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N-body correlations in exotic nuclear systems

Scientific report

2011-2014

One of the most active fields of the modern nuclear physics is the investigation of exotic nuclear systems, like proton/neutron rich nuclei by using radioactive beams and fission, or superheavy elements through fusion and α-decay processes. The motivation of this research is a better knowledge of the nucleon-nucleon interaction potential with a special emphasys on the isovector channel. Apart the interest this issue presents in itself it is worhwile to mention the important role it plays in determining the structure and evolution of compact astrophysical objects and supernovae. In this project we investigated some of these issues.

We will shortly describe in chronological order our main results.

2011

I.1. The influence of the alpha-clustering on electromagnetic and alpha transitions in ^{212}Po

We described recently discovered unnatural negative parity states in ^{212}Po in terms 3particle-1hole (3p-1h) excitations of the double magic nucleus ^{208}Pb. These states are connected to the ground state by relative large dipole electromagnetic transitions. Normal positive parity states have also large B(E2) values. As an essential ingredient we considered on top of the standard single particle basis a Gaussian component centered on the nuclears suface with 10% amplitude weight. This ingredient allowed to simultaneously describe not only dipole electromagnetic transitions in the following Table,

I^-	J^+	E_{MSM} (MeV)	$E(^{212}Po(I^-))$ (MeV)	$E(^{212}_{exp}Po(I^-))$ (MeV)	$B(E1)^{(1)}_{th}$ ($10^4 W.u.$)	$B(E1)^{(2)}_{th}$ ($10^4 W.u.$)	$B(E1)_{exp}$ ($10^4 W.u.$)
4^-	4^+	-0.303	1.808	1.744	9	11	25
	6^+	-0.107	2.201	1.946	2	4	11
6^-	6^+	-0.213	1.886	1.787	36	117	66
	8^+	-0.490	2.197	2.016	3	8	19
8^-	6^+	-0.489	1.816	1.751	42	143	200
	8^+	-0.215	2.240	1.986	8	24	-
10^-	8^+	-0.360	2.135	2.465	2	1	18

but also relative large B(E2) values the Table below

	^{210}Po		^{210}Pb		^{212}Po	
$J' \to J$	$B(E2)_{exp}$	$B(E2)_{th}$	$B(E2)_{exp}$	$B(E2)_{th}$	$B(E2)_{exp}$	$B(E2)_{th}$
$4 \to 2$	4.6(2)	12.9	3.2(7)	3.5		20.8
$6 \to 4$	3.0(1)	8.9	2.2(3)	2.4	13.5(36)	14.4
$8 \to 6$	1.18(3)	3.9	0.62(5)	1.0	4.60(9)	5.8

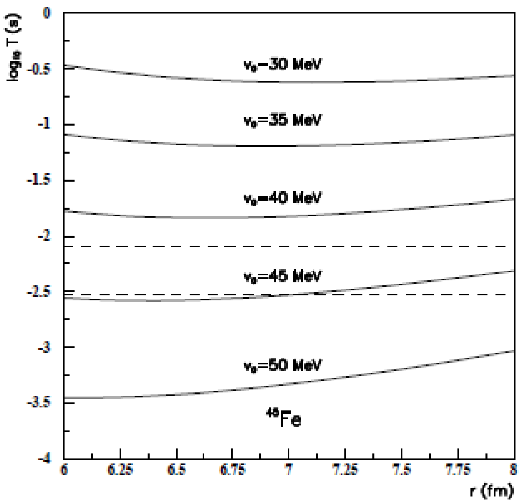
and the absolute alpha-decay width [2].

These results support the idea of the surface alpha-clustering in ^{208}Pb.

