NANOFIZICA DEPUNERILOR DE CLUSTERI ATOMICI SEMI-SFEROIDALI (NANCASS)

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DATE PROIECT

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Director Proiect: Prof. Dr. Dorin Poenaru

Pagina de web a proiectului

http://proiecte.nipne.ro/pn2/index.php?id=17

Institutia: Institutul National de Cercetare-Dezvoltare pentru Fizica si Inginerie Nucleara Horia Hulubei (IFIN-HH) din Bucuresti

Departamentul Fizica Teoretica. Pagini de web ale directorului de proiect:

http://www.theory.nipne.ro/˜poenaru

http://fias.uni-frankfurt.de/˜poenaru

REZUMATUL PROIECTULUI

Principalul obiectiv al proiectului este obtinerea unei intelegeri mai bune a mecanismelor de formare a clusterilor atomici depusi pe suprafete plane, cu aplicabilitate in nanotehnologii, microelectronica sau medicina. Pentru a explora in mod sistematic diverse configuratii intalnite in practica va trebui sa dispunem de o metoda capabila sa furnizeze rezultate numerice rezonabil de rapide folosind tehnica de calcul moderna. Vom adapta la clusteri atomici depusi pe suprafata metoda corectiilor de paturi pe care am utilizat-o in studiul stabilitatii nucleelor grele si supragrele. Forma cea mai simpla pe care o vom considera la inceput va fi cea de semi-sferoid, pentru care vom calcula energiile dependente de deformare in cadrul modelului picaturii de lichid (MPL). Rezolvand ecuatia Schroedinger, vom dezvolta un nou model uni-particula de oscilator armonic tridimensional avand ca suprafete echipotentiale acelasi tip de suprafata. Nivelele de energie ale acestui model vor fi utilizate ca date de intrare pentru calculul corectiilor de paturi si imperechere. Suprafetele de energie potentiala in functie de deformare si numarul de atomi ai clusterului vor avea minime pentru care se va obtine maximum de stabilitate. Aceste minime se vor datora degenerarii mari obtinute pentru numerele magice de atomi combinate cu minimele MPL. Vom incerca sa obtinem relatii analitice pentru energiile de suprafata si curbura ale clusterilor atomici semi-sferoidali alungiti sau turtiti, precum si pentru nivelele de energie ale modelului in paturi. In etapele urmatoare vom incerca sa simulam mai bine diferite experimente considerand forme mai complexe, introducand un termen proportional cu patratul momentului cinetic in Hamiltonian, o tensiune superficiala variabila in MPL, etc.

ECHIPA DE CERCETARE

Director: Prof. Dr. Dorin Poenaru, CS1

Cercetator cu experienta: Dr. Radu Alexandru Gherghescu, CS1

Cercetator in formare: Vasile Ionut Traian, C

Gradul de implicare al tinerilor cercetatori

Avem un tanar in Bucuresti si o doctoranda la Frankfurt pe Main, Germania, cu care colaboram (Dna Veronica Dick). Dumneaei a contribuit substantial la realizarea lucrarii pe care am prezentat-o in 2009 la Conferinta de la Dresda (a se vedea lista de comunicari).

Tanarul din Bucuresti este interesat de tehnica informationala in cadrul colectivului de Tehnologii Informationale si de Comunicatie din IFIN-HH. In afara unor lucrari curente privind reprezentari grafice pentru publicatii, Dsa se ocupa de implementarea unor coduri foarte complexe de calcul utilizate pe larg in domeniul Nanofizicii, cum ar fi codul Carr-Parrinello pentru calcule de dinamica moleculara, la care vom apela si noi pe viitor cand intentionam sa abordam microscopic cele mai interesante probleme de nanofizica care se pot desprinde din rezultatele noastre obtinute prin metoda macroscopica-microscopica.

Dsa a avut o contributie importanta la realizarea unei lucrari de cercetare intitulata *Hemispheroidal and cylindrical charged metallic clusters* cu autori D. N. Poenaru, R. A. Gherghescu, W. Greiner si I.T. Vasile, care urmeaza sa fie publicata in Annals of the Academy of Romanian Scientists, Physics Series.

Obiective si activitati si gradul de realizare (I)

Etapa A. Energia de legatura a clusterilor metalici sferici si semi-sferici in modelul picatura de lichid. (2007-12-15)

1. Energia de legatura a clusterilor metalici sferici in functie de numarul de atomi ai clusterului; model picatura de lichid
   (a) Determinarea energiei de volum
   (b) Determinarea energiei de suprafata si de curbura
2. Energia de legatura a clusterilor metalici semi-sferici in functie de numarul de atomi ai clusterului; model picatura de lichid
   (a) Determinarea energiei de volum
   (b) Determinarea energiei de suprafata si de curbura

Realizate integral.

Obiective si activitati si gradul de realizare (II)

Etapa B. Energii de deformare ale clusterilor sferoidali, semi-sferoidali si cu forme intermediare. Expresii analitice in modelul picatura de lichid. (2008-10-31)

1. Expresii generale ale energiilor de suprafata si curbura pentru forme de clusteri cu simetrie axiala
   (a) Energia de suprafata a unui cluster cu simetrie axiala
   (b) Energia de curbura a unui cluster cu simetrie axiala
2. Variatia cu deformarea si numarul de atomi a energiilor de suprafata si curbura pentru clusteri sferoidali, semi-sferoidali precum si cu forme intermediare
   (a) Expresii analitice pentru energia de suprafata a sferoizilor, semi-sferoizilor si formelor intermediare
   (b) Expresii analitice pentru energia de curbura a sferoizilor, semi-sferoizilor si formelor intermediare

Realizate integral.

Obiective si activitati si gradul de realizare (III)

Etapa C. Modele uni-particula de oscilator sferoidal si semi-sferoidal armonic. Influenta momentului cinetic orbital. (2009-09-15)

1. Model uni-particula de oscilator sferoidal armonic. Influenta termenului proportional cu patratul momentului cinetic orbital
   (a) Expresii analitice pentru nivelele de energie ale oscilatorului sferoidal functie de deformare in absenta termenului $\mathbf{l}^2$
   (b) Elementele de matrice si diagonalizarea numerica dupa includerea termenului $\mathbf{l}^2$
2. Model uni-particula de oscilator semi-sferoidal armonic. Influenta termenului proportional cu patratul momentului cinetic orbital si a unor forme intermediare
   (a) Expresii analitice pentru nivelele de energie ale oscilatorului semi-sferoidal functie de deformare in absenta termenului $\mathbf{l}^2$
   (b) Elementele de matrice si diagonalizarea numerica dupa includerea termenului $\mathbf{l}^2$

Realizate integral.

Obiective si activitati si gradul de realizare (IV)

Etapa D. Energia de deformare totala a clusterilor metalici semi-sferoidali calculata prin metoda macroscopica-microscopica. Corectii de paturi si imperechere. (2010-09-15)

1. Adaptarea la clusteri atomici a metodei corectiilor de paturi si imperechere nucleare
   (a) Calculul corectiilor de paturi si imperechere ca diferenta dintre suma energiilor discrete si marimea corespunzatoare pentru densitati de nivele mediate
   (b) Determinarea ecartului dintre doua paturi succesive si verificarea corectiilor minime la numere magice
2. Energia de deformare totala: model picatura de lichid plus corectii de paturi si imperechere
   (a) Insumarea energiilor si reprezentarea grafica in 3D
   (b) Determinarea formelor de echilibru ale starilor fundamentale si izomere

Etapa D, cu termen in luna Sept. 2010 este in curs de realizare

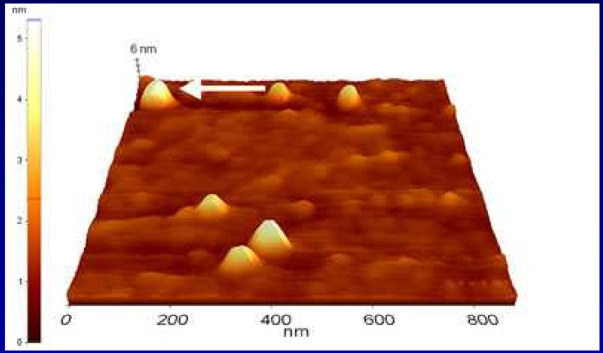
Rezultatele obtinute

METODA MACROSCOPICA-MICROSCOPICA folosita in Fizica Nucleara este potrivita deoarece electronii de valenta delocalizati ai clusterilor metalici formeaza un lichid Fermi ca si nucleonii din nucleu (CARACTER MULTIDISCIPLINAR AL PROIECTULUI).

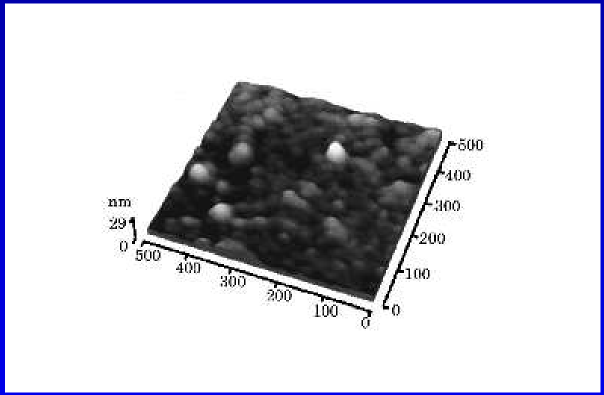
- Explicarea formelor de clusteri atomici depusi pe suprafete plane, observate cu microscoape “Atomic Force Microscopy (AFM)” care se pot aproxima prin hemisferoizi alungiti superdeformati (energie de interactie neglijabila).
- Explicarea formelor de clusteri atomici depusi pe suprafete plane, observate cu AFM care se pot aproxima prin hemisferoizi turtiti (energie de interactie cu substratul mare, putand fi simulata cu o tensiune superficiala negativa).
- Reproducerea numerelor magice din spectrele de masa ale clusterilor metalici liberi folosind un oscilator armonic tridimensional cu simetrie axiala al carui Hamiltonian contine si un termen proportional cu patratul momentului cinetic.
- Elaborarea unui nou model uni-particula pentru clusteri atomici hemisferoidali depusi pe suprafete, cu remarcabile proprietati de simetrie. Interesant de remarcat ca degenerarea maxima a starilor acestui model se obtine la o superdeformare prolate corespunzatoare unui raport de semiaxe c/a=2, la care si energia de deformare in cadrul modelului picaturii de lichid este minima.

Forme alungite (prolate) - experimental

Microscopie ultrasensibila: “Scanning Tunneling Microscope” — 1981 Gerd Binnig and Heinrich Rohrer (Nobel Prize 1986). “Atomic Force Microscope”.



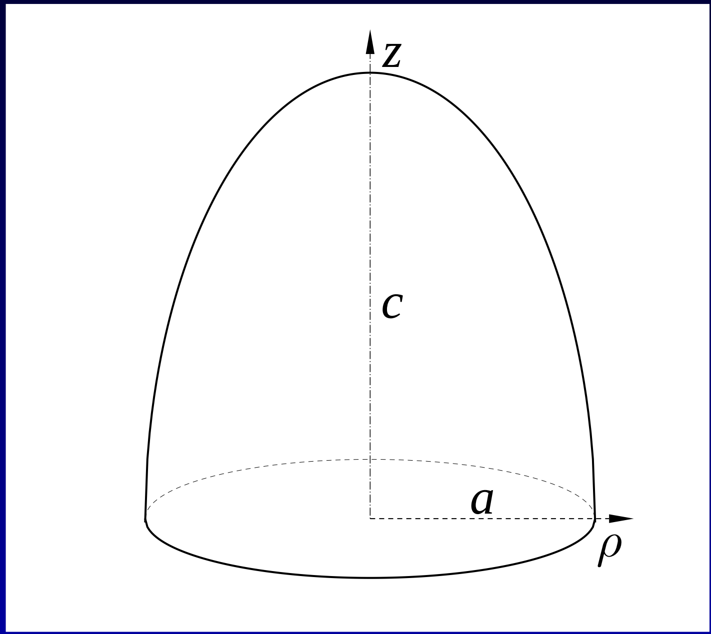
Nanoparticule de aur pe o suprafata de sticla. B. Bonanni and S. Cannistraro, *J. Nanotechnology Online*, Nov. 11, 2005. DOI: 10.2240/azojono0105.



Clusteri de argint pe suport de Si(111). K. Seeger, R.E. Palmer, Appl. Phys. Lett. 74 (1999) 1627.

Forme hemisferoidale alungite

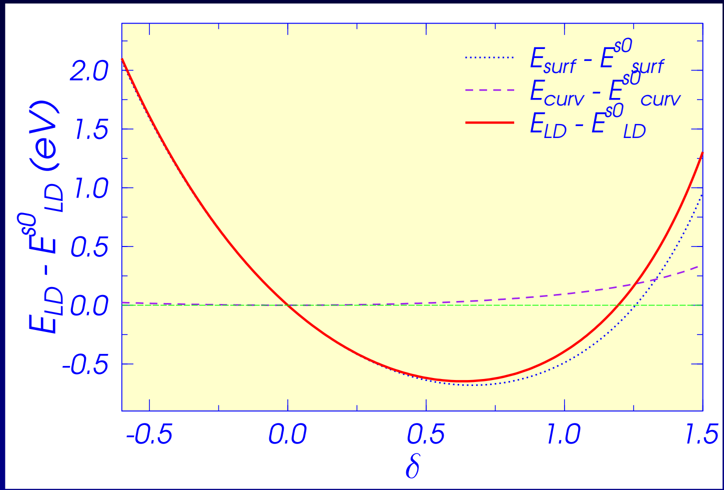
Hemispheroid cu axa de simetrie $\perp$ pe planul suportului

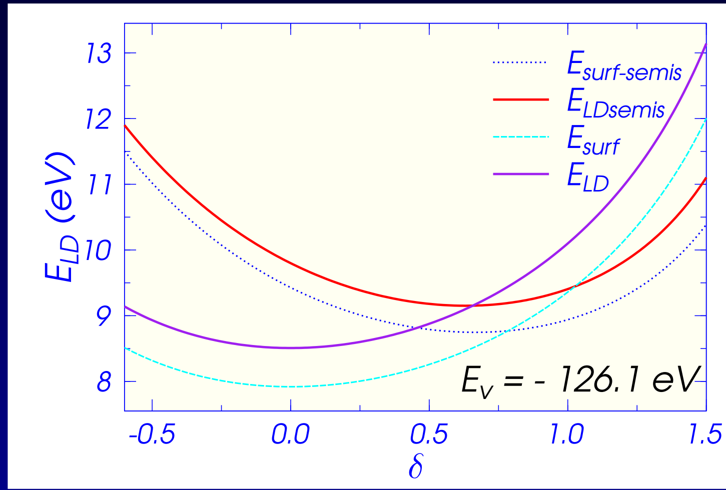


$$\rho^2 = \begin{cases} (a/c)^2(c^2 - z^2) & z \geq 0 \\ 0 & z < 0 \end{cases}$$

$c > a$ – **alungit (prolate)** $c < a$ – **turtit (oblate)**

Forme alungite - (teorie) MPL Na_{56} cluster hemisferoidal

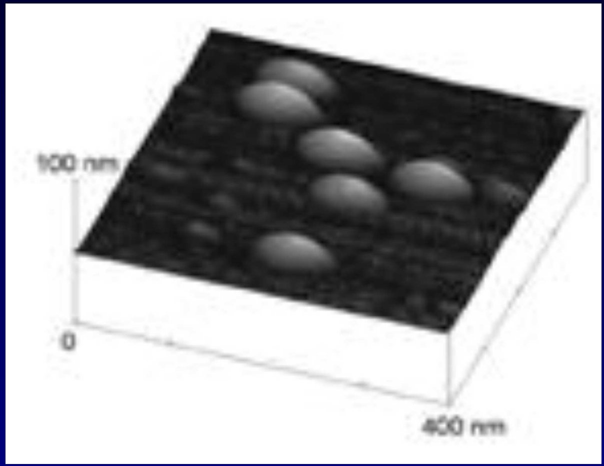




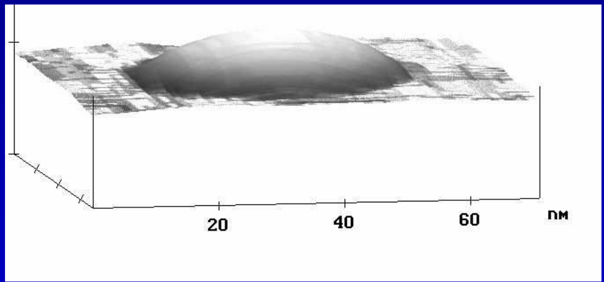
$c/a = (2+\delta)/(2-\delta)$

Energia de deformare MPL (suprafata + curbura) relativ la o emisfera si valori absolute. Valoarea de echilibru (minimum) are loc pt. forme prolate supradeformate cu $\delta = 0.65\ \ (c/a = 1.96)$. Pt sferoid: $\delta_{min} = 0$.

