Nuclear Structure far from Stability

Gull Lake, Oct. 7 2002

I. Motivation

II. Status of present theories

III. Covariant Density Functional Theory

IV. Pairing correlations

V. New phenomena far from stability

- Quenching of spin-orbit
- Neutron skins
- Neutron halos

VI. Beyond mean field

VII. Excited states

VIII. Conclusions and outlook

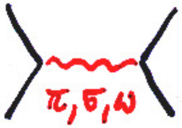
NN - Sattering Data

nonrel. Analysis

relativ. Analysis

Bonn, Paris, Argonne

(… 2-body LS, Tensor…)



rel. Bonn-potential

$\Downarrow$ non-relat. Brückner

$\Downarrow$ rel. Brückner

$$\frac{p^2}{2m} + \sum \underbrace{G(\rho)\cdot\rho}_{W}$$

$$\begin{pmatrix} V - S & \vec{\sigma}(\vec{p} + \vec{V}) \\ \vec{\sigma}(\vec{p} + \vec{V}) & -2m + V + S \end{pmatrix}$$

Kinematics:

$$E_k = \frac{\vec{p}^{\,2}}{2m}$$

$$E_k = \sqrt{\vec{p}^{\,2} + m^2}$$

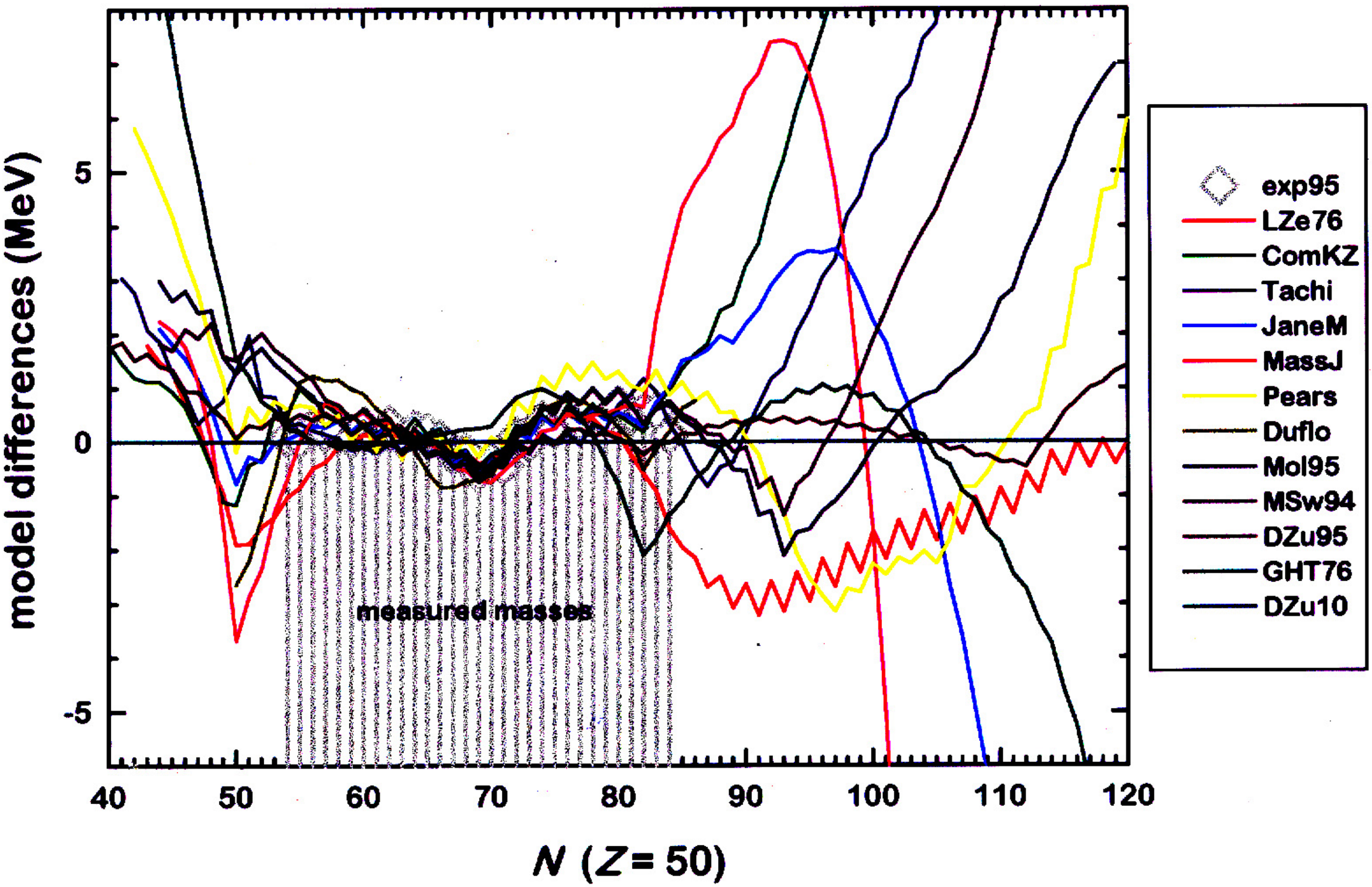
Dynamics:

