Exploring symmetry energy and level density parameters with isospin effects

LEA Colliga, november 23-24, 2009, Paris

INDRA+Vamos @ Spiral
Outlooks

Introduction
• Symmetry energy
• Level density parameters

Experimental set-up
• Indra (4Π array) + Vamos (spectrometer)

Preliminary results
• $^{34-36-40}$Ar+$^{58-60-64}$Ni @ 13 A MeV => FE cross sections
• $^{40-48}$Ca+$^{40-48}$Ca @ 35 A MeV => IMF isotopic yields

Improvements
• FAZIA (isotopic resolution on 4Π) + RIBs
Symmetry energy

The knowledge of the density dependence of nuclear symmetry $E$ is important in nuclear physics and astrophysics for understandings:

**Low density:**
Neutron skin, pigmy resonance, nuclear structure at the drip line, competition between mechanisms, neutron distillation in fragmentation, neutron star formation and crust

**High density:**
Neutron star mass-radius relation, transition to a deconfined phase, formation of black holes
First experimental measurements

First determination at $T=0$ and $\rho=\rho_0$, from fits on binding energies with liquid drop mass formula, with a symmetry term.

$$E_{\text{sym}}(N,Z) = C_{\text{sym}}(A) \cdot \frac{(N-Z)^2}{A}$$

Bulk term only (Bethe-Weizsaker)
$$C_{\text{sym}}(A) = C_{\text{sym}} \sim 32 \text{ MeV}$$

Bulk $\pm$ surface terms (Myers & Swiatecky, Moller & Nix)
$$C_{\text{sym}}(A) = C_V + C_S \cdot A^{-1/3}$$

Accepted values of $C_{\text{sym}} \sim 28-32 \text{ MeV}$
To a good approximation, at T=0, the EOS of nuclear matter is:

\[ \frac{E}{A}(\rho, I) = \frac{E}{A}(\rho, I=0) + \frac{E_{\text{sym}}}{A}(\rho) \times I^2 \]

symmetric matter

with

\[ I = \frac{(N-Z)}{A} \]

\[ \frac{E_{\text{sym}}}{A}(\rho) = C_{\text{sym}}(\rho) = C_{\text{sym}}(\rho_0) \left( \frac{\rho}{\rho_0} \right)^\gamma \]

\( \gamma \) define the stiffness of the EOS and allows comparison with models \( \Rightarrow \) still highly debated


B.A. Li PRL102 (2009)
Experimental tools

To explore different densities, heavy-ion collisions provide the only ways to compress/expand nuclear matter.

Observables sensitive to $E_{\text{sym}}$

**At subsaturation density:**
- competition of reaction mechanisms: fusion vs deep inelastic
- isospin diffusion
- N/Z of fast nucleon emission
- isospin distillation: isospin content of light fragments, $^3\text{H}/^3\text{He}$ or $^7\text{Li}/^7\text{Be}$
- neck fragmentation at Fermi energies
- neutron skin

**At suprasaturation density:**
- n-p collective flows
- meson production
Summary of experimental results

From Marie-France Rivet, Ecole Joliot Curie 2009

=> Not a so clear answer and still highly debated
How to go further?

Theoretically:
• implementation of predictive EOS
• analyse the results of calculations in the same way as data
• compare codes with all existing data

Experimentally:
• use of RIBs for evolution with isospin
• improve the detection to get Z and A over a larger range in particles and angular solid angle
• high statistics experiments
• new experiment to constrain the evaporative part (codes)

We measure cold fragments. Transport or statistical models consider hot fragments
⇒ in between we need a de-excitation code

⇒ Experiment on level density parameter with isospin : e494S
⇒ Experiment on symmetry energy : e503
A possible access to the symmetry energy in infinite matter

Heavy ion collisions $\Rightarrow$ Multifragmentation $\Rightarrow$ isotopic composition of fragments at low density $\rho<\rho_0$


$K(N,Z)$ a global isotopic distribution constructed by combining all yields of the fragments obtained in different systems to get the larger N/Z distribution as possible

40,48,60Ca+$^{40,48,60}$Ca and $^{46}$Fe+$^{46}$Fe @ 35 A MeV

Fitting procedure with 3 parameters $\xi, \eta, \zeta$

\[ K(N, Z) = \xi(Z) N + \eta(Z) + \zeta(Z) \frac{(N - Z)^2}{N + Z} \]
Accessing the symmetry energy...

\[ K(N, Z) = \xi(Z)N + \eta(Z) + \xi(Z) \frac{(N - Z)^2}{N + Z} \]

\[ \zeta(Z) = C_{sym} \left( \overline{A(Z)} \right) / T \]

\[ \zeta(Z) \propto 1 - k(2Z)^{-1/3} \]

\[ k = -\frac{C_s}{C_v} \]

\( \zeta(Z) \) independent of Z \( \Rightarrow \) negligible surface effects \( \Rightarrow \) symmetry E of infinite matter

\( \Rightarrow \) Need to be experimentaly confirm : e503 experiment
Effects on secondary decay

Secondary decay need to be taken into account for comparison with experimental data.