Forme turtite (oblate) - experimental



Clusteri de Bi pe suprafata de SiO_2. J.C. Partridge, S.A. Brown *et al.*, *Phys. Stat. Sol. (a)* **203** (2006) 1217



Unul dintre clusterii din figura de sus. Simon A. Brown, private communication, 2008

Simularea interactiei cu suprafata

Modificam tensiunea superficiala a bazei circulare **de la** σ **la** $i\sigma$**, i** $\in (-1.98, 2)$. i este *factorul de interactie*.

Pentru $i = 1$ obtinem cazul precedent.

$E = E_{base} + E_{ext} = i\sigma S_{base} + \sigma S_{ext}$

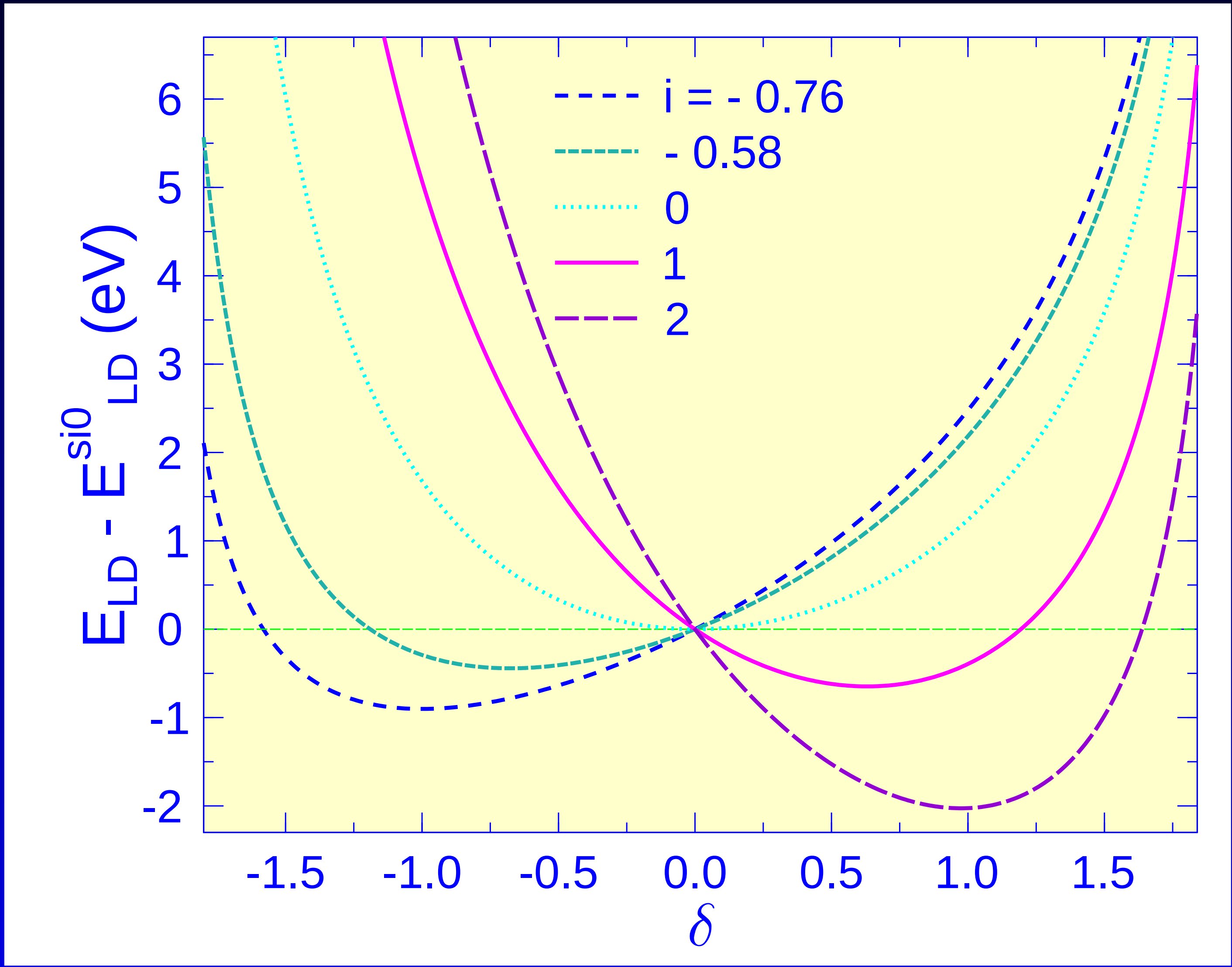
Curbura unei suprafete plane este nula deci E_{curv} ramane nemodificata. Pentru $\delta = 0$ (hemisfera):

$$E_s^{si0} = i\sigma(\pi R_s^2) + \sigma(2\pi R_s^2) = 4^{-2/3}(2 + i)E_s^0$$

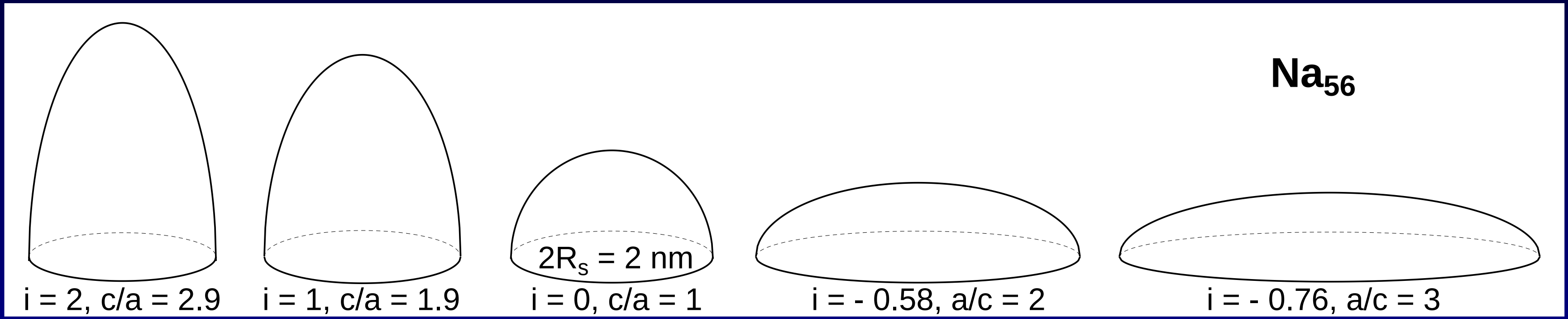
$$E_c^{si0} = 2\pi R_s \gamma_c = 4^{-1/3} E_{curv}^0$$

γ_c – tensiunea de curbura

Minime ale energiei de deformare MPL, Na_{56}



Forme de echilibru MPL ale Na_{56}



$i = 2$ hyperdeformed prolate

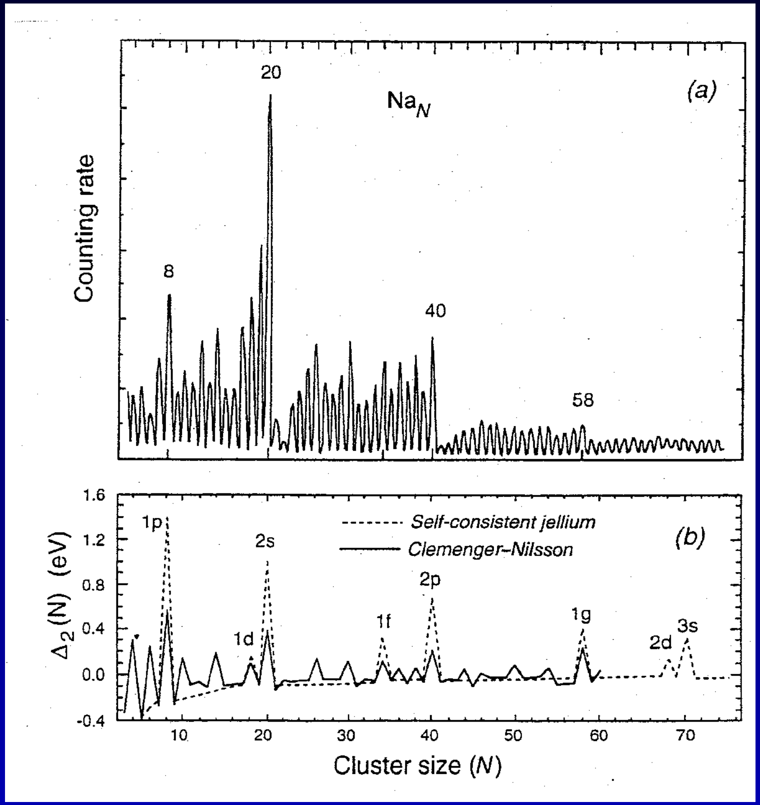
$i = 1$ superdeformed prolate

$i = 0$ hemisphere

$i = -0.58$ superdeformed oblate

$i = -0.76$ hyperdeformed oblate.

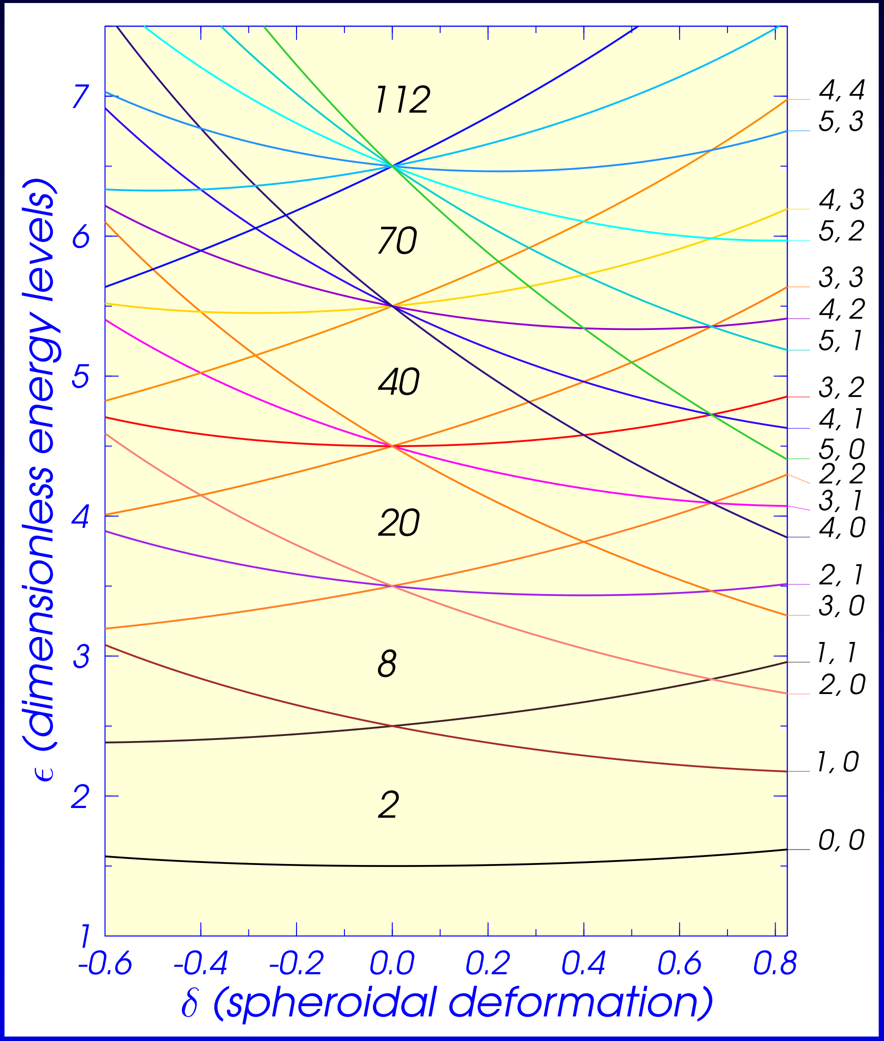
Spectru de mase experimental. Clusteri de Na liberi



(a) Spectru de mase experimental. Maxime majore la **numere magice: 8, 20, 40, 58.**
(b) Diferente de ordinul 2 ale energiilor electronice calculate.

W. D. Knight *et al. Phys. Rev. Lett.* **52** (1984) 2141–2143.
Noi am obtinut prin calcul aceste numere magice:
R.A. Gherghescu, D.N. Poenaru, A.V. Solov'yov, W. Greiner, *Int. J. Mod. Phys. B* **22** (2008) 4917-4935.

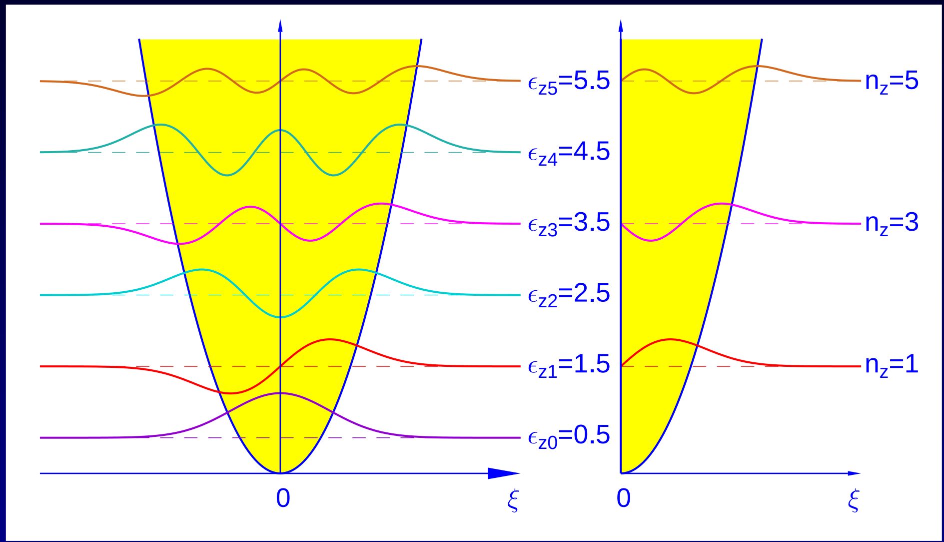
Nivele uniparticula calculate pentru forme sferoidale



Nre cuantice: $n, n_\perp$.
Pentru $\delta > 0$ (prolate) la $n_\perp = 0$ energia scade cu deformarea exceptand $n = 0$, $\epsilon(n_\perp = 0) = [2n+3-\delta(n-1/2)]/[(2-\delta)^{1/3}(2+\delta)^{2/3}]$
Cand $n_\perp = n$ energia creste $\epsilon(n_\perp = n) = [2n+3+\delta(n+1/2)]/[(2-\delta)^{1/3}(2+\delta)^{2/3}]$
De remarcat o a doua degenerare la $\delta = 2/3$

Numere magice teoretice la $\delta = 0$ in absenta termenului $\mathbf{l^2}$: 2, 8, 20, 40, 70, 112, ...

