Magicity of neutron rich isotopes: Lorentz tensor effect

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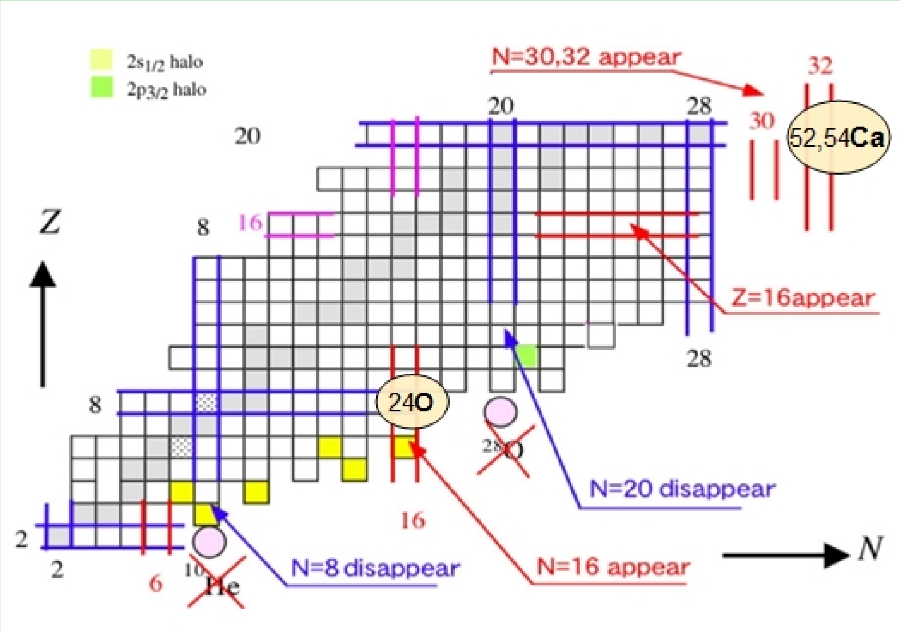
OUTLINE

Nuclear magic numbers: New features far from stability

Dramatic evolution of single-particle states in exotic nuclei
Physics mechanism: central force? spin-orbit? tensor force? three body force?...



R. Kanungo, Phys. Scr. T (2013)

Theoretical challenges

- Covariant density functional (CDF) theory: Why covariant?
  - Connection to QCD: large vector and scalar fields.
  - Relativistic saturation mechanism.
  - Self-consistent spin-orbit coupling guaranteed by Lorentz covariance.
- Relativistic Hartree-Fock (RHF) vs Relativistic Hartree (RH or RMF)
  - Tensor force originating from the exchange Fock term.

Theoretical challenges

- Covariant density functional (CDF) theory: Why covariant?
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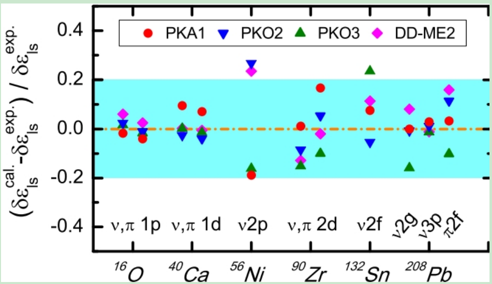
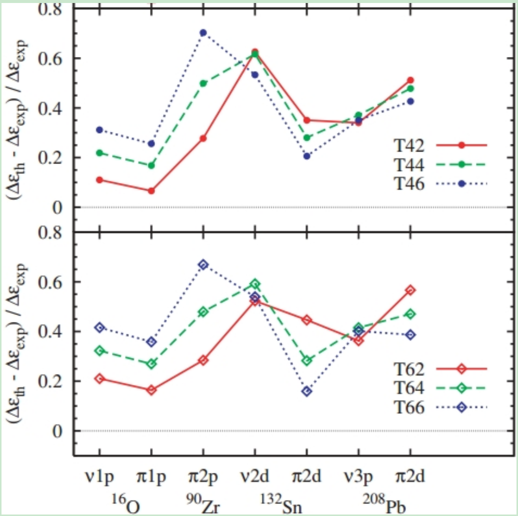
- Relativistic Hartree-Fock (RHF) vs Relativistic Hartree (RH or RMF)
  - Tensor force originating from the exchange Fock term.
- Good reproduction of SO splitting from light to heavy nuclei



J.Li, et al, Phys. lett. B (2014)

- Relative differences are typically 20% when both partners are particle or hole states.
- Compared to the non-relativistic Skyrme-Hartree-Fock calculations, better agreement with the data is obtained by the CDF models.