$$W(r)$$

$$S(r), (V, \vec{V})$$

$$\rho_s, (\rho, \vec{j})$$

comparison of mass model predictions



MISTRAL Collaboration *CSNSM-Orsay*

Ab-initio calculations

Urbana - Argonne (Greens function Monte Carlo)

Tuscon - Livermore (No-Core Shell Model)

Seattle

Non-relativistic

NN and NNN forces

$A \leq 10, 12, \ldots$

Shell-Model calculations

Strasbourg - Madrid (conventional Lanczos) 10^8

Tokyo (Monte Carlo Shell Model) 10^{12}

Madrid - Delaware (Renormalization - Group) 10^{129}

Passadena - Yale (Partition Function)

limited spaces (sd, pf, ... ?)

effective interactions, monopole part

Center of mass problem

Continuum Shell Model

Mean-Field-Methods (Effective Field Theories)
(Density-Functional-Theories)

Nilsson-Strutinski (Mic-Mac)

Density-dep. Hartree-Fock (Skyrme, Gogny)

Relativistic Mean Field

universal

mostly only groundstates

specific excited states

Extensions beyond Mean-Field

Cluster Models

Phaenomenolog. Models ...

All these theories contain phenomenological parameters!

The general concept of mean field theories is:

$$E = \langle \Psi | H | \Psi \rangle = \langle \Phi | \hat{H}_{eff} | \Phi \rangle = E[\hat{\rho}]$$

(density functional theory of Kohn and Sham)

Mean field and the effective interaction:

$$h = \frac{\delta}{\delta \hat{\rho}} E[\hat{\rho}], \quad \text{and} \quad V = \frac{\delta^2}{\delta \hat{\rho}^2} E[\hat{\rho}].$$

This concept is very general. It allows:

- correlations (e.g. Brueckner) in $\hat{H}_{eff}$
- symmetry restauration $\hat{H}_{eff} \to \hat{P}^I \hat{H}_{eff} \hat{P}^I$
- coupling to vibrations $\hat{H}_{eff} \to \hat{H}_{eff}(E)$
- dynamics in time-dependent mean field theory (RPA)

$$\Phi(\vec{r}_1 \ldots \vec{r}_A) = \mathcal{A}\{\varphi_1(\vec{r}_1) \ldots \varphi_A(\vec{r}_A)\}$$

$$\hat{\rho}(\vec{r}, \vec{r}\,') = \langle \Phi | \psi^+(\vec{r}\,') \psi(\vec{r}) | \Phi \rangle$$

$$= \sum_{i=1}^{A} | \varphi_i(\vec{r}) \rangle \langle \varphi_i(\vec{r}\,') |$$

Determination of H_{eff} ?