Nou model de oscilator armonic (HO hemisferoidal)



HO tridim. cu simetrie axiala $H\Psi = E\Psi$

$H = T + V_\rho(\rho) + V_z(z)$

$\Psi = \psi^m_{n_r}(\eta)\Phi_m(\varphi)Z_{n_z}(\xi)$

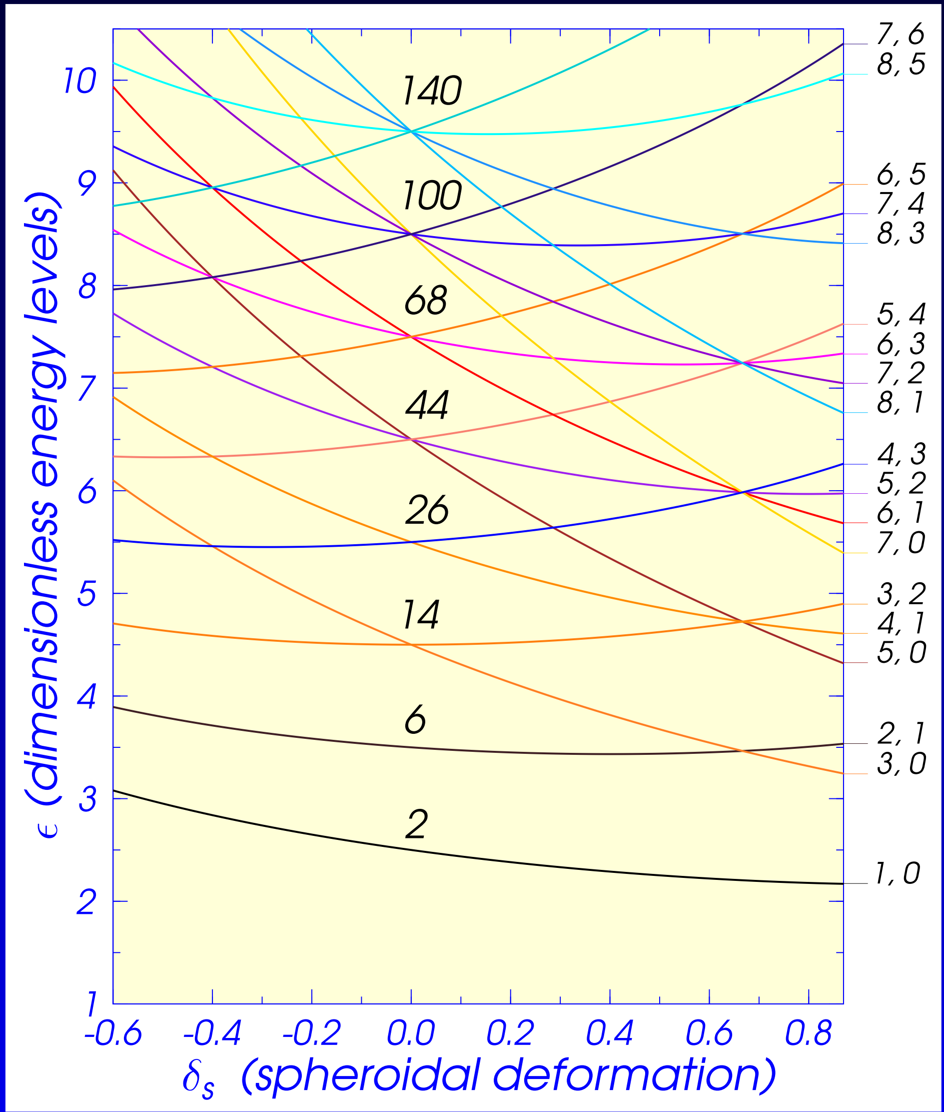
$E_n = \hbar\omega_\perp(n_\perp + 1) + \hbar\omega_z(n_z + 1/2)$

Nrul cuantic principal $n = n_\perp + n_z = 0, 1, 2, 3, ...n$

$Z_{n_z}(\xi) = N_{n_z} e^{-\xi^2/2} H_{n_z}(\xi) \quad \xi = zR_0/\sqrt{\hbar/M\omega_z}$ - adimens.

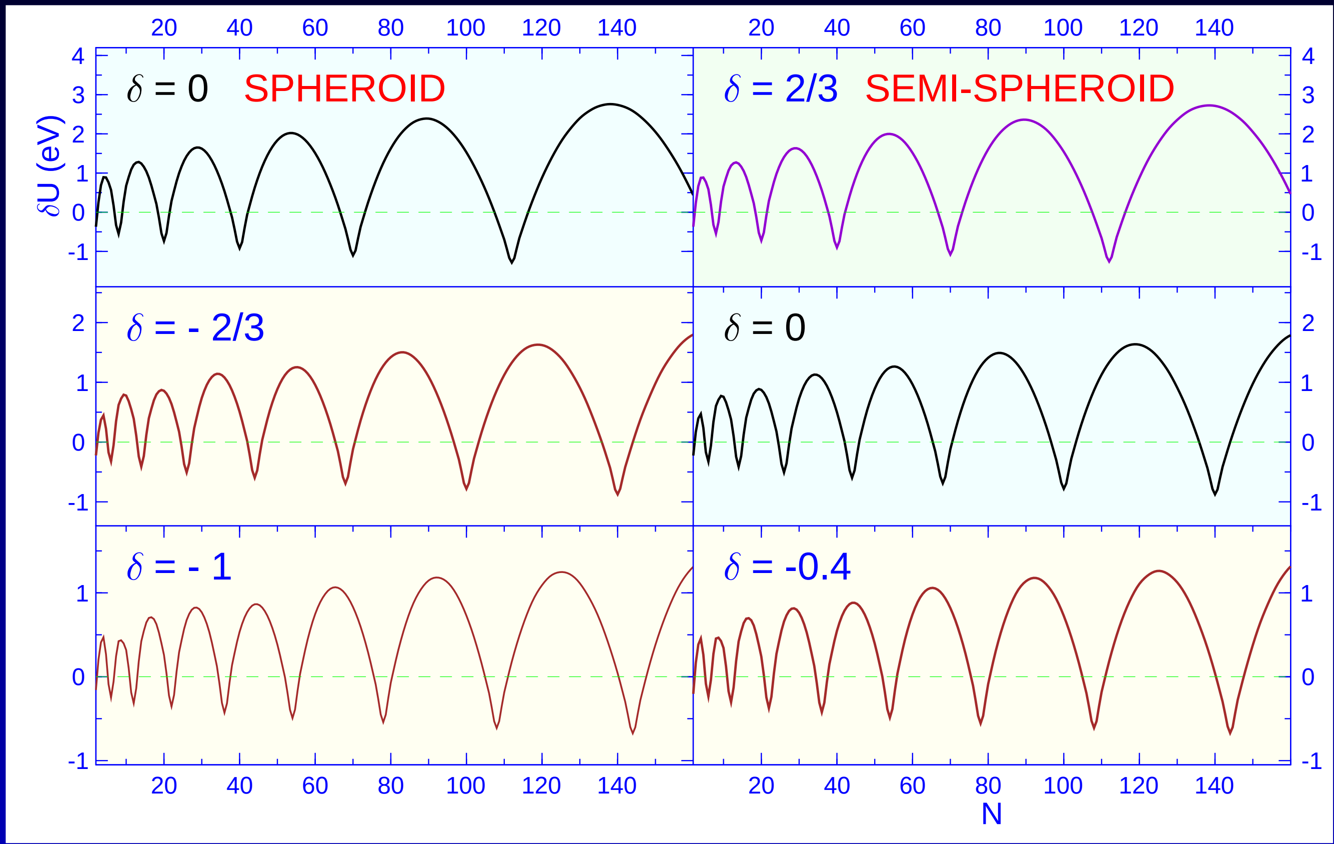
N_{n_z} - ct de ortonorm. Polinoame Hermite cu paritate $(-1)^{n_z}$ deci $H_{2n_z}(-\xi) = H_{2n_z}(\xi)$ si $H_{2n_z+1}(-\xi) = -H_{2n_z+1}(\xi)$. Pt HO hemisferoidal $V_z(0) \to \infty$. Deci $Z_{n_z}(\xi = 0) = 0$. **Raman doar numere n_z impare.**

Nivele ale noului model HO hemisferoidal



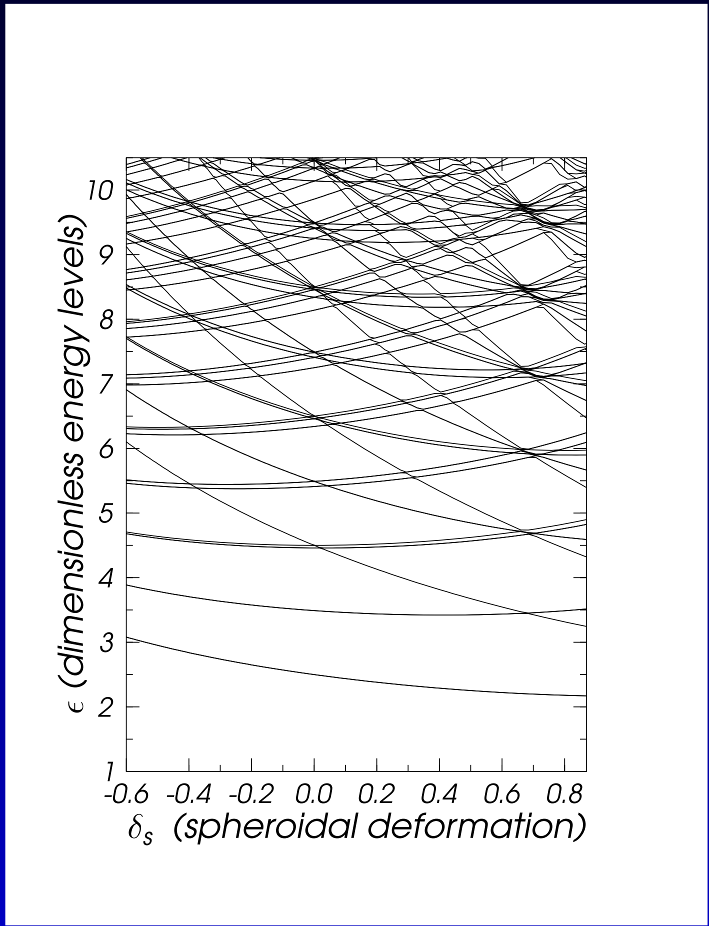
La fiecare pereche de $(n, n_\perp)$, se accepta doar acele numere cuantice pt. care $n_z = n - n_\perp \geq 1$ — sunt numere impare. Numerele magice pt emisfera ($\delta = 0$) sunt identice cu cele ale osc. armonic sferoidal avand $\delta = -2/3$ (forme turtite superdeformate) $\delta = -2/3$ adica 2, 6, 14, 26, 44, 68, 100, 140, ...

Compararea degenerarilor



Surprinzator: nre magice ale hemisferoizilor superdef. prolate ($\delta = 2/3$) sunt identice cu cele obtinute la forme sferice pt. oscilatorul sferoidal $(n + 1)(n + 2)(n + 3)/3 =$ 2, 8, 20, 40, 70, 112, 168 ..., etc

Influenta termenului l^2

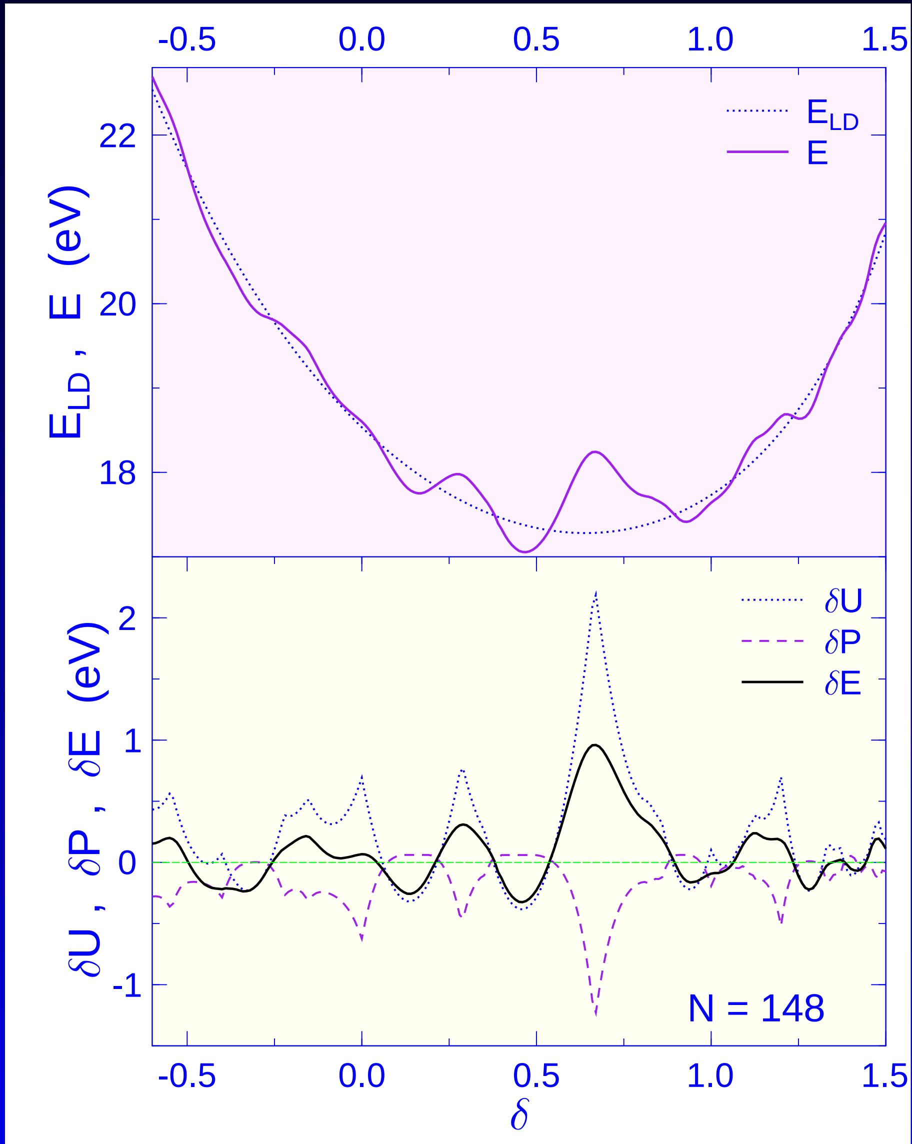


Pt nivele joase (primele 10 paturi inchise), secventa numerelor magice la degenerarea maxima, $\delta = 2/3$, ramane aceeasi: $N = 2, 8, 20, 40, 70, 112, 168$.