The results depend on the chosen $a \Rightarrow a$ should be determined: e494S experiment.
Level density parameter

Central collisions around 15 A MeV

Overlap of the density distribution of the colliding system

Fused system

Intermediate state: completely equilibrated system CN

Lack of the entrance channel memory

Decay determined by the statistical weights of possible final states

$\rho, a$
Exploration of the deexcitation properties of hot nuclei formed by fusion reactions with the N/Z from the p drip line to stable nuclei

\( \text{Ar} + \text{Ni} \rightarrow \text{Pd} \)

**The physic case**

**Event by event complete information:**
- Fusion residue detection and identification by the Vamos spectrometer (\(Z, A, E\))
- LCP in coincidence measured by the \(4\pi\) INDRA multidetector (Mult, \(Z, A, E\))
- + neutron multiplicity by \(A\) conservation

⇒ Complete study of the properties of the c.n. (cross section, mass asymmetry effects, deexcitation properties, thermodynamics…)
⇒ access to the level density parameter
Level density parameter: N/Z dependence

Fermi-gas model: \[ a = \frac{\pi^2}{6} (g_n + g_p) \propto A^{2/3} \left( N^{1/3} m_n + Z^{1/3} m_p \right) \approx mA \left[ 1 - \frac{1}{9} \left( \frac{N - Z}{A} \right)^2 \right] \]

Very scarce information is available
Extrapolations starting from stable nuclei lead to empirical parametrisations of the form:

\[ a = \alpha A / \exp[\beta (N-Z)^2] \]

Two of them give important variations for \( a(N/Z) \)

RIBs beams offer a great chance to perform measurements on a large range of isotopes

Such kind of basic thermodynamical properties are of fundamental interest

extrapolation according to:
The two experiments coupling INDRA and Vamos

**Symmetry energy experiment: E503**
Goal: experimental verification of AMD predictions
- $^{40}\text{Ca} + ^{40}\text{Ca} @ 35 \text{ A MeV}$
- $^{40}\text{Ca} + ^{48}\text{Ca} @ 35 \text{ A MeV}$
- $^{48}\text{Ca} + ^{40}\text{Ca} @ 35 \text{ A MeV}$
- $^{48}\text{Ca} + ^{48}\text{Ca} @ 35 \text{ A MeV}$

Both experiment performed at Ganil in spring 2007

**Isospin dependence of level density parameter: E494S**
Goal: study of the decay properties of CN with different isospins
- $^{34}\text{Ar} + ^{58}\text{Ni} @ 13.5 \text{ A MeV} \Rightarrow ^{92}\text{Pd}$
- $^{36}\text{Ar} + ^{58}\text{Ni} @ 13.3 \text{ A MeV} \Rightarrow ^{94}\text{Pd}$
- $^{36}\text{Ar} + ^{60}\text{Ni} @ 13.3 \text{ A MeV} \Rightarrow ^{96}\text{Pd}$
- $^{40}\text{Ar} + ^{60}\text{Ni} @ 12.7 \text{ A MeV} \Rightarrow ^{100}\text{Pd}$
- $^{40}\text{Ar} + ^{64}\text{Ni} @ 12.7 \text{ A MeV} \Rightarrow ^{104}\text{Pd}$
The two experiments coupling INDRA and Vamos

**INDRA**
- ~90% of 4π solid angle
- low E thresholds
- good E resolution
- large dynamic range in E and identification capability

=> good event by event characterization

**Vamos**
- large acceptance (100 msr)
- momentum acceptance 10%
- rotation around the target
- versatile focal plane detection setting

=> good products detection Z, A, Q, θ, φ
First results on N/Z level density dependence

E494S not yet fully calibrated

=> Quantitative information on FE cross section for Ar+Ni

Analysis limited to INDRA

Nor E or Z identification available so far

Selection FE residues, fragments selected on the basis of reaction mechanisms in which they have been produced