T. Lesinski, et al, Phys. Rev. C (2007)

Lorentz tensor in relativistic Hartree-Fock

Lorentz tensor in relativistic Hartree-Fock

A. Bouyssy (1987)

- Lagrangian density

$$\mathcal{L}(\psi, \phi, A), \qquad \phi = (\sigma^{\mathrm{S}}, \omega^{\mathrm{V}}, \rho^{\mathrm{V}}, \rho^{\mathrm{T}}, \pi^{\mathrm{PV}}) \tag{1}$$

- System Hamiltonian

$$H = \int d\boldsymbol{x} \bar{\psi} \left(-i\boldsymbol{\gamma} \cdot \boldsymbol{\nabla} + M\right) \psi + \frac{1}{2} \int d\boldsymbol{x} d\boldsymbol{x}' \bar{\psi}(\boldsymbol{x}) \bar{\psi}(\boldsymbol{x}') \Gamma_{\phi} D^{\phi} \psi(\boldsymbol{x}') \psi(\boldsymbol{x}) \tag{2}$$

Interaction matrices $\Gamma_{\phi}(\boldsymbol{x}, \boldsymbol{x}')$, Yukawa Propagators $D_{\phi}(\boldsymbol{x}, \boldsymbol{x}')$

- Lorentz tensor product:

$$\Gamma_{\pi} \equiv \frac{-1}{m_{\pi}^2} \left(f_{\pi} \vec{\tau} \gamma_5 \gamma_{\mu} \partial^{\mu}\right)_x \cdot \left(f_{\pi} \vec{\tau} \gamma_5 \gamma_{\nu} \partial^{\nu}\right)_{x'} \tag{3}$$

$$\Gamma_{\rho}^{\mathrm{T}} \equiv \frac{1}{4M^2} \left(f_{\rho} \sigma_{\nu k} \vec{\tau} \partial^{k}\right)_x \cdot \left(f_{\rho} \sigma^{\nu l} \vec{\tau} \partial_{l}\right)_{x'} \tag{4}$$

In the relativistic framework, the tensor contribution can be estimated ONLY when the Fock term is included, because this contribution does not have any effect at the simple Hartree level (RH or RMF).

Lorentz tensor in non-relativistic limit

- Lorentz tensor:

$$\Gamma_\pi \equiv \frac{-1}{m_\pi^2}\left(f_\pi \vec{\tau}\gamma_5\gamma_\mu\partial^\mu\right)_x \cdot \left(f_\pi \vec{\tau}\gamma_5\gamma_\nu\partial^\nu\right)_{x'} \tag{5}$$

$$\Gamma_\rho^{\mathrm{T}} \equiv \frac{1}{4M^2}\left(f_\rho \sigma_{\nu k}\vec{\tau}\partial^k\right)_x \cdot \left(f_\rho \sigma^{\nu l}\vec{\tau}\partial_l\right)_{x'} \tag{6}$$

- Non-relativistic limit:
  - ☞ $\pi - PV$

$$V_\pi^T(\boldsymbol{r}) = f_\pi^2\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\, S_{12}\left(1 + \frac{3}{m_\pi r} + \frac{3}{(m_\pi r)^2}\right)\frac{e^{-m_\pi r}}{r} \tag{7a}$$

$$V_\pi^C(\boldsymbol{r}) = f_\pi^2\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\; \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2\, \frac{e^{-m_\pi r}}{r} \tag{7b}$$

  - ☞ $\rho - T$

$$V_\rho^T(\boldsymbol{r}) = -f_\rho^2\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\, S_{12}\left(1 + \frac{3}{m_\rho r} + \frac{3}{(m_\rho r)^2}\right)\frac{e^{-m_\rho r}}{r} \tag{8a}$$

$$V_\rho^C(\boldsymbol{r}) = 2f_\rho^2\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\; \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2\, \frac{e^{-m_\rho r}}{r} \tag{8b}$$

  where S_{12} refers to the tensor operator

$$S_{12}(\boldsymbol{r}) \equiv 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{e}_r)(\boldsymbol{\sigma}_2 \cdot \boldsymbol{e}_r) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \tag{9}$$

The central term $V^C_{\pi(\rho)}$ plays an important role in the shell formation, which is different but as important as the Wigner term $V^T_{\pi(\rho)}$.