La deformari oblate foarte mari (forme de “placinta”) care aproximeaza o situatie de 2D, unul dintre nrele magice este 6, in acord cu experimentele: Chiu et al.

Ya-Ping Chiu *et al.*, Magic Numbers of Atoms in Surface-Supported Planar Clusters, *Phys. Rev. Lett.* **97** (2006) 165504.

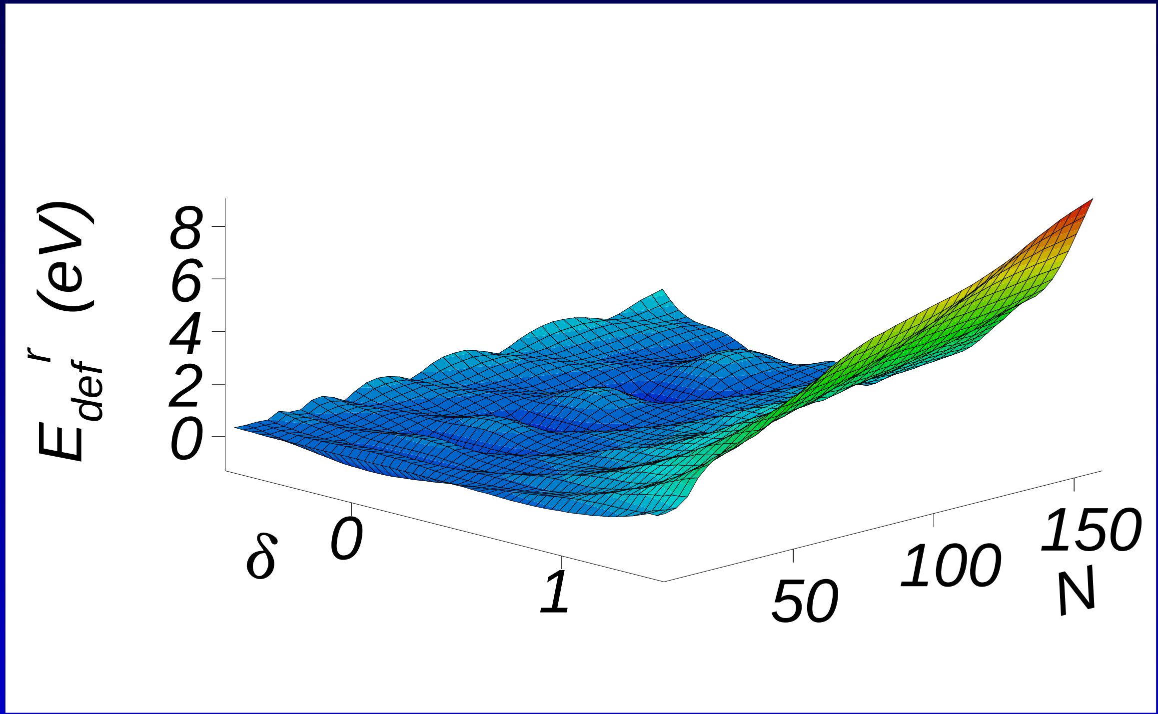
Metoda Macro-Micro. Na_{148} semisferoidal



$E_v = -333$ eV nu a fost inclusa in E_{LD} si E. SUS: energia de deformare MPL (punctat) si totala. JOS: corectii de paturi si imperechere pentru nivelele oscilatorului armonic semisferoidal, folosind parametrul de deformare δ. Rezulta o deformare de echilibru a starii fundamentale $\delta = 0.47$

Suprafete de energie potentiala in 3D

$$E^r_{def} = E_{LD} - E^0_{LD} + \delta E$$



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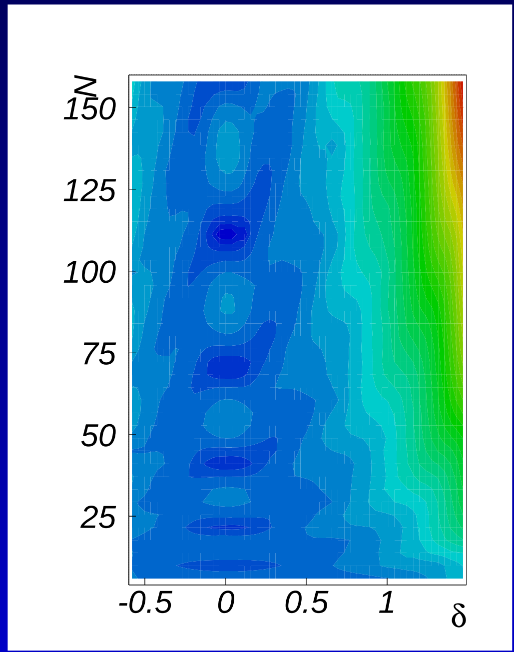


Contour plot

Articole ISI (1-6)

1. *D.N. Poenaru, R.A. Gherghescu, A.V. Solov'yov, W. Greiner,* Liquid drop stability of a superdeformed prolate semi-spheroidal atomic cluster, *Europhysics Letters (EPL)* **79** (2007) 63001. Factor impact (2008): 2.203

2. *R. A. Gherghescu, D. N. Poenaru, A. V. Solov'yov, W. Greiner,* Deformed shell closures for light atomic clusters, *International Journal of Modern Physics B* **22** (2008) 4917-4935. Factor impact: 0.558

3. *D.N. Poenaru, R.A. Gherghescu, A. V. Solovyov, W. Greiner,* Hemispheroidal quantum harmonic oscillator, *Physics Letters A* **372** (2008) 5448-5451. Factor impact: 2.174

4. *D.N. Poenaru, R.A. Gherghescu, I.H. Plonski, A.V. Solov'yov, W. Greiner,* Macroscopic-microscopic theory of semi-spheroidal atomic cluster, *The European Physical Journal D* **47** (2008) 379-393. HIGHLIGHT PAPER. Factor impact: 1.397

5. *D. N. Poenaru, I. H. Plonski,* Shell and pairing corrections for atomic cluster physics, *Romanian Reports in Physics*, **60** (2008) 529-538.

6. *D. N. Poenaru, R. A. Gherghescu, I. H. Plonski, A. V. Solov'yov, W. Greiner,* Hemispheroidal atomic clusters on planar surfaces, *Romanian Journal of Physics*, **54** (2009) 457-466.

Articole ISI (7-11)

7. *D.N. Poenaru, R.A. Gherghescu, A.V. Solov'yov, W. Greiner,* Oblate equilibrium shapes of hemispheroidal atomic clusters, *EPL* **88** (2009) 23002. Factor impact: 2.203

8. *D.N. Poenaru, R.A. Gherghescu, W. Greiner,* Special properties of ^{264}Fm and of atomic clusters emitting singly charged trimers, *J. Phys. G* **36** (2009) 125101.Factor impact: 5.270

9. *D. N. Poenaru, W. Greiner,* Extension of superasymmetric fission theory from cluster decay to nanophysics, *Nuclear Physics A* **834** (2010) 163c-166c. Factor impact: 1.959

10. *R. A. Gherghescu, D. N. Poenaru, A. V. Solov'yov, W. Greiner,* Hemispheroidal atomic clusters on planar surfaces, *Physica E* **42** (2010) 1555-1562. Factor impact: 1.230

11. *D. N. Poenaru, R. A. Gherghescu, W. Greiner,* Stable Spheroidal Cap Shapes of Deposited Atomic Cluster, *International Journal of Modern Physics B* **23** (2010) accepted. Factor impact: 0.558.

Conferinte Internationale (1-3)

1. *D.N. Poenaru,* Shell corrections stabilizing superheavy nuclei and semi-spheroidal atomic clusters. Invited talk. in Exotic Nuclei and Nuclear/Particle Astrophysics (II), (Proc. Carpathian Summer School of Physics, Sinaia, Romania, 2007) American Institute of Physics (AIP) Conference Proceedings No. 972, Melville, NY, 2008, pp. 165-173, Eds. L. Trache and S. Stoica, ISBN 978-0-7354-0490-8.

2. *D. N. Poenaru, R. A. Gherghescu, I. H. Plonski, A. V. Solov'yov, W. Greiner,* New deformed single-particle shell model, Invited talk, in Latest Advances in Atomic Cluster Collisions (Proc. of the International Symposium on Atomic Cluster Collisions: structure and dynamics from the nuclear to the biological scale, GSI Darmstadt, Germany, 2007), Imperial College Press, London, UK, 2008, Eds J.-P. Connerade and A. V. Solov'yov, pp. 128-137, ISBN 978-1-84816-237-2.

3. *D. N. Poenaru, R. A. Gherghescu, I. H. Plonski, A. V. Solov'yov, W. Greiner,* Potential energy surfaces of semi-spheroidal atomic clusters, Oral presentation, Nuclear Cluster Conference, 3-7 September, 2007, Stratford-upon-Avon, UK. Published in *Journal of Physics: Conference Series,* **111** (2008) 012047.

Conferinte Internationale (4-6)

4. D. N. Poenaru, R. A. Gherghescu, A. V. Solov'yov, W. Greiner, Interaction energy at the end cup of a deposited atomic cluster, Invited talk, International Symposium on Atomic Cluster Collisions: structure and dynamics from the nuclear to the MesoBioNano scales (ISACC2008) St. Petersburg, Russia, June 3-7 2008. Unpublished.

5. R. A. Gherghescu, D. N. Poenaru, A. V. Solov'yov, W. Greiner, Ground state and shape isomer deformations of alkali metal atomic clusters, Invited talk, International Symposium on Atomic Cluster Collisions: structure and dynamics from the nuclear to the MesoBioNano scales (ISACC2008) St. Petersburg, Russia, June 3-7 2008. Unpublished.

6. D. N. Poenaru, R. A. Gherghescu, A. V. Solov'yov, W. Greiner, Fission of deposited atomic clusters, Invited talk, 4th International Symposium on Atomic Cluster Collisions: structure and dynamics from the nuclear to the MesoBioNano scales (ISACC2009), Ann Arbor, MI, USA, July 14-18, 2009, In AIP Conf. Proc. No. 1197, American Institute of Physics, New York, 2009, Eds A. V. Solov'yov and E. Surdutovich, pp. 48-56, ISBN 978-0-7534-0734-3.

Conferinte Nationale

1. *D. N. Poenaru, R. A. Gherghescu, I. H. Plonski, A. V. Solov'yov, W. Greiner*, Hemispheroidal atomic clusters on planar surfaces, Oral presentation, National Conference on Physics, Bucharest, 10-12 September 2008, Unpublished.

2. *V. Dick, D. N. Poenaru, R. A. Gherghescu, I. H. Plonski, A. Lyalin, A. Solov'yov, W. Greiner,* Liquid drop plus shell corrections model for deformed atomic cluster on the surface, Oral Communication, Deutsche Physikalische Geselschaft Spring Meeting, Dresden, Germany, 22-27 March 2009 - the largest Conference in Europe (more than 5000 participants), Unpublished.

Seminarii in strainatate

1. D. N. Poenaru, Macroscopic-microscopic approach to atomic cluster physics, Theoretical MesoBioNano Science Group, Frankfurt Institute for Advanced Studies (FIAS), J. W. Goethe University, 17 April 2007.

2. D. N. Poenaru, Atomic clusters on surfaces, Institut fuer Theoretische Physik der Justus Liebig Universitaet, Giessen, 23 May 2008.

3. D. N. Poenaru, Shell correction method for the analysis of stability of deformed atomic clusters, Special Lecture, Theoretical MesoBioNano Science Group, FIAS, 5 Dec 2008.

4. D. N. Poenaru, Charged metallic clusters, Theoretical MesoBioNano Science Group, FIAS, 6 May 2009.

5. D. N. Poenaru, Metallic clusters as ideal trimer emitters, Institut fuer Theoretische Physik der Justus Liebig Universitaet, Giessen, 17 Sept. 2009.

6. D. N. Poenaru, Competition of collective and single-particle properties of fermions in Nuclear and Atomic Cluster Decays, Theoretical MesoBioNano Science Group, FIAS, 4 nov. 2009.

Alte rezultate obtinute (I)

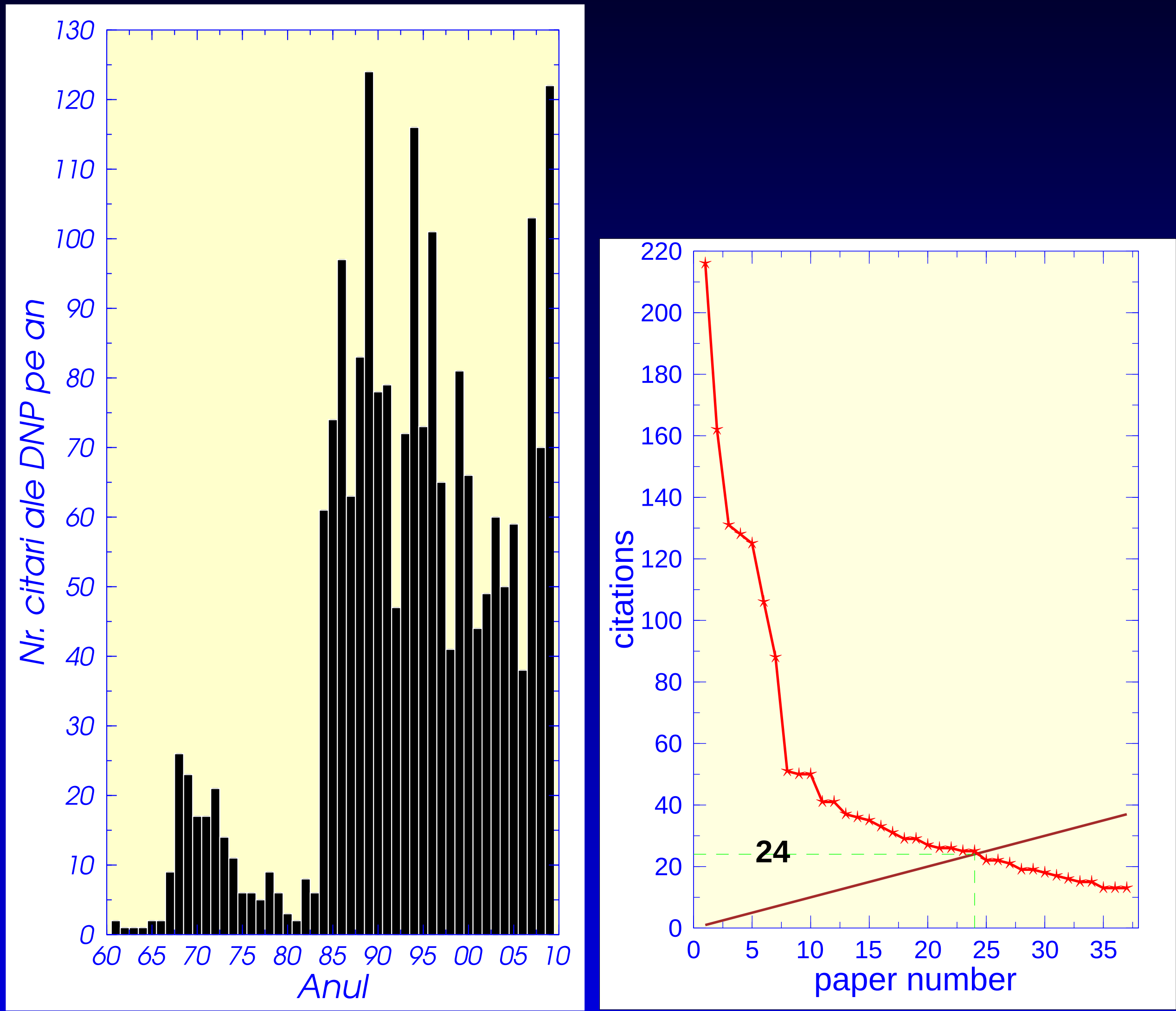
Dr. Radu Alexandru Gherghescu, Ocupa primul loc in clasificarea AdAstra a autorilor cu cele mai multe publicatii in domeniul Fizicii Nucleare, raportate la numarul de autori in perioada 2002-2006.

