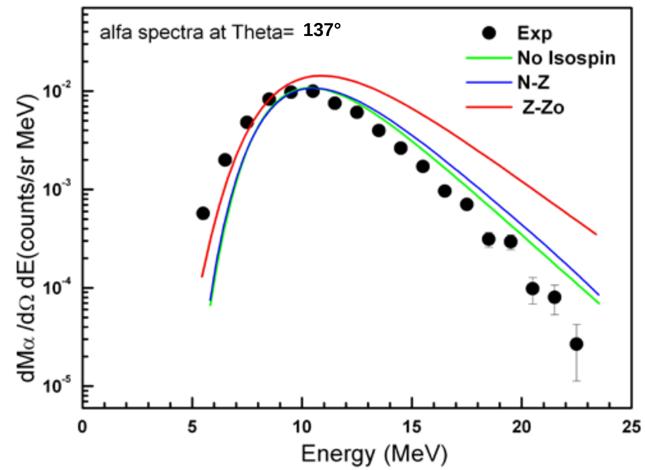
a reduction due to the effect of Z-Zo

$^{32}S + ^{107}Ag$ a E_{LAB} = 180 MeV: data vs SM simulations

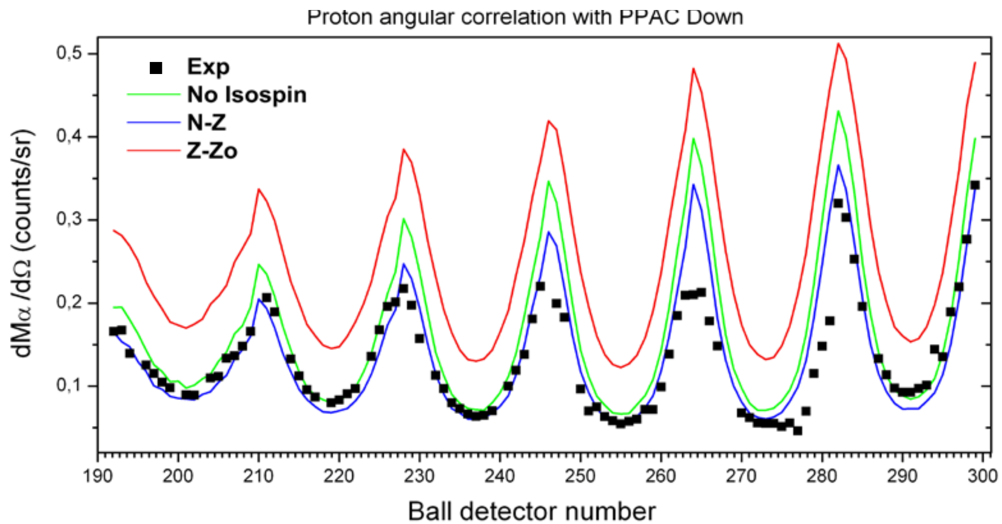
Multiplicity distribution of alpha particles

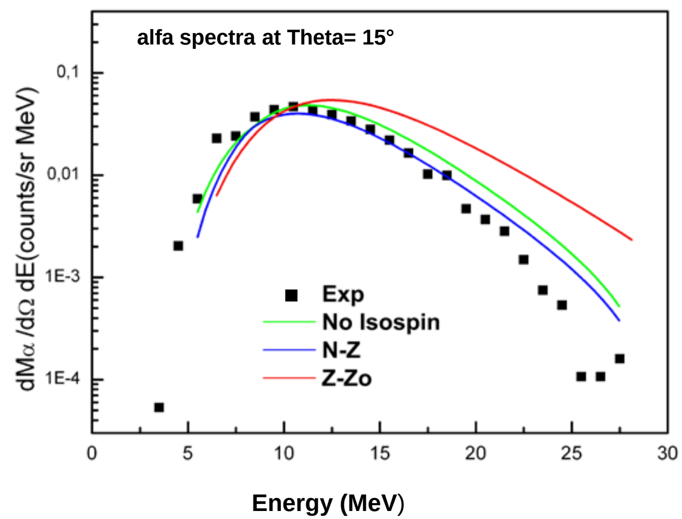


α energy spectrum



No evidence of Z-Zo effects – No possible to discriminate between st. and N-Z





Al Quraishi parameters are not appropriate for this Ex (?)