2012

II.1. Description of ternary emission processes by using three-body dynamics

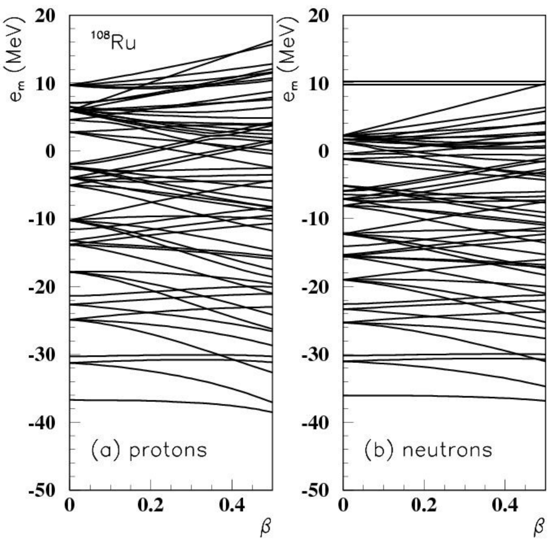
We made a systematics of the proton emission process [1] and based on these results we described two-proton emission process [6,11]. This is a rare process in proton rich nuclei and its description involves the three-body dynamics. We used pairing wave function as a boundary condition on the nuclear surface in order to solve the Schroedinger equation describing two-proton emission. As an inter-proton potential we used a nuclear Gaussian plus Coulomb interaction. It turns out that the half-life of ^{45}Fe emitter is very sensitive with respect to the strength of the nuclear interaction between protons [6], as can be seen from the Figure below

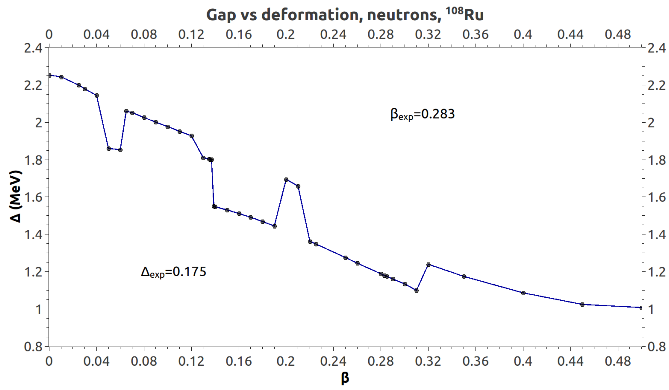


Thus, two-proton emission is a powerfull tool to investigate exotic proton-rich nuclei.

II.2. The use of paring G-matrix elements for hyperdeformed nuclei

Pairing interaction has an important role for fissioning hyperdeformed configurations. Our purpose was to investigate the dependence of pairing gap parameter with respect to the quadrupole deformation. We renormalized the realistic Paris potential in the siglet monopole channel to the model space of a finite nucleus and estimated the matrix elements in the deformed single particle basis, shown in the left panel below. We have shown that the gap parameter strongly depends on the quadrupole deformation, as can be seen in the right panel below.





II.3 Statistical ensemble inequivalence in stellar baryonic matter

The aim of our study was to investigate to what extend the dis-homogeneities that characterize the baryonic matter in the crust of neutron star can lead to statistical ensemble inequivalence. The stellar matter at sub-saturation densities is depicted as a mixture of interacting unbound nucleon gas and an ideal gas of clusters. In order to have the correct limit in the density regime pertinent for the crust-core transition, unbound nucleons have been described within a non-relativistic mean-field approach with Skyrme effective interactions. The Fisher model was adopted for the clusterized component. By resolving the system thermodynamics in the canonical and grand-canonical ensembles, we have shown that

a) there is a density domain not accessible grand-canonically and which suggests the existence of a first-order phase transition,

b) these density domain is accessible only canonically and shows an abnormal behavior of the chemical potential - baryonic density relation.