D. N. Poenaru impreuna cu A. Sandulescu si W. Greiner sunt inclusi in Encyclopaedia Britannica pentru prezicerea ”heavy-ion radioactivity” sau ”cluster radioactivity”.
Au fost confirmate experimental in centre din intreaga lume emisiile spontane de: 14-C, 20-O, 23-F, 22,24-26-Ne, 28,30-Mg si 32-34-Si din nuclee grele cu Z=87-96.

In 2009 directorului de proiect i s-a facut deosebita cinste de a denumi Dorin Poenaru laboratorul de fizica al Colegiului National Emanuil Gojdu din Oradea.

Tot in 2009 i s-a conferit de catre Deutsche Forschungsgemeinschaft o distinctie rara de MERCATOR Gastprofessur, la Frankfurt Institute for Advanced Studies, unde impreuna cu Dr. R. A. Gherghescu colaboreaza cu directorul fondator Prof. Dr. Dr.h.c.mult. Walter Greiner si cu grupul de Theoretical MesoBioNano Science coordonat de catre Prof. Dr. Andrey Solov'yov. prin intermediul acestui grup cercetatorii romani au activat in cadrul retelei de excelenta EXCELL a Comisiei Europene.

Alte rezultate obtinute (II)



D. N. Poenaru are un numar de peste 2100 citari cumulate (a se vedea figura) si factorul Hirsch = 24.

Alte rezultate obtinute (III)

Pe paginile de web http://www.theory.nipne.ro/˜poenaru si http://fias.uni-frankfurt.de/˜poenaru/ sunt accesibile 7 prezentari, printre care:

1. Macroscopic-Microscopic Method for Atomic Cluster Physics, Special Lecture MesoBioNano Sci, FIAS, 2008
2. Hemispheroidal single-particle Shell Model, Seminar talk, DFT, IFIN-HH, 2009
3. Charged Metallic Clusters, ISACC09 Symposium, Ann Arbor, MI, USA, 2009

Colaborator extern (nefinantat): Dr. Ileana Hania Plonski, CS1

Colaboratori din strainatate (proiect DFG, Bonn, proiect EXCELL al CE, Bruxelles):

Prof. Dr. Dr.h.c.mult. Walter Greiner, Director fondator al Frankfurt Institute for Advanced Studies (FIAS), Johann Wolfgang Goethe University, Uni Campus Riedberg, Ruth-Moufang-Str. 1 D-60438 Frankfurt am Main, Germany http://fias.uni-frankfurt.de/˜greiner

Prof. Dr. Andrey Solov'yov, Fellow Frankfurt Institute for Advanced Studies seful grupului Theoretical MesoBioNano Science, Coordonator Proiect FP7 Network of excellence EXCELL http://fias.uni-frankfurt.de/mbn

Doctorand Veronika Dick, Frankfurt Graduate School for Science, Frankfurt Institute for Advanced Studies

Dr Andrey Lyalin, fost membru al grupului Theoretical MesoBioNano Science, FIAS, in prezent la Hokkaido University, Japan

NANOPHYSICS OF DEPOSITED SEMI-SPHEROIDAL ATOMIC CLUSTERS (NANCASS)

OUTLINE

- The Project
- Abstract
- Research team
- Involvement degree of young researchers
- Objectives, activities and degree of achievement
- Obtained results
- Published articles
- Other results obtained

THE PROJECT

Project Code: 161. Comission: 1. Subcomission: 1D.

Type of the project: Exploratory research

Contract 123/01.10.2007

Director of the Project: Prof. Dr. Dorin Poenaru

Web site of the project

http://proiecte.nipne.ro/pn2/index.php?id=17

Institute: Horia Hulubei National Institute of Research & Development for Physics and Nuclear Engineering (IFIN-HH), Bucharest

Department of Theoretical Physics. Prof. Poenaru's Web sites: http://www.theory.nipne.ro/~poenaru

http://fias.uni-frankfurt.de/~poenaru

ABSTRACT

The main idea of the project is to advance significantly the understanding of mechanisms of growth of atomic clusters deposited on planar surfaces, potentially applicable in nanotechnology, microelectronics or medicine. In order to explore in a systematic way different configurations which can be met in practice we need a theoretical method able to give numerical results in a reasonably short computer running time. The nuclear shell correction method we have used to study the stability of heavy and superheavy nuclei, will be adapted to atomic clusters deposited on a surface. The simplest shape to be considered first is the semi-spheroid, for which we shall calculate the deformation-dependent surface and curvature liquid drop model (LDM) energies. A new single-particle shell model of a three-dimensional harmonic oscillator with equipotential surfaces of the same shape will be developed by solving the Schroedinger equation. The energy levels of this model will be used as input data for shell and pairing corrections. The potential energy surfaces versus the deformation and the number of atoms in the cluster will show minima at which the best stability will be obtained. They will be the result of the largest degeneracy of magic numbers combined with the LDM minima. We shall derive analytical relationships for the surface and curvature energies of oblate and prolate semi-spheroidal atomic clusters and for the energy levels of the shell model as well. In the next steps we shall try to simulate better the experiments by considering more complex shapes, a term proportional to the square of angular momentum in the Hamiltonian, a variable surface tension, etc.

RESEARCH TEAM

Director: Prof. Dr. Dorin Poenaru, CS1

Experienced researchers: Dr. Radu Alexandru Gherghescu, CS1

Young researcher: Vasile Ionut Traian, C

Involvement degree of young researchers

We have a young researcher in Bucharest and a PhD student in Frankfurt am Main, Germany, who cooperates with us. Mrs Veronica Dick had a substantial contribution to the work we presented in 2009 at the German National Conference in Dresden (see the list below).

The young researcher in Buharest is mostly interested in computing within the Departemnt of Information Technology from IFIN-HH. Besides many current graphic plots for our publications, he is working hard to implement on our desktop computers some very complex codes which are used in Nanophysics, e.g. Carr-Parrinello molecular dynamics, we would like to run in the future when we shall approach with other models the most interesting problems of Nanophysics which may result from our research obtained by using the Macroscopic-Microscopic method.

Mr I.T. Vasile also contributed to the research paper entitled *Hemispheroidal and cylindrical charged metallic clusters* authored by D. N. Poenaru, R. A. Gherghescu, W. Greiner and I.T. Vasile, to be published in Annals of the Academy of Romanian Scientists, Physics Series.

Objectives, activities and degree of achievement (I)

Stage A. Binding energy of a spherical and semi-spherical metallic cluster within liquid drop model. (2007-12-15)

1. Binding energy of a spherical metallic cluster function of number of atoms; liquid drop model
   (a) Volume energy
   (b) Surface and curvature energy
2. Binding energy of a semi-spherical metallic cluster function of number of atoms; liquid drop model
   (a) Volume energy
   (b) Surface and curvature energy

Integrally accomplished.

Objectives, activities and degree of achievement (II)

Stage B. Deformation energy of spheroidal, semi-spheroidal and intermediate shape atomic clusters. Analytical relationships within liquid drop model. (2008-10-31)

1. General relationships of surface and curvature energies for axially-symmetric atomic clusters
   (a) Surface energy of an axially-symmetric atomic cluster
   (b) Curvature energy of an axially-symmetric atomic cluster
2. Variation with deformation and the number of atoms of surface and curvature energies for spheroidal, semi-spheroidal and intermediate shape clusters
   (a) Analytical relationships for surface energy of spheroidal, semi-spheroidal and intermediate shape clusters
   (b) Analytical relationships for curvature energy of spheroidal, semi-spheroidal and intermediate shape clusters

Integrally accomplished.

Objectives, activities and degree of achievement (III)

Stage C. Single-particle models of spheroidal and semi-spheroidal harmonic oscillator. Influence of the orbital momentum. (2009-09-15)

1. Single-particle model of harmonic spheroidal oscillator. Influence of a term proportional with the square of angular momentum
   (a) Analytical relationships for energy levels of a spheroidal oscillator versus deformation without the $\mathbf{l}^2$ term
   (b) Matrix elements and numerical diagonalization after including the $\mathbf{l}^2$ term
2. Single-particle model of harmonic semi-sferoidal oscillator. Influence of a term proportional with the square of angular momentum and of intermediate shapes
   (a) Analytical relationships of energy levels of a semi-spheroidal oscillator versus deformation without the $\mathbf{l}^2$ term
   (b) Matrix elements and numerical diagonalization after including the $\mathbf{l}^2$ term

Integrally accomplished.

Objectives, activities and degree of achievement (IV)

Stage D. Total deformation energy of a semi-spheroidal metallic cluster within macroscopic-microscopic approach. Shell and pairing corrections. (2010-09-15)

1. Adaptation of nuclear shell and pairing corrections to atomic clusters
   (a) Shell and pairing corrections calculated as a difference of the sum of dicrete energies and the corresponding quantity for smoothed level density
   (b) Energy spacing between two successive closed shells and checking the minima of shell correction at magic numbers
2. Total deformation energy: liquid drop model plus shell and pairing corrections
   (a) Adding the shell and pairing corrections to the macroscopic deformation energy and producing the 3D graphics
   (b) Finding the equilibrium shapes of the ground and isomeric shapes of metallic clusters

Stage D to be delivered in 2010 September is in process of achievemnt

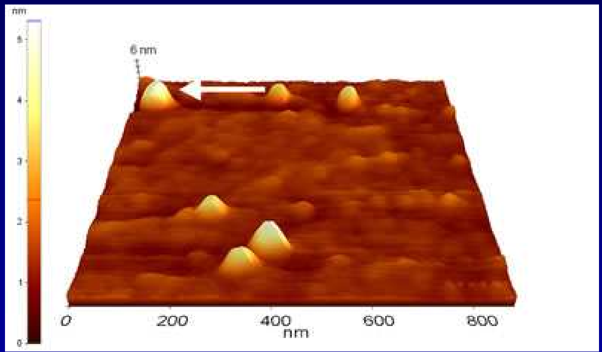
Obtained results

THE MACROSCOPIC-MICROSCOPIC METHOD is suitable since delocalized conduction electrons of a metallic cluster form a Fermi liquid like the nucleons in an atomic nucleus (MULTIDISCIPLINARY CHARACTER OF THE PROJECT).

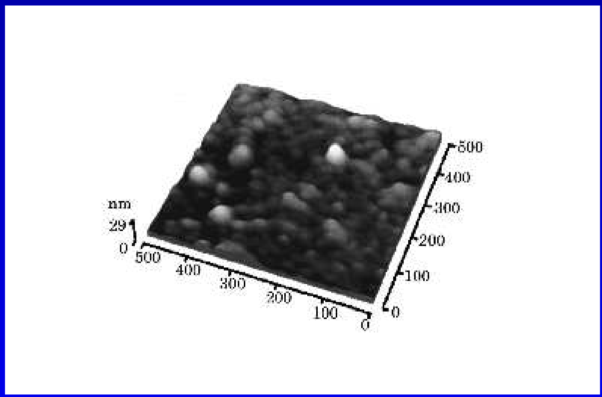
- Explaining the deposited atomic cluster shapes experimentally observed with Atomic Force Microscopy (AFM) which may be approximated by prolate superdeformed hemispheroids (the interaction energy with the substrate is neglijible small).
- Explaining the deposited atomic cluster shapes experimentally observed with AFM which may be approximated by oblate superdeformed hemispheroids (the interaction energy with the substrate is large and may be approximated with a negative surface tension).
- Reproducing the magic numbers observed in mass spectra of free metallic atomic clusters using a threedimensional spheroidal harmonic oscillator whose Hamiltonian contains a term proportional with the square of angular momentum.
- Development of a new single-particle shell model for a hemispheroidal deposited atomic cluster with remarkable symmetry properties. The maximum degeneracy of this model is reached at a superdeformed prolate deformation corresponding to c/a=2 semiaxes ratio, at which also the LDM deformation energy is minimum.

Prolate shapes - experimental

Ultrasensitive microscopy: Scanning tunneling microscope (STM) — 1981 Gerd Binnig and Heinrich Rohrer (Nobel Prize 1986). Atomic Force Microscope (AFM), etc.



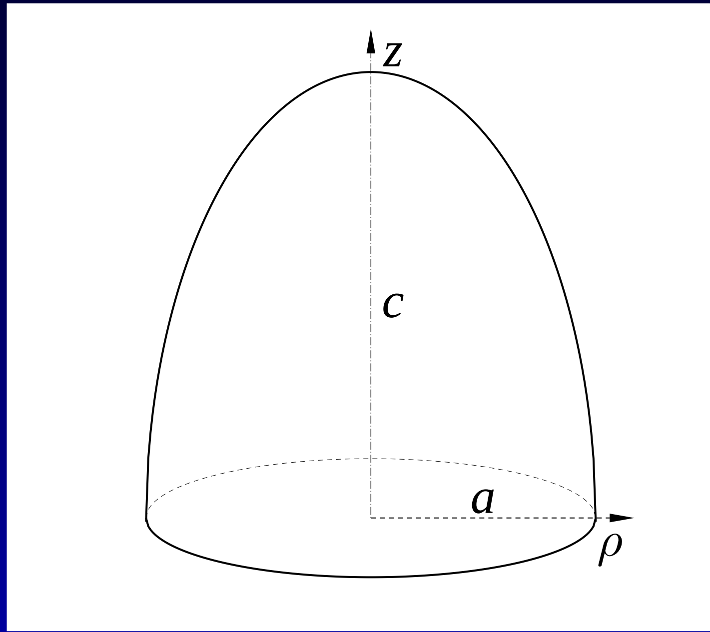
Au colloids deposited on a special glass. B. Bonanni and S. Cannistraro, *J. Nanotechnology Online*, Nov. 11, 2005. DOI: 10.2240/azojono0105.



Ag clusters deposited on Si(111) surface. K. Seeger, R.E. Palmer, Appl. Phys. Lett. 74 (1999) 1627.