- Strutinski : $E(\beta) = E_{LDM}(\beta) + \delta E_{sh}(\beta)$

- Density Functionals : $E[\hat{\rho}] = \langle \phi | T + \underbrace{t_0 + t_{1,2}\, p^2 + t_3\, \rho^\alpha + W_0 V_{LS}}^{V} | \phi \rangle$

  (Skyrme, Gogny) $= E[\rho, \tau, \vec{j}, \vec{s}, J_{\mu\nu}, \vec{T}]$

- Relativistic Mean Field

$$\mathcal{L}[\psi, \sigma, \omega, \rho \ldots]$$

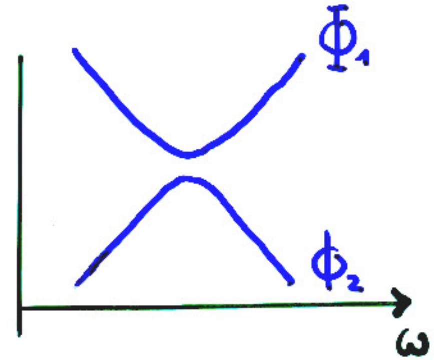
$$\Leftrightarrow \quad E[\hat{\rho}_{rel}]$$

$$\hat{\rho}_{rel}(\vec{r}, \vec{r}') = \sum_{i=1}^{A} |\psi_i(\vec{r})\rangle\langle\psi_i(\vec{r}')|$$

Limits of Mean Field Theory:

- Level crossings

  diabatic or adiabatic ?