Relativistic Hartree-Fock-Bogoliubov equation

- RHFB equation: H. Kucharek(1991)

$$\int d\boldsymbol{r}' \begin{pmatrix} h(\boldsymbol{r},\boldsymbol{r}') - \lambda & \Delta(\boldsymbol{r},\boldsymbol{r}') \\ \Delta(\boldsymbol{r},\boldsymbol{r}') & -h(\boldsymbol{r},\boldsymbol{r}') + \lambda \end{pmatrix} \begin{pmatrix} \psi_U(\boldsymbol{r}') \\ \psi_V(\boldsymbol{r}') \end{pmatrix} = E \begin{pmatrix} \psi_U(\boldsymbol{r}) \\ \psi_V(\boldsymbol{r}) \end{pmatrix} \tag{10}$$

The integro-differential equations are solved by using a Dirac Woods – Saxon basis

- h: Dirac-HF Hamiltonian
  - ☞ PKO3: σ-S, ω-V, ρ-V and π-PV — W.H Long, et al.,(2006,2007)
  - ☞ PKA1: σ-S, ω-V, ρ-V, π-PV and ρ-T

- Δ: Pairing potential
  - ☞ Gogny D1S — J. Berger(1984)

$$V(\boldsymbol{r},\boldsymbol{r}') = \sum_{i=1,2} e^{((r-r')/\mu_i)^2} (W_i + B_i P^\sigma - H_i P^\tau - M_i P^\sigma P^\tau) \tag{11}$$

In our study, the effect of Lorentz tensor is deduced from the systematic deviation between the RHFB modeling (with tensor) and the RHB modeling (without tensor).

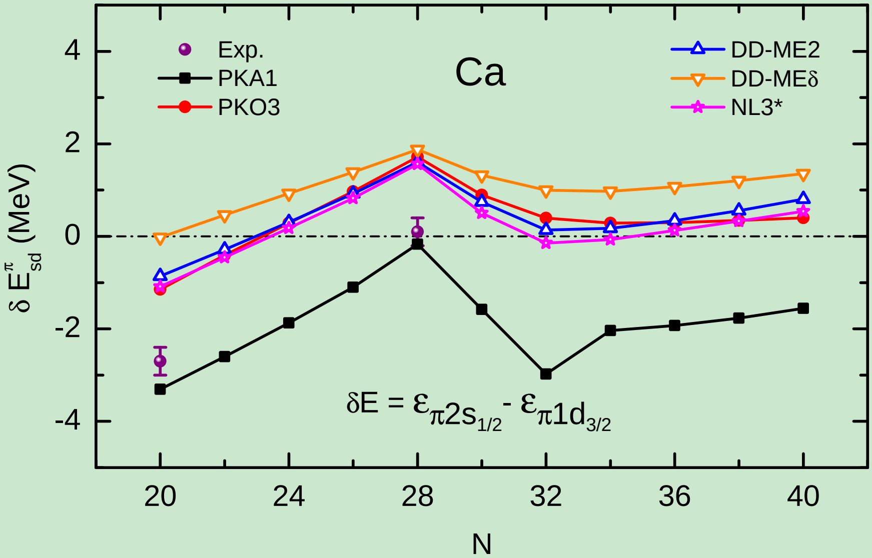
Results

Evolution of proton $\pi 2s_{1/2} - \pi d_{3/2}$ in Ca isotopes

The contribution of the Lorentz tensor is significant!