Hemisferoidal shapes

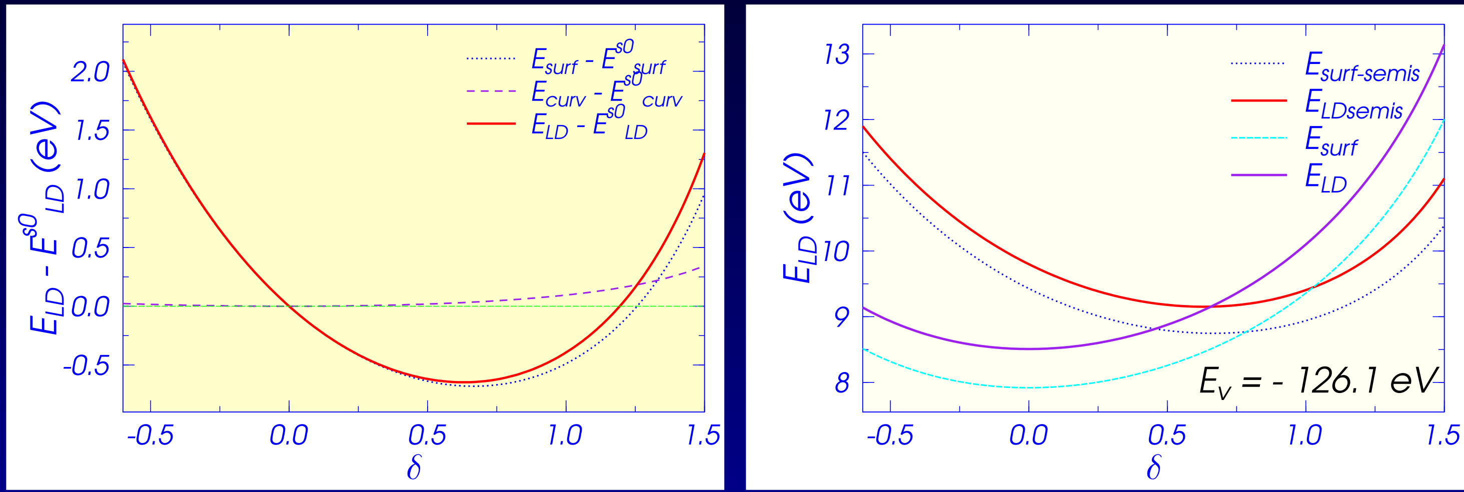
Hemispheroid with symmetry axis $\perp$ on the support plane



$$\rho^2 = \begin{cases} (a/c)^2(c^2 - z^2) & z \geq 0 \\ 0 & z < 0 \end{cases}$$

$c > a$ **– prolate** $c < a$ **– oblate**

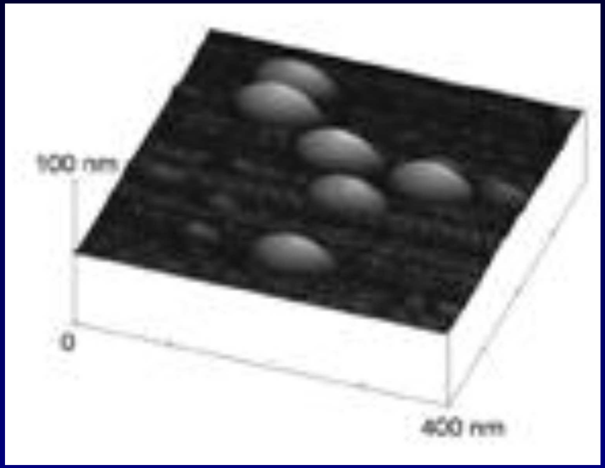
Prolate shapes - MPL, Na_{56} hemispheroidal cluster



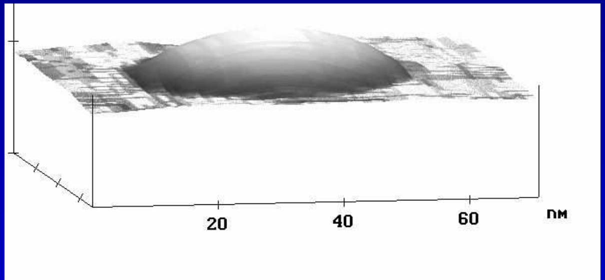
$c/a = (2 + \delta)/(2 - \delta)$

Surface plus curvature deformation energy with respect to a hemisphere and absolute values. The minimum is around the supereformed prolate shape with $\delta = 0.65\ \ (c/a = 1.96)$, unlike for a spheroid ($\delta = 0$).

Oblate clusters - experiment



AFM image of Bi clusters supported on a SiO_2 surface. J.C. Partridge, S.A. Brown *et al.*, *Phys. Stat. Sol. (a)* **203** (2006) 1217



One of the cluster from the above figure. Simon A. Brown, private communication, 2008

Simulating the interaction with the support

Surface tension of the base is changed **from σ to $i\sigma$, $\mathbf{i \in (-1.98, 2)}$**. i is the *interaction factor*.

For $i = 1$ one has the previously studied case.

$E = E_{base} + E_{ext} = i\sigma S_{base} + \sigma S_{ext}$

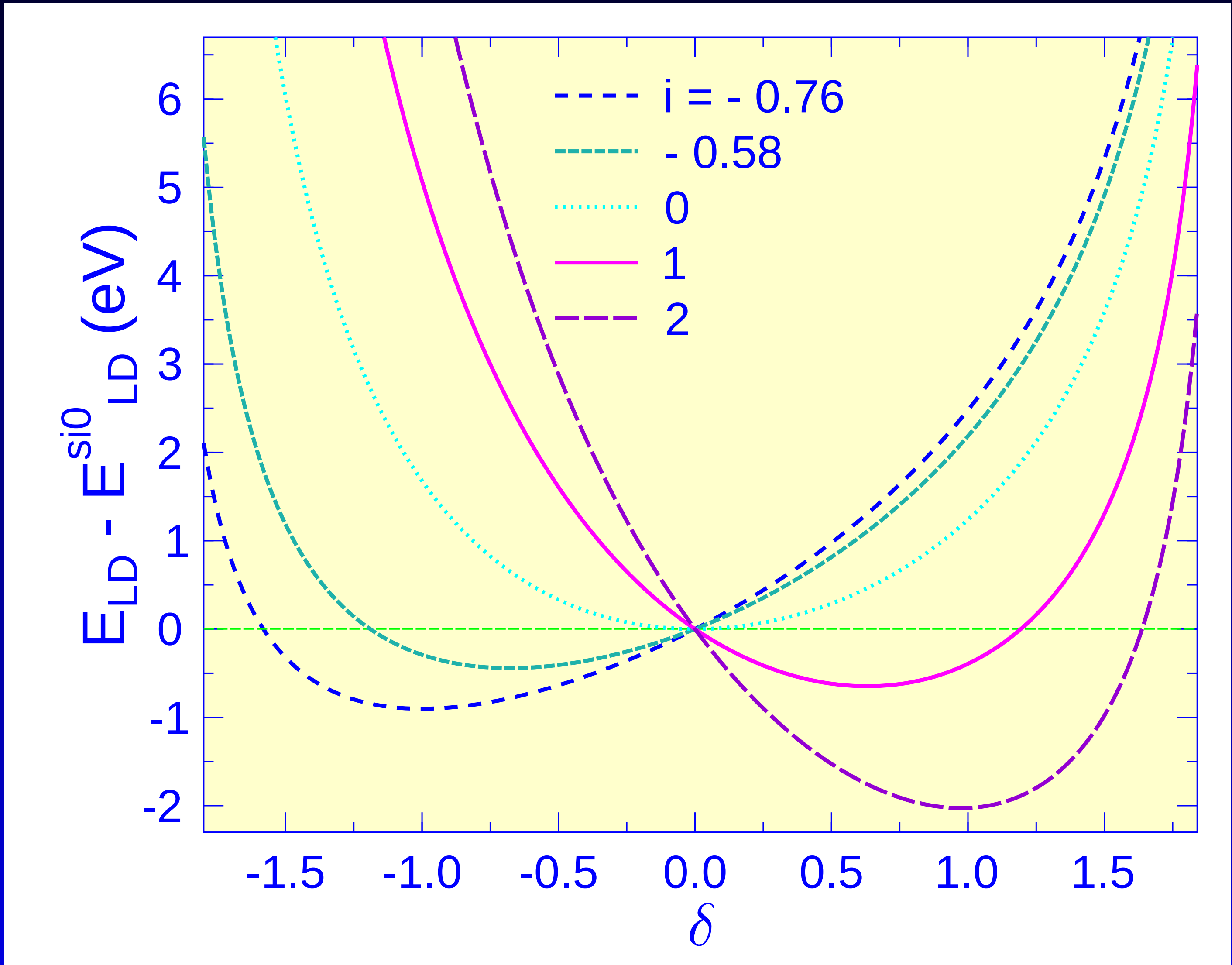
The curvature of a planar surface is zero, hence E_{curv} remains unchanged. For $\delta = 0$ (hemisphere):

$$E_s^{si0} = i\sigma(\pi R_s^2) + \sigma(2\pi R_s^2) = 4^{-2/3}(2+i)E_s^0$$

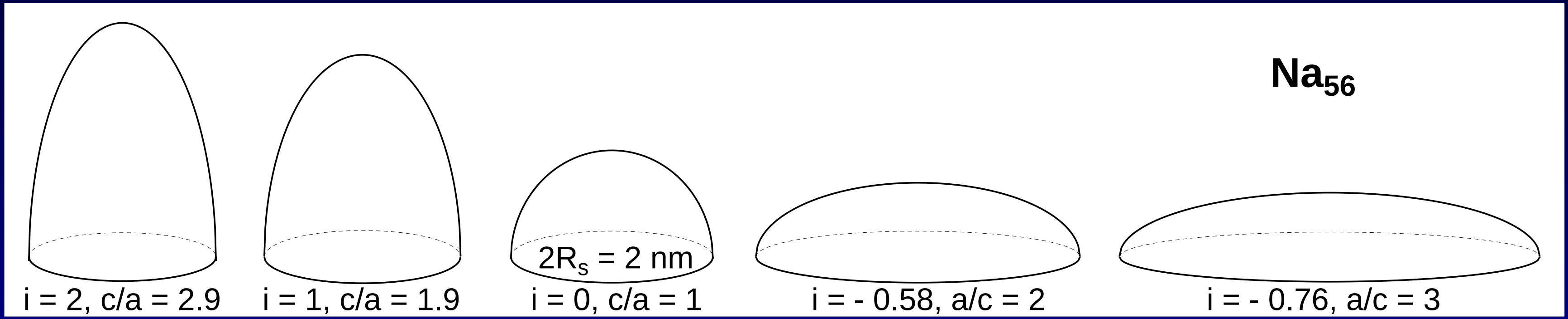
$$E_c^{si0} = 2\pi R_s \gamma_c = 4^{-1/3} E_{curv}^0$$

γ_c – curvature tension

Minima of LDM deformation energy, Na_{56}



LDM echilibrium shapes of Na_{56}



$i = 2$ hyperdeformed prolate

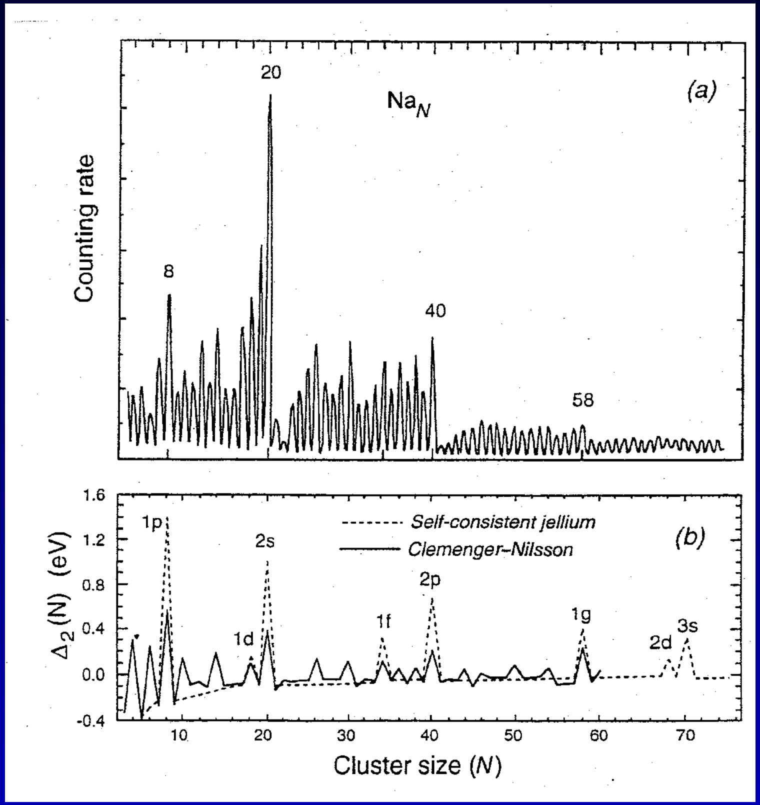
$i = 1$ superdeformed prolate

$i = 0$ hemisphere

$i = -0.58$ superdeformed oblate

$i = -0.76$ hyperdeformed oblate.

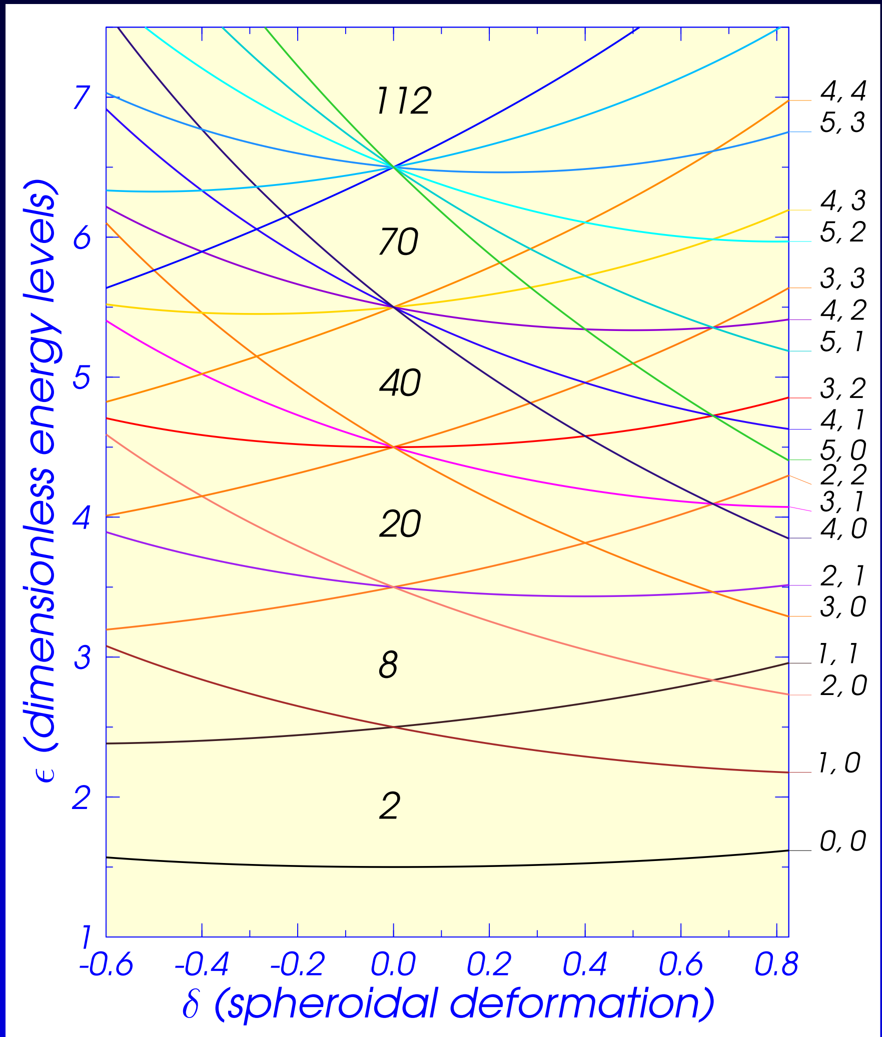
Mass spectrum of Na free clusters



(a) Mass spectrum detected with a quadrupole mass analyser. Major peaks at **numere magice: 8, 20, 40, 58.**
(b) Calculated 2nd differences in total electronic energies.