Strangeness-driven phase transitions

If hyperons do exist in neutron stars, one has investigate whether they produce a phase transition, as expected in systems with competing short- and long-range interactions. The issue was addressed by investigating three systems:

a) a simple neutron-lambda mixture which allowed us to build the full phase diagram of compressed baryonic matter with strangeness; three phase transition regions have been evidenced; of relevance for neutron star physics, a strangeness-driven phase transition occurs; it is explored under strange-equilibrium;

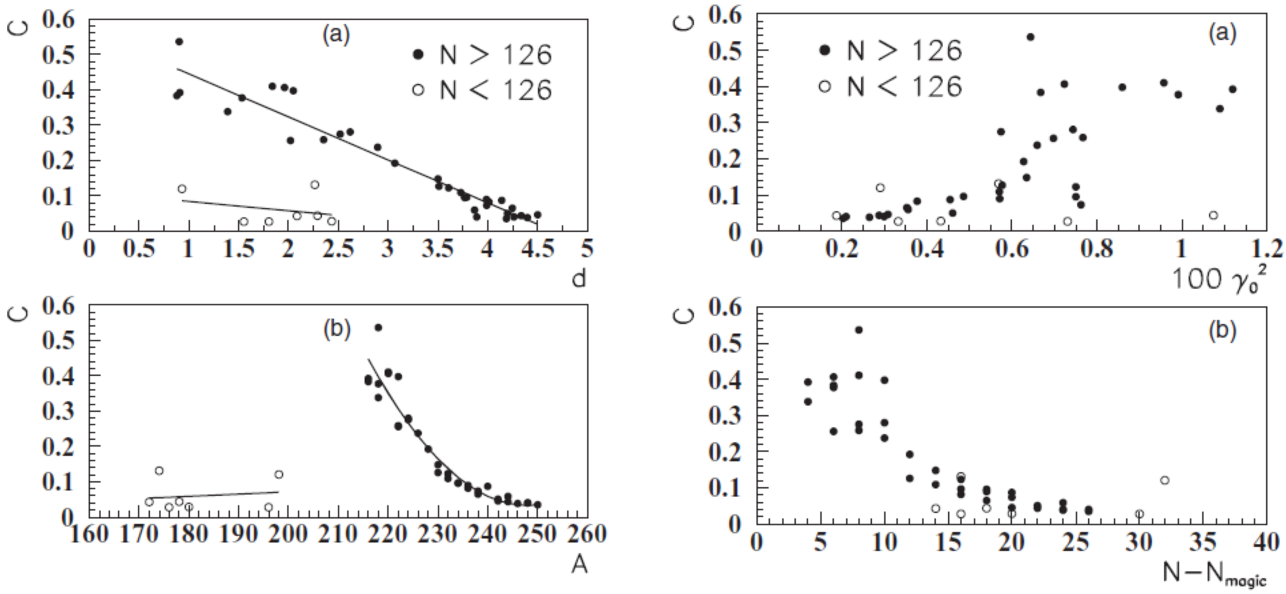
b) a neutron, proton, lambda and electron system was exploited in order to see whether the previously found strangeness-driven phase transition is explored also under beta-equilibrium and whether it persists the quenching effect of the uncompressible electron gas; phenomenological consequences of the critical points have been worked-out; it was shown that correlations beyond mean-field typical to the surroundings of a critical point dramatically diminish the neutrino men-field path and, thus, slow down the star cooling

c) the phase diagram of the full baryonic octed was investigated at low temperature; several phase transitions regions have been found; their stability with respect to model and parameter dependence was checked; if was found that important hyperonic abundances are compatible with both hyperonic phase transitions and two solar mass massive neutron stars. All the above mentioned studies have been performed within a non-relativistic mean-field model.