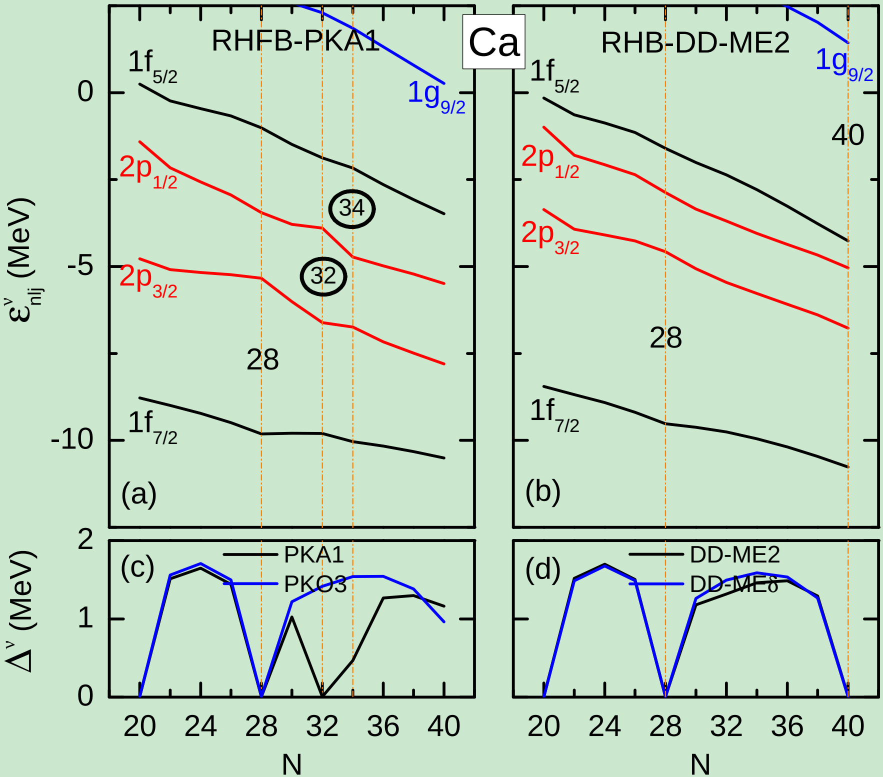
ρ-tensor coupling improve the agreement with the experimental dates

$$\delta E_{sd} = E(\pi 2s1/2) - E(\pi 1d3/2) \quad (12)$$



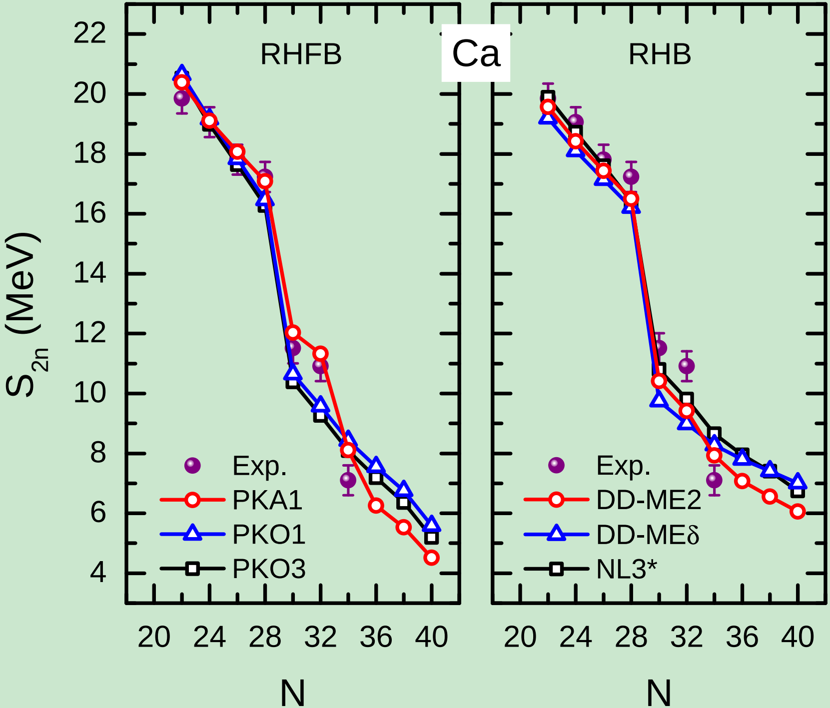
Neutron single-particle spectra of Ca isotopes: RHFB vs RHB

Neutron-neutron interaction: Remarkable fluctuations are governed by Lorentz tensor!