W. D. Knight *et al. Phys. Rev. Lett.* **52** (1984) 2141–2143.
We obtained theoretically these magic numbers:
R.A. Gherghescu, D.N. Poenaru, A.V. Solov'yov, W. Greiner, *Int. J. Mod. Phys. B* **22** (2008) 4917-4935.

Spheroidal HO energy levels



Label: $n, n_\perp$.

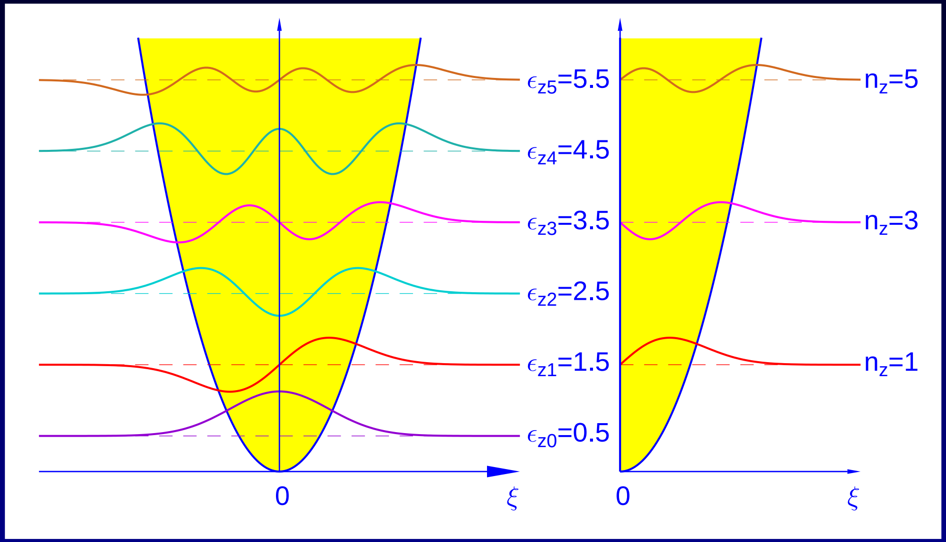
For $\delta > 0$ (prolate shape) at $n_\perp = 0$ the energy decreases with deformation, except for $n = 0$, $\epsilon(n_\perp = 0) = [2n+3-\delta(n-1/2)]/[(2-\delta)^{1/3}(2+\delta)^{2/3}]$

When $n_\perp = n$ it increases $\epsilon(n_\perp = n) = [2n+3+\delta(n+1/2)]/[(2-\delta)^{1/3}(2+\delta)^{2/3}]$

Remark a 2nd degeneracy at $\delta = 2/3$

Theoretical magic numbers at $\delta = 0$: 2, 8, 20, 40, 70, 112, ...

New (hemispheroidal) HO



Axially-symmetric 3dim HO $H\Psi = E\Psi$

$H = T + V_\rho(\rho) + V_z(z)$

$\Psi = \psi_{n_r}^m(\eta)\Phi_m(\varphi)Z_{n_z}(\xi)$

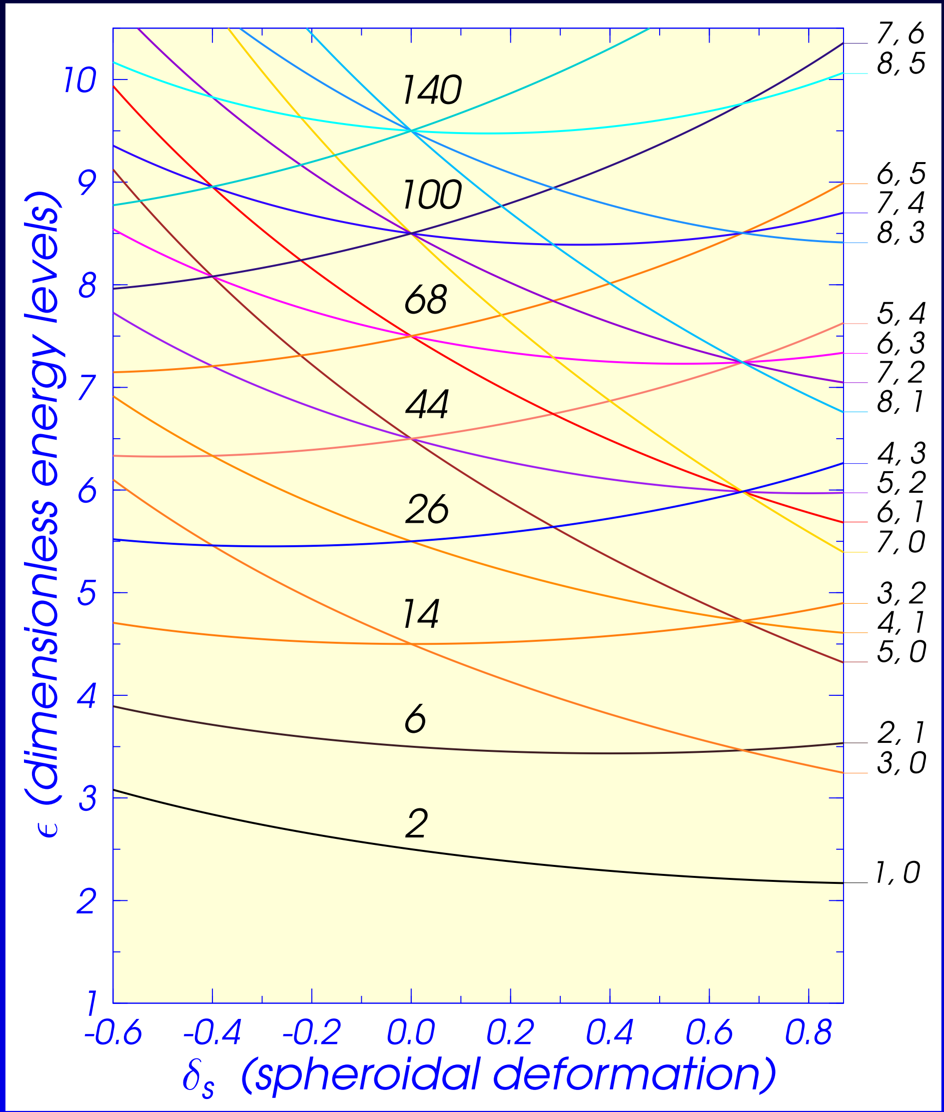
$E_n = \hbar\omega_\perp(n_\perp + 1) + \hbar\omega_z(n_z + 1/2)$

The main quantum number $n = n_\perp + n_z = 0, 1, 2, 3, ...n$

$Z_{n_z}(\xi) = N_{n_z} e^{-\xi^2/2} H_{n_z}(\xi)$ $\quad \xi = zR_0/\sqrt{\hbar/M\omega_z}$ - dim.less

N_{n_z} - ortonorm.constant Hermite polynomials with parity $(-1)^{n_z}$ meaning $H_{2n_z}(-\xi) = H_{2n_z}(\xi)$ and $H_{2n_z+1}(-\xi) = -H_{2n_z+1}(\xi)$. For hemispheroidal HO $V_z(0) \to \infty$. One should have $Z_{n_z}(\xi = 0) = 0$. **Only odd n_z values remain.**

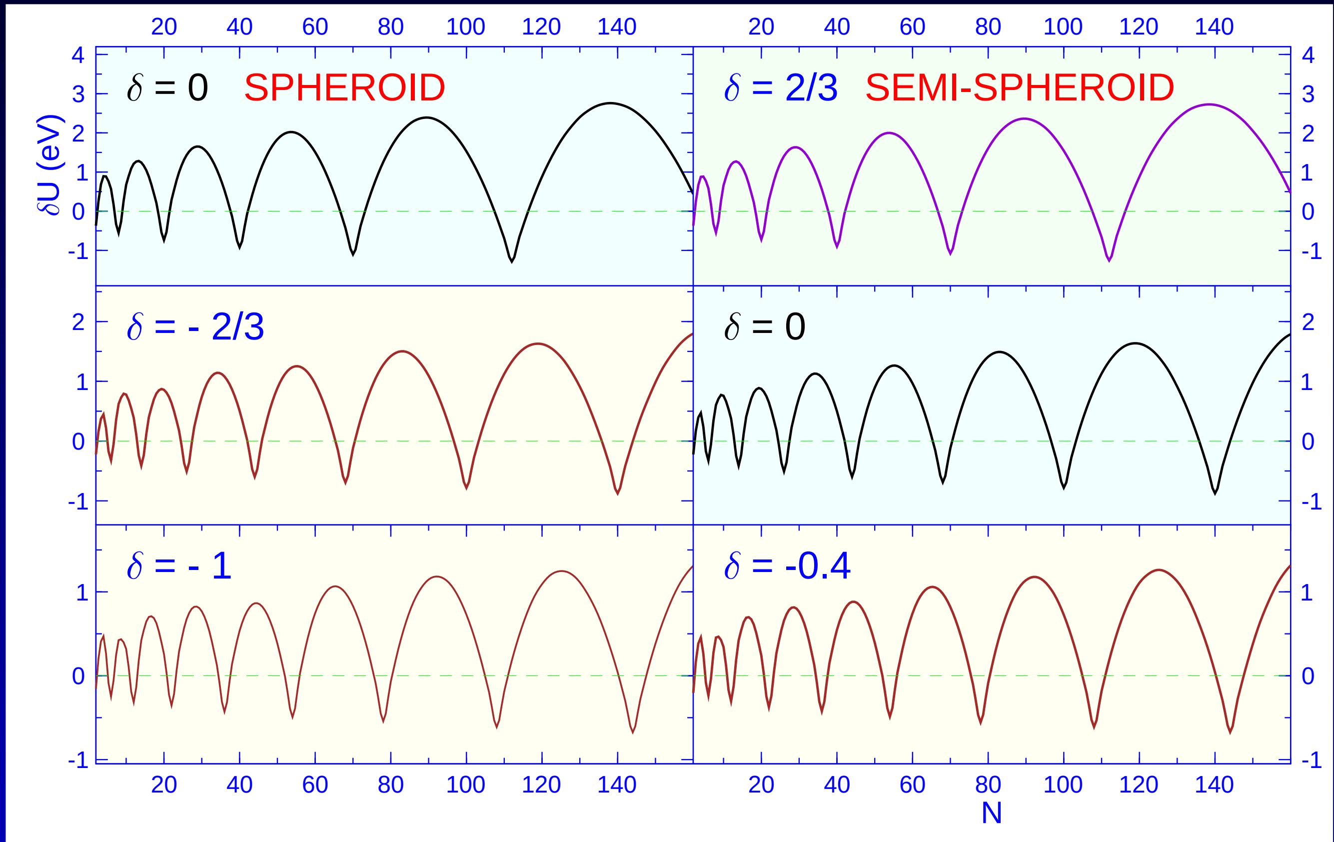
Hemispheroidal HO en. levels



At every pair $(n, n_\perp)$, labeling an energy level, only those values are acceptable which lead to $n_z = n - n_\perp \geq 1$ — odd numbers.

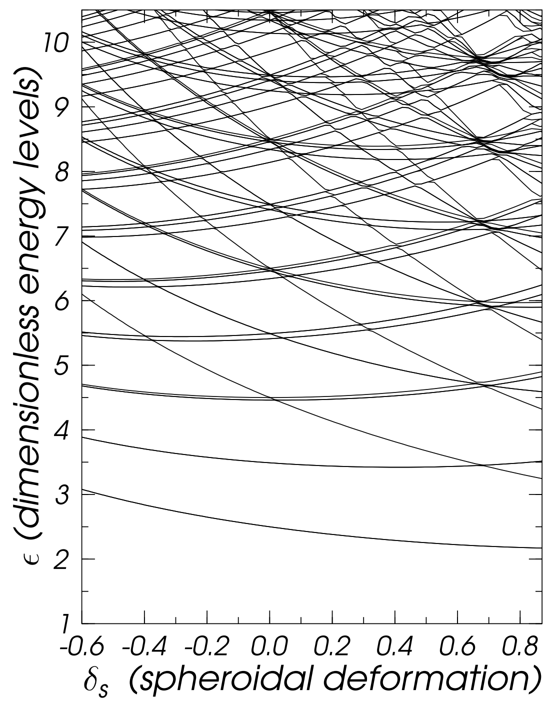
The hemispherical magic numbers are equal to those obtained at the oblate spheroidal superdeformed shape, $\delta = -2/3$ i.e. 2, 6, 14, 26, 44, 68, 100, 140, ...

Comparison of degeneracies



Striking: magic nbers at the prolate superdef. shape ($\delta = 2/3$) are identical to those obtained at the spherical shape $(n+1)(n+2)(n+3)/3 =$ 2, 8, 20, 40, 70, 112, 168 ...

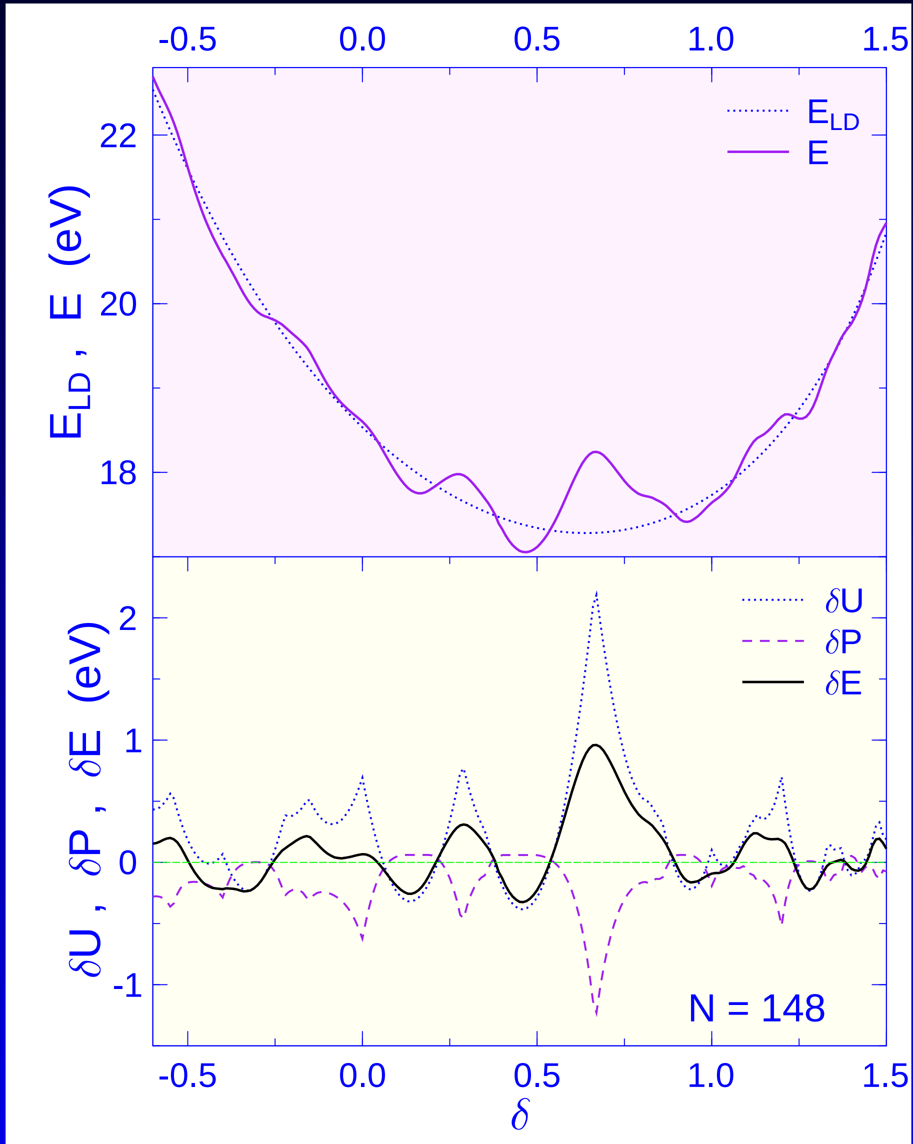
Influence of l^2 term (II)



For lower levels (say up to 10 closed shells), the sequence of the magic numbers at the maximum degeneracy, $\delta = 2/3$, remain the same: $N = 2, 8, 20, 40, 70, 112, 168$. At very large oblate deformations, leading to "pan-cake" shapes approximating a 2D situation, one of the magic number is 6, in agreement with the experiments of Chiu et al.