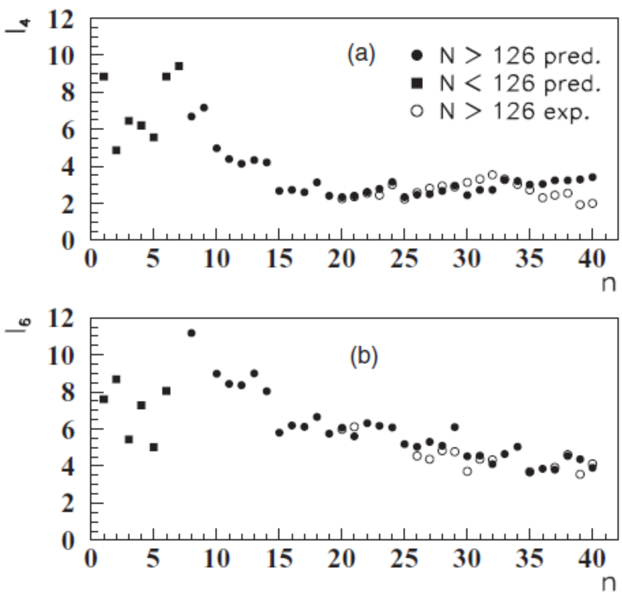
2013

III.1. Investigation of alpha-clustering properties in heavy and superheavy nuclei

Alpha-clustering is an important feature of nuclear systems, especialy for superhevy nuclei, which can be detected only by investigating alpha-decay chains. We described alpha decays to ground and excited low-lying states of even-even nuclei. We used coherent states to describe nuclear states. The deformation parameter was fixed by fitting energy levels. In order to describe alpha-decay dynamics we used quadrupole-quadrupole interaction. By fitting the decay widths to the lowest states we obtained a linear dependence of the coupling strength versus the deformation parameter, as predicted by the formalism, This as can be seen in the left (a) panel below. The strength parameter linearly dependes on the reduced wifdth (right (a) panel). It has large values above double magic nuclei and decreases witrh respect to the neutron number (right (b) panel) [8,10,16]



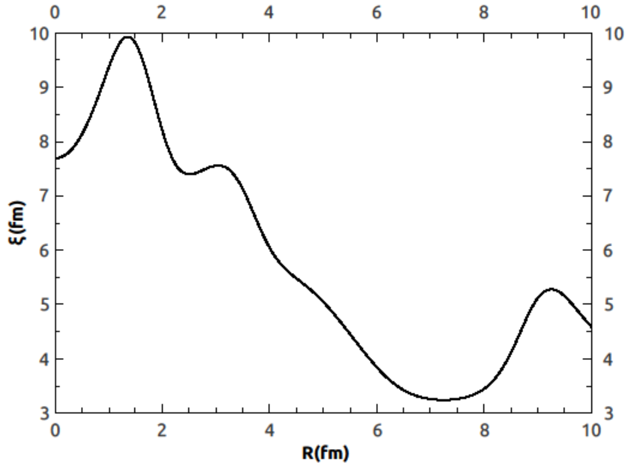
The intensities to 4^+ and 6^+ levela are well reproduced by using the above coupling strength, as can be seen in the Figure below.



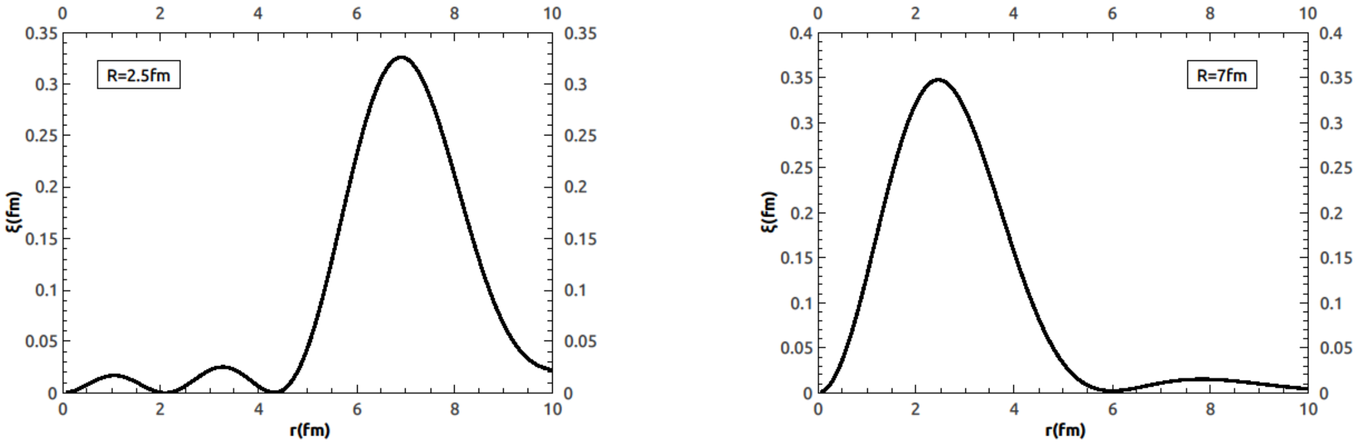
Thus, alpha decay spectroscopy in a powerfull tool to investigate alpha-clustering in nuclei.