Two-neutron separation energies: RHFB vs RHB

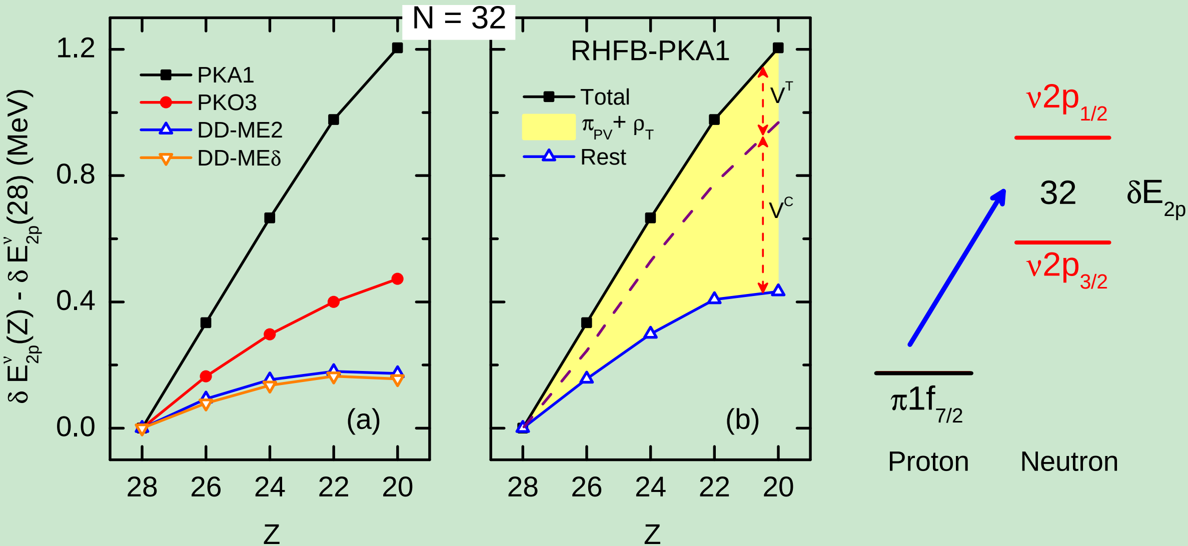
$$S_{2n} = B(N,Z) - B(N-2,Z) \tag{13}$$



Spin-orbit splitting of $\nu 2p$ along N=32: RHFB vs RHB

Proton-neutron interaction: Strong Lorentz tensor force! Most of the Lorentz tensor contribute to its central term!