Ya-Ping Chiu *et al.*, Magic Numbers of Atoms in Surface-Supported Planar Clusters, *Phys. Rev. Lett.* **97** (2006) 165504.

M-MA hemisph. Na_{148} cluster

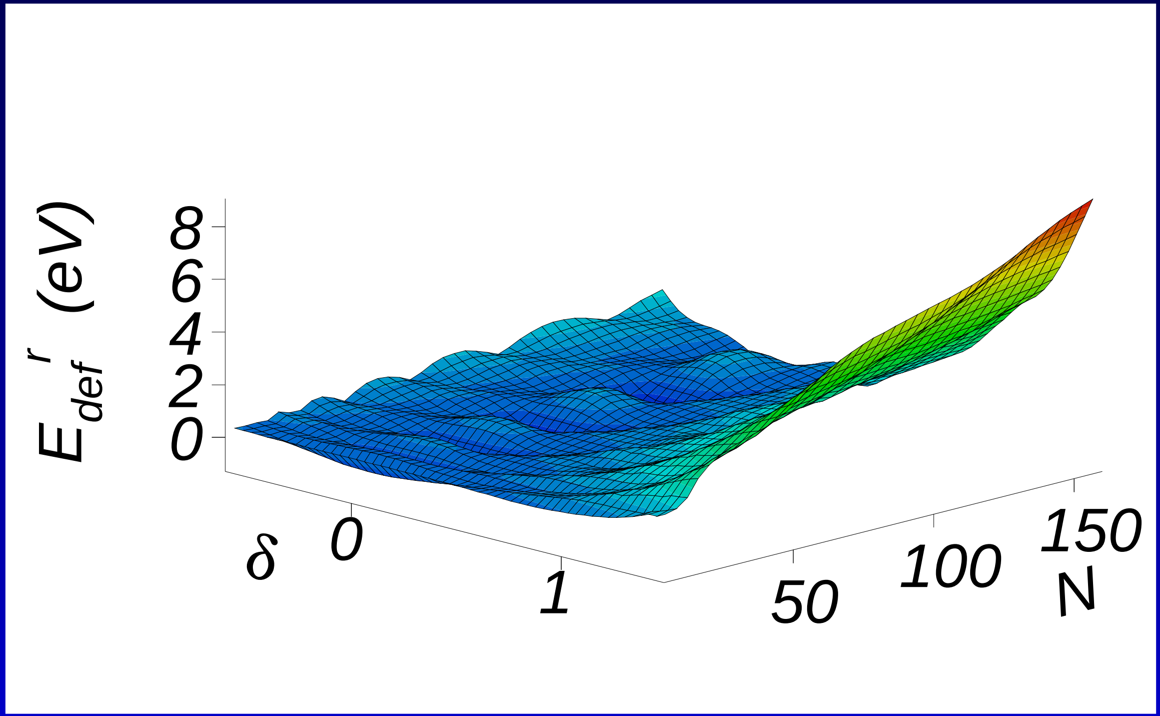


$E_v = -333$ eV was not included in E_{LD} and E. Liquid drop and total deformation energy (top), shell plus pairing corrections for hemispheroidal harmonic oscillator energy levels using the deformation parameter δ (bottom). Ground state shape prolate

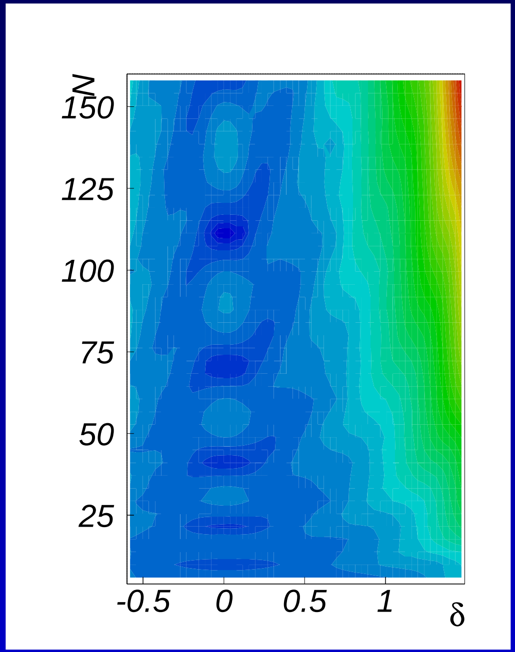
$\delta = 0.47$

Total M-M rel. def. energy

$$E^r_{def} = E_{LD} - E^0_{LD} + \delta E$$



PES



Contour plot

Published ISI articles (1-6)

1. *D.N. Poenaru, R.A. Gherghescu, A.V. Solov'yov, W. Greiner,* Liquid drop stability of a superdeformed prolate semi-spheroidal atomic cluster, *Europhysics Letters (EPL)* **79** (2007) 63001. Impact factor (2008): 2.203

2. *R. A. Gherghescu, D. N. Poenaru, A. V. Solov'yov, W. Greiner,* Deformed shell closures for light atomic clusters, *International Journal of Modern Physics B* **22** (2008) 4917-4935. Impact factor: 0.558

3. *D.N. Poenaru, R.A. Gherghescu, A. V. Solovyov, W. Greiner,* Hemispheroidal quantum harmonic oscillator, *Physics Letters A* **372** (2008) 5448-5451. Impact factor: 2.174

4. *D.N. Poenaru, R.A. Gherghescu, I.H. Plonski, A.V. Solov'yov, W. Greiner,* Macroscopic-microscopic theory of semi-spheroidal atomic cluster, *The European Physical Journal D* **47** (2008) 379-393. HIGHLIGHT PAPER. Impact factor: 1.397

5. *D. N. Poenaru, I. H. Plonski,* Shell and pairing corrections for atomic cluster physics, *Romanian Reports in Physics*, **60** (2008) 529-538.

6. *D. N. Poenaru, R. A. Gherghescu, I. H. Plonski, A. V. Solov'yov, W. Greiner,* Hemispheroidal atomic clusters on planar surfaces, *Romanian Journal of Physics*, **54** (2009) 457-466.

Published ISI articles (7-11)

7. *D.N. Poenaru, R.A. Gherghescu, A.V. Solov'yov, W. Greiner,* Oblate equilibrium shapes of hemispheroidal atomic clusters, *EPL* **88** (2009) 23002. Impact factor: 2.203

8. *D.N. Poenaru, R.A. Gherghescu, W. Greiner,* Special properties of ^{264}Fm and of atomic clusters emitting singly charged trimers, *J. Phys. G* **36** (2009) 125101.Impact factor: 5.270

9. *D. N. Poenaru, W. Greiner,* Extension of superasymmetric fission theory from cluster decay to nanophysics, *Nuclear Physics A* **834** (2010) 163c-166c. Impact factor: 1.959

10. *R. A. Gherghescu, D. N. Poenaru, A. V. Solov'yov, W. Greiner,* Hemispheroidal atomic clusters on planar surfaces, *Physica E* **42** (2010) 1555-1562. Impact factor: 1.230

11. *D. N. Poenaru, R. A. Gherghescu, W. Greiner,* Stable Spheroidal Cap Shapes of Deposited Atomic Cluster, *International Journal of Modern Physics B* **23** (2010) accepted. Impact factor: 0.558.

International Conferences (1-3)

1. *D.N. Poenaru,* Shell corrections stabilizing superheavy nuclei and semi-spheroidal atomic clusters. Invited talk. in Exotic Nuclei and Nuclear/Particle Astrophysics (II), (Proc. Carpathian Summer School of Physics, Sinaia, Romania, 2007) American Institute of Physics (AIP) Conference Proceedings No. 972, Melville, NY, 2008, pp. 165-173, Eds. L. Trache and S. Stoica, ISBN 978-0-7354-0490-8.

2. *D. N. Poenaru, R. A. Gherghescu, I. H. Plonski, A. V. Solov'yov, W. Greiner,* New deformed single-particle shell model, Invited talk, in Latest Advances in Atomic Cluster Collisions (Proc. of the International Symposium on Atomic Cluster Collisions: structure and dynamics from the nuclear to the biological scale, GSI Darmstadt, Germany, 2007), Imperial College Press, London, UK, 2008, Eds J.-P. Connerade and A. V. Solov'yov, pp. 128-137, ISBN 978-1-84816-237-2.

3. *D. N. Poenaru, R. A. Gherghescu, I. H. Plonski, A. V. Solov'yov, W. Greiner,* Potential energy surfaces of semi-spheroidal atomic clusters, Oral presentation, Nuclear Cluster Conference, 3-7 September, 2007, Stratford-upon-Avon, UK. Published in *Journal of Physics: Conference Series,* **111** (2008) 012047.

International Conferences (4-6)

4. D. N. Poenaru, R. A. Gherghescu, A. V. Solov'yov, W. Greiner, Interaction energy at the end cup of a deposited atomic cluster, Invited talk, International Symposium on Atomic Cluster Collisions: structure and dynamics from the nuclear to the MesoBioNano scales (ISACC2008) St. Petersburg, Russia, June 3-7 2008. Unpublished.

5. R. A. Gherghescu, D. N. Poenaru, A. V. Solov'yov, W. Greiner, Ground state and shape isomer deformations of alkali metal atomic clusters, Invited talk, International Symposium on Atomic Cluster Collisions: structure and dynamics from the nuclear to the MesoBioNano scales (ISACC2008) St. Petersburg, Russia, June 3-7 2008. Unpublished.

6. D. N. Poenaru, R. A. Gherghescu, A. V. Solov'yov, W. Greiner, Fission of deposited atomic clusters, Invited talk, 4th International Symposium on Atomic Cluster Collisions: structure and dynamics from the nuclear to the MesoBioNano scales (ISACC2009), Ann Arbor, MI, USA, July 14-18, 2009, In AIP Conf. Proc. No. 1197, American Institute of Physics, New York, 2009, Eds A. V. Solov'yov and E. Surdutovich, pp. 48-56, ISBN 978-0-7534-0734-3.

National Conferences

1. *D. N. Poenaru, R. A. Gherghescu, I. H. Plonski, A. V. Solov'yov, W. Greiner,* Hemispheroidal atomic clusters on planar surfaces, Oral presentation, National Conference on Physics, Bucharest, 10-12 September 2008, Unpublished.

2. *V. Dick, D. N. Poenaru, R. A. Gherghescu, I. H. Plonski, A. Lyalin, A. Solov'yov, W. Greiner,* Liquid drop plus shell corrections model for deformed atomic cluster on the surface, Oral Communication, Deutsche Physikalische Geselschaft Spring Meeting, Dresden, Germany, 22-27 March 2009 - the largest Conference in Europe (more than 5000 participants), Unpublished.

Seminars abroad

1. D. N. Poenaru, Macroscopic-microscopic approach to atomic cluster physics, Theoretical MesoBioNano Science Group, Frankfurt Institute for Advanced Studies (FIAS), J. W. Goethe University, 17 April 2007.
2. D. N. Poenaru, Atomic clusters on surfaces, Institut fuer Theoretische Physik der Justus Liebig Universitaet, Giessen, 23 May 2008.
3. D. N. Poenaru, Shell correction method for the analysis of stability of deformed atomic clusters, Special Lecture, Theoretical MesoBioNano Science Group, FIAS, 5 Dec 2008.
4. D. N. Poenaru, Charged metallic clusters, Theoretical MesoBioNano Science Group, FIAS, 6 May 2009.
5. D. N. Poenaru, Metallic clusters as ideal trimer emitters, Institut fuer Theoretische Physik der Justus Liebig Universitaet, Giessen, 17 Sept. 2009.
6. D. N. Poenaru, Competition of collective and single-particle properties of fermions in Nuclear and Atomic Cluster Decays, Theoretical MesoBioNano Science Group, FIAS, 4 nov. 2009.

Other results obtained (I)

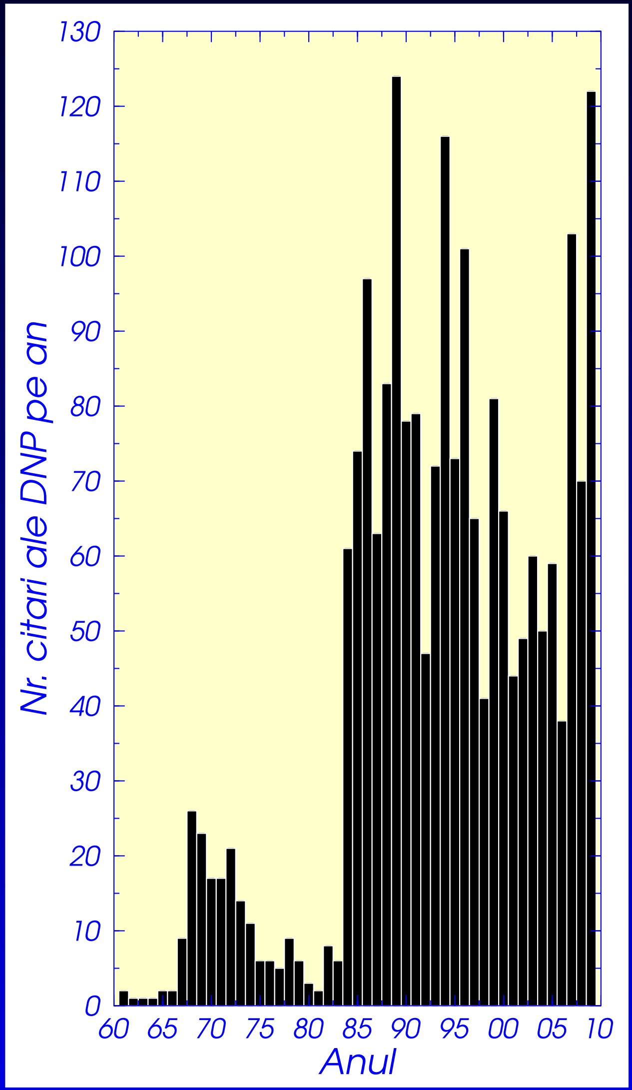
Dr. Radu Alexandru Gherghescu, is on the first place in the hierarchy of the Romanian Nuclear Physicists with larger number of publications within the period 2002-2006 made by AdAstra Organization.