III.2. Investigation of nuclear correlations

We investigated pairing correlation by computing the correlation length in even-even nuclei [17]. Corellation length is defined as the rooth mean squared computed with the pairing density. We used Gaussian two-body interaction. Correlation length has large values inside nucleus and decreases up to 2 fm on the surface, as can be seen in the Figure below for ^{48}Cr [18].



The corerence *ξ(R,r)* is peaked around 7 fm for a small value of the center of mass radius *R=2.5 fm,* while for *R=7 fm it* is peaked around 2 fm, as can be seen from the Figure below.



Finally, we used for the Gaussian width parameter the value given by the mean value of the coherence length <*ξ*>=6 fm and reproduced the half life of the two proton emitter 45Fe for the realistic value of the biproton strength V=35 MeV. Thus, the coherence length can bring useful information for nucleui structure of exotic proton rich nuclei.

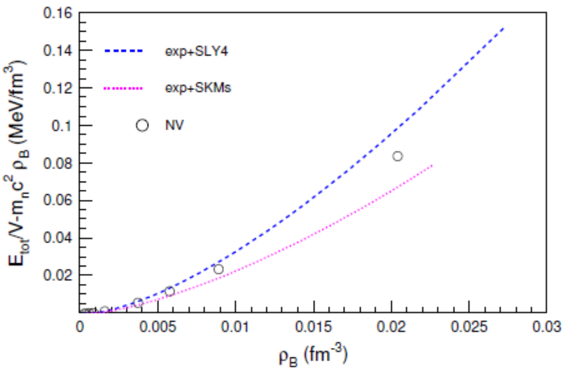
2014

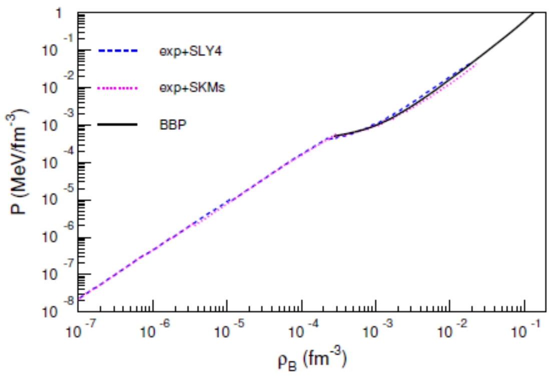
IV.1. Derivation of a new equation of state for stellar matter with smooth behavior for all range of validity

The evolution of core-collapsing stars leading to supernovae explosions or black-hole formation rely on accurate nuclear physics information through equations of states and interaction rates. The aim is challenging the more as huge density, temperature and isospin-asymmetry domains are spanned. In order to modelize the sub-saturated density domain in an unitary way we have developed a formalism valid at both zero and finite temperature. We have shown that the single nucleus approximation is the correct zero-temperature limit of the nuclear statistical equilibrium case.

The proposed framework was used to derive the crust composition and energetic corresponding to different effective nucleon-nucleon interactions.