^{60}Ni $\rightarrow$ ^{52}Ca, proton $\pi 1f7/2$ state is removed



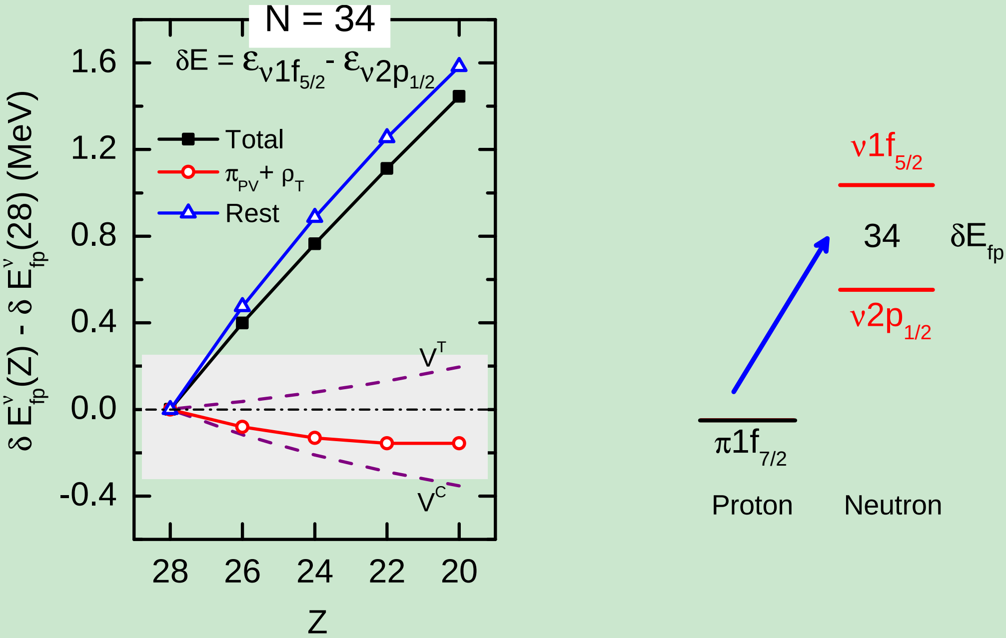
RHF: PKO3, PKA1

RH: DD-ME2, DD-MEd

Evolution of $\nu 1f_{5/2} - \pi 2p_{3/2}$ along N=34 isotones

Proton-neutron interaction: Cancelation between the Wigner-tensor and the central terms!

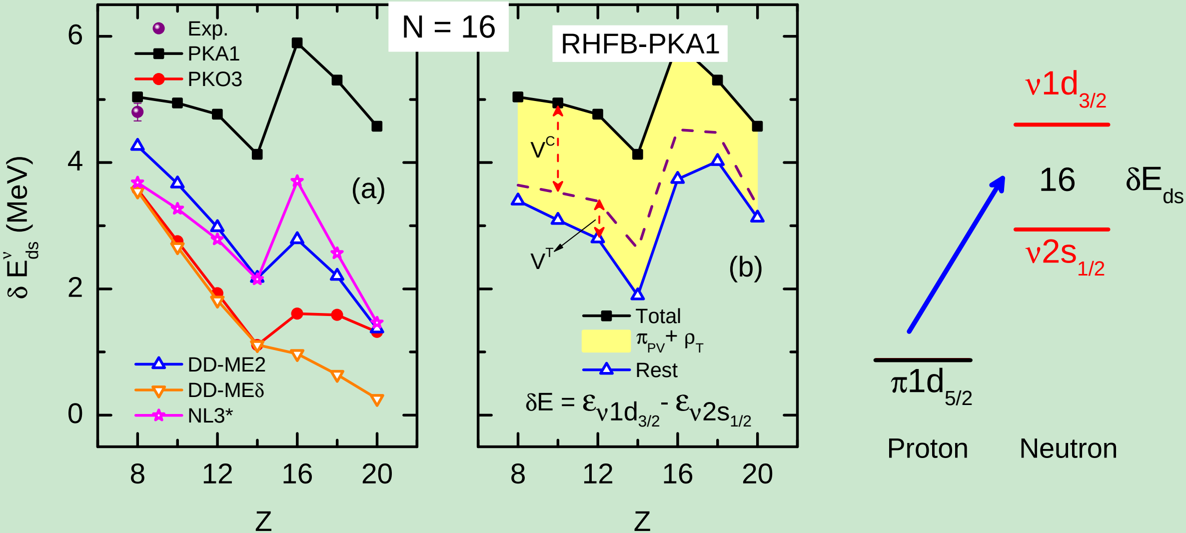
^{62}Ni $\rightarrow$ ^{54}Ca, proton $\pi 1f7/2$ state is removed



Evolution of $\nu d_{3/2} - \nu 2s_{1/2}$ along N=16 isotones

Lorentz tensor increase the energy differences between neutron $\nu d_{3/2}$ and $\nu 2s_{1/2}$ states

^{24}O $\rightarrow$ ^{30}Si, proton $\pi 1d5/2$ state is filled



RHF: PKO3, PKA1

RH: DD-ME2, DD-MEd, NL3*

Summary

- Lorentz tensor contributes significantly to the shell evolution.
- The magicity of $N = 16$ and 32, originate from the Lorentz tensor.
- The magicity of $N = 34$ gap, originates from the kinetic and isoscalar terms.
- From the s.p. energy gap, we predict $N = 16$, 32 and 34 as (sub)magic number, confirming the experimental measurements for 2_1^+ energies.

Summary

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Collaborators:

Prof. Jérôme Margueron	IPN, Lyon & Université Lyon-1
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Prof. Nguyen Van Giai	IPN, Orsay & Université Paris-Sud

Thank you for your attention!