⇒ preliminary selection

Central collisions

• Fusion-Fission:
  2 fragments with masses close to half of the total mass of the system

• Fusion-Evaporation:
  Evaporated light particles
  1 heavy residue (Z ~ 30-40 GEMINI)
  ⇒ low Ekin and high A-Z

Peripheral collisions DIC

2 heavy fragments QP and QT
Comparison of the experimental and simulated differential angular cross sections for the five Ar+Ni reactions

Experimental data

Gemini simulations

P. Marini PhD thesis

=> Differential FE cross sections decrease as CN mass decreases
σ_{FE} decreases as the CN mass (N/Z) decreases
- σ_{FE} decreases much more than σ_{reaction} => isospin effects
- σ_{Rutherford} has the opposite trend

Strong decrease of σ_{FE} for ^{92}\text{Pd} CN => opening of new de-excitation channels?
Experimental cross sections for Ar+Ni reactions

INDRA limited to $7^\circ < \theta < 27^\circ \Rightarrow$ two procedures have been tested to correct from the geometrical acceptance

$\Rightarrow$ In the future Vamos data will provided additional information
First results on the symmetry E experiment

A. Chbihi - P. Marini et al.

Calibration-identification still in progress

Preliminary results for a given Bp and a single Si of Vamos focal plane
E503: isotopic identification for IMFs

A. Chbihi - P. Marini et al.
First result on the symmetry E experiment

\[ K(N, Z) = \sum_{i} w_i (N - \ln(\text{Yields})) \]

For comparison with AMD calculations:
- analysis for all Bρ and all detectors
- take into account secondary decays
- central collisions selection by INDRA multiplicity
Two experiments coupling INDRA and VAMOS

Isospin dependence of level density parameter
- Preliminary results
- Need of VAMOS data analysis
- Dependence of $\sigma_{FE}$ on the CN isospin
- Possible opening of a new de-excitation channel near the drip line for $^{92}$Pd

Symmetry energy in multifragmentation
- Comparison with AMD calculations
- Analysis of all data
- Secondary decays to be taken into account
  knowledge of decay properties (a,\rho...) required
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Very good uniformity ntd Si detector

$^{84}\text{Kr} + ^{58}\text{Ni}$ @ 35 A MeV LNS Catania
Perspectives

Single shape analysis on one Si with digital electronic

$^{84}\text{Kr} + ^{58}\text{Ni} \at 35 \text{ A MeV LNS Catania}$
Perspectives

Single shape analysis on one Si with digital electronic

$^{129}$Xe+$^{58}$Ni @ 35 A MeV LNS Catania

E vs rise time of Q signal
Level densities govern the statistical decay of excited nucleus
=> basic ingredients for statistical models

Up to now fusion-evaporation reactions were studied through inclusive measurements (A or Z of residues or light particle spectra)

For the very first time we will be able to have information on the residue and all the evaporated particles in coincidence

⇒ all decay chains will be measured, disentangled and weighed

For example:
Ar+Ni -> p+xn+Rh
Ar+Ni -> α+xn+Ru
Ar+Ni -> 2p+xn+2n+Ru
Ar+Ni -> p+d+(x+1)n+Ru
Ar+Ni -> 2p+d+yn+Tc
....

E spectra for all evaporated particles will be measured with INDRA
Level density parameters

For comparison with statistical model

1st constraint: $E_{\text{CIN}}$ spectra of all evaporated particles

2nd constraint: all exit channels for the same residue of c.n.
Fit experimental multichance emission spectra with GEMINI simulations for example:

Cannot fit with constant level density parameter $a$.

A depend on $A$ and $E^*$ which decrease all along the evaporation chain.

An effective $a_{\text{eff}}$ is necessary into Gemini calculations:
Starting from experimental slopes we constrain an $a_{\text{eff}}$ which then evolves with $E^*$, in the model, all along the deexcitation chain.

$$\rho(E^*) \propto \exp\left[2\sqrt{a_{\text{eff}}(E^*)E^*}/E^{*2}\right]$$

$$a_{\text{eff}}(E^*) = \frac{A}{K+k\frac{E^*}{A}}$$

Experimental spectra $\leftrightarrow$ Gemini simulations

Then by iteration we find level densities and level density parameters consistent with data.

INDRA is able to measure such kind of variation on the slope of all evaporated particles.

But now information on the dependence of $a$ with $N/Z$ is also necessary.