On a short term we aim to contribute to the international effort (http://compose.obspm.fr/) of building equations of states ready-to implement in hydro-dynamical simulations of star evolution by providing in tabular form the relations between different thermodynamic observables.





List of papers

Published papers

01. C. Qi, *D.S. Delion*, R.J. Liotta, and R. Wyss, *Effects of formation properties in one-proton radioactivity,* Physical Review **C85**, 011303 (2012).

02. *D.S. Delion*, R.J. Liotta, P. Schuck. A. Astier, and M.-G. Porquet, *Shell model plus cluster description of negative parity states in ^{212}Po,* Physical Review **C85**, 064306 (2012).

03. F. Gulminelli and *Ad. R. Raduta, Ensemble in-equivalence in supernova matter within a simple model,* Physical Review C **85**, 025803 (2012).

04. F. Gulminelli, *Ad. R. Raduta,* and M. Oertel, *Phase transition toward strange matter,* Physical Review C **86**, 025805 (2012).

05. *D.S. Delion* and J. Suhonen, *Unified description of 2^+_1 states within the deformed quasiparticle random-phase approximation,* Physical Review **C87,** 024309 (2013).

06. *D.S. Delion*, R.J. Liotta, and R. Wyss, *Simple approach to two-proton emission,* Physical Review **C87,** 034328 (2013).

07. *D.S. Delion* and R.J. Liotta, *Shell-model representation to describe alpha emission.* Physical Review **C87,** 041302(R) (2013).

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10. *D.S. Delion* and *A. Dumitrescu, Coherent state description of alpha transitions to excited states in even-even nuclei,* Romanian Journal of Physics **58**, 1167 (2013).

11. *L. Ixaru* and *D.S. Delion, Two proton emission: a numerical approach,* Romanian Journal of Physics **58**, 1396 (2013).

12. *Ad. R. Raduta*, F. Aymard, and F. Gulminelli, *Clusterized nuclear matter in the (proto-)neutron star crust and the symmetry energy,* European Physical Journal **A** 50, 24 (2014).

13. P. Papakonstantinou, J. Margueron, F. Gulminelli, and *Ad.R. Raduta*, *Densities and energies of nuclei in dilute matter,* Physical Review **C** 88, 045805 (2014).

14. *D.S. Delion,* J. Suhonen, *Effective axial-vector strength and β-decay systematics,* European Physics Letters **107**, 52001 (2014).

15. *D.S. De lio,* R.J. Liotta, C. Qi, R. Wyss, *Probing shape coexistence by alpha decays to 0^+ states,* Physical Review C **90,** 061303(R) (2015).

16. *D.S. Delion, A. Dumitrescu, Alpha decay fine structure in even-even nuclei,* Atomic Data Nuclear Data Tables **101,** 1 (2015).

Submitted papers

17. *Ad. R. Raduta*, F. Gulminelli, M. Oertel, *Thermodynamics of baryonic matter with strangeness within non-relativistic energy density functional model,* arXiv:1406.0395.

18. *D.S. Delion, V.V. Baran, Pairing versus quarteting coherence length in nuclei,* Physical Review **C** (submitted)

19. F. Gulminelli*, Ad. R. Raduta*, Unified treatment of sub-saturation stellar matter at zero and finite temperature, (in preparation)

20. *L. Ixaru, D.S. Delion, A new numerical approach to solve the two proton emission problem* Computer Physics Communications (in preparation)

21. M. Oertel, C. Providência, F. Gulminelli, *A. R. Raduta*, *Hyperons in neutron star matter within relativistic mean-field models,* arXiv:1412.4545, submitted to Journal of Physics G

Conferences

C01. *D.S. Delion*, *L. Ixaru, V.V. Baran, Probing pairing interaction by two-proton emission,* International workshop “SARFEN”, Trento, Italy, 26-27 March, 2012.
http://www.ectstar.eu/node/38

C02. *D.S. Delion*, *Clustering features in decay processes,* International Summer School for Advanced Studies “Dynamics of open nuclear Systems”, Predeal, Romania, 9-20 July, 2012. Journal of Physics: Conference Series **413**, 012011 (2013).

C03. *D.S. Delion* and *A. Dumitrescu, Nuclear structure versus alpha-clustering and alpha-decay,* “Clustering aspects in nuclei”, Beijing, China, 1-26 April, 2013.
http://www.kitpc.ac.cn/?p=ProgDetail&id=PI20130401&i=main

C04. *D.S. Delion* and *A. Dumitrescu*, *Systematics of the alpha decay fine structure,* “Alpha decay as a probe of nuclear structure”, Stockholm, Sweden, 12-13.09, 2013.
http://www.nuclear.kth.se/alpha/presentation.htm

C05. *Ad. R. Raduta,* F. Gulminelli, M. Oertel, J. Margueron, *Strangeness-driven phase transition in stellar matter,* “Nuclear Physics in Astrophysics VI”, Lisbon, Portugal, 19-25 May 2013.
http://npa6.cii.fc.ul.pt/NPA6_webpage/NPA6_detailed_timetable.html

C06. *Ad. R. Raduta,* F. Aymard, F. Gulminelli, *Clusterized nuclear matter in the (proto-)neutron star crust and the symmetry energy,* “Eurisol - User Group Topical Meeting”, Krakow, Poland, 1-3 July 2013.
http://eurisol.ifj.edu.pl/

C07. *Ad. R. Raduta,* F. Gulminelli, *Equation(s) of state and phase transitions in stellar matter,* "Seventh European summer school on experimental nuclear astrophysics" Santa Tecla, Italy, 15-27 September 2013.
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C08. *Ad. R. Raduta,* F. Gulminelli, *The nuclear symmetry energy and the neutron star crust, The birth and death of neutron stars*, International workshop, Florence, Italy, March 2014.
https://indico.cern.ch/event/264202/

C09. *Ad. R. Raduta,* F. Gulminelli, *Clusterization in stellar matter*, ECT-Workshop, Simulating the Supernova Neutrinosphere with Heavy Ion Collisions, 7-14 April 2014, Trento, Italy.
http://www.ectstar.eu/node/771

C10. *Ad. R. Raduta,* F. Gulminelli, *Hyperons in stellar matter*, CARPATHIAN SUMMER SCHOOL OF PHYSICS 2014 Exotic Nuclei and Nuclear/Particle Astrophysics (V), From nuclei to stars, July 13 - 26, 2014, Sinaia, Romania.
http://www.nipne.ro/indico/conferenceTimeTable.py?confId=141#20140716

C11. *Ad. R. Raduta,* F. Gulminelli, *Clusterized nuclear matter in the (proto-)neutron star crust and the symmetry energy,* Advanced many-body and statistical methods in mesoscopic systems II, September 1 - 5, 2014, Brasov, Romania

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C12. *D.S. Delion,* R.J. Liotta, A. *Dumitrescu, Alpha-decay – a computational challenge*, Computational challenges in nuclear physics, Sept. 15 - Oct. 10 2014, Stockholm, Sweden

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C.13. *V.V. Baran, D.S. Delion, Pairing coherence length in nuclei,* Advanced many-body and statistical methods in mesoscopic systems II, September 1 - 5, 2014, Brasov, Romania

http://www.theory.nipne.ro/Brasov-Meso2014/presentation/Baran_Virgil_Jr_prez.pdf

C.14. *A. Dumitrescu, D.S. Delion,* Systematics of the α-decay fine structure in even-even nuclei, Advanced many-body and statistical methods in mesoscopic systems II, September 1 - 5, 2014, Brasov, Romania

http://www.theory.nipne.ro/BrasovMeso2014/presentation/Dumitrescu_Alexandru_prez.pdf

C.15. *D.S. Delion, V.V. Baran, Pairing versus quarteting coherence length,* From nuclear structure to particle-transfer reactions and back II, Nov. 10-14, 2014, Trento, Italy