$$|\psi\rangle = \alpha_1 |\phi_1\rangle + \alpha_2 |\phi_2\rangle$$

$\rightarrow$ GCM: $|\psi\rangle = \int f(q)\, |\phi(q)\rangle$

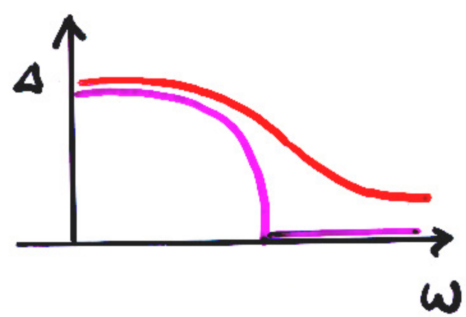
- Dissipation and Damping

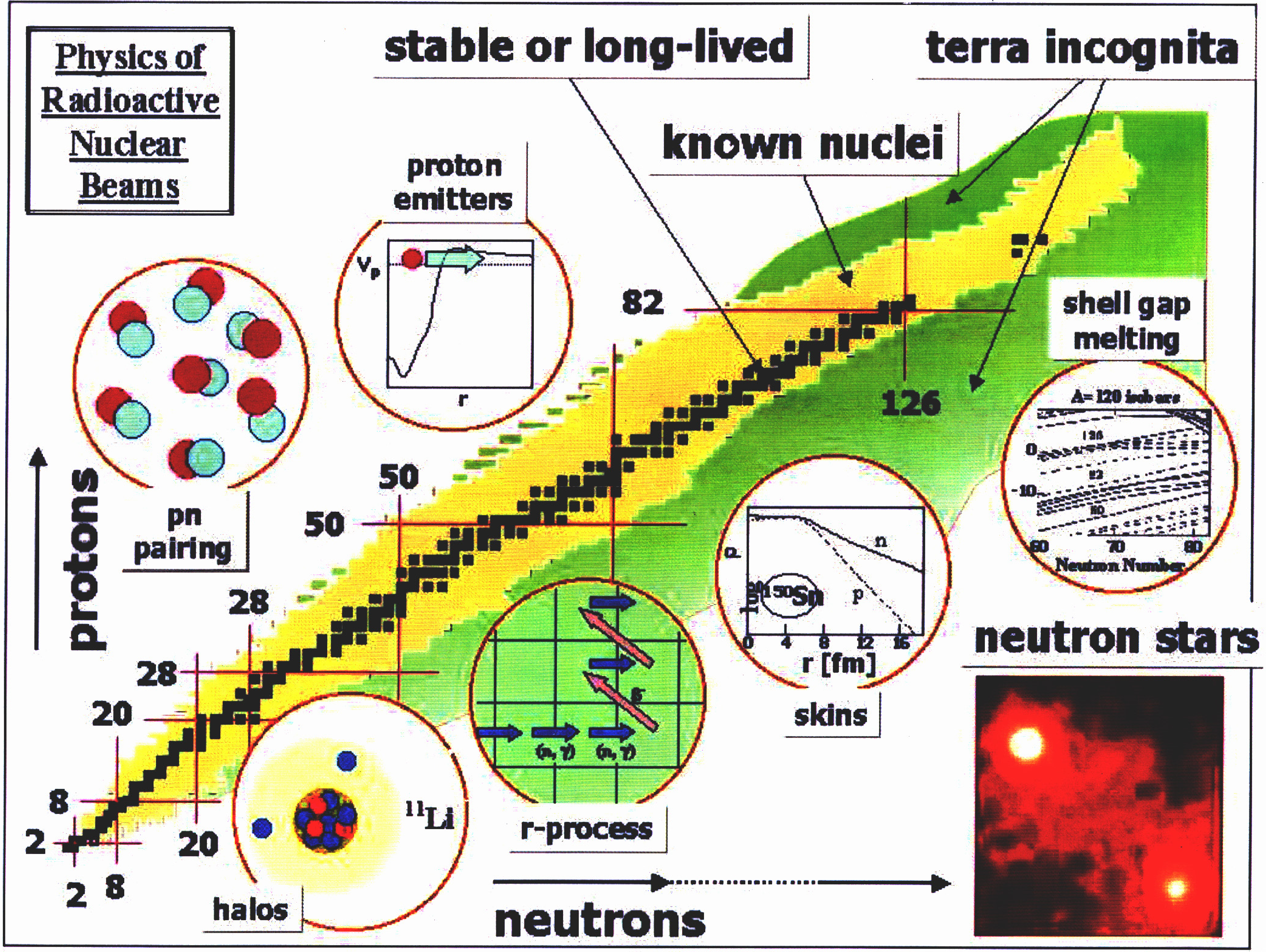
  Width of Giant Resonances

  Mean Fields with imaginary parts ?

- Region of Phase-Transitions:

  Collapse of RPA





Physics of Radioactive Nuclear Beams
stable or long-lived
terra incognita
known nuclei
proton emitters
V_p
r
82
126
shell gap melting
A=120 isobars
Neutron Number
50
50
28
28
20
20
8
8
2
2
pn pairing
protons
neutrons
^{11}Li
halos
r-process
(n, γ)
(n, γ)
n
p
^{150}Sn
r [fm]
skins
neutron stars

Why relativistic ?

Experimental hints!

- Success of rel. Brueckner Theory — E/A , ρ_0
- Large Spin-orbit in nuclei (with proper sign) — magic numbers
- Weak isospin dependence of spin-orbit — isotopic shifts
- Pseudospin symmetry (Ginocchio 1997) — single particle structure ($\mu \approx 0.5$)

  (Chiral symmetry ?)
- Relativistic saturation mechanism ($\rho_s \neq \rho$)
- Nuclear magnetism: magnetic moments
  moments of inertia: $\oint$
  incompressibility of nucl. matter
- Simplicity and elegance!

Non-relativistic kinematics!

Conclusions

Nuclei are relativistic systems!

large scalar and vector fields S and V

S is attractive
V is repulsive $\qquad S \approx V$

- $S - V$ is small $\Rightarrow$ small velocity, nonrelativistic kinema
- $S + V$ is large $\Rightarrow$ large spin-orbit (week isospin dep.)
- $V/S \approx 1$ $\Rightarrow$ pseudospin symmetry
- $\rho_s \neq \rho$ $\Rightarrow$ relativistic saturation mechanisme
- systems without timereversal symmety
  $\Rightarrow \vec{V}$ nuclear magnetism
- unified and universal description of nuclear properties
- Simplicity and Elegance!

One needs ~ 6 phenomenological parameter

qualitative agreement with QCD-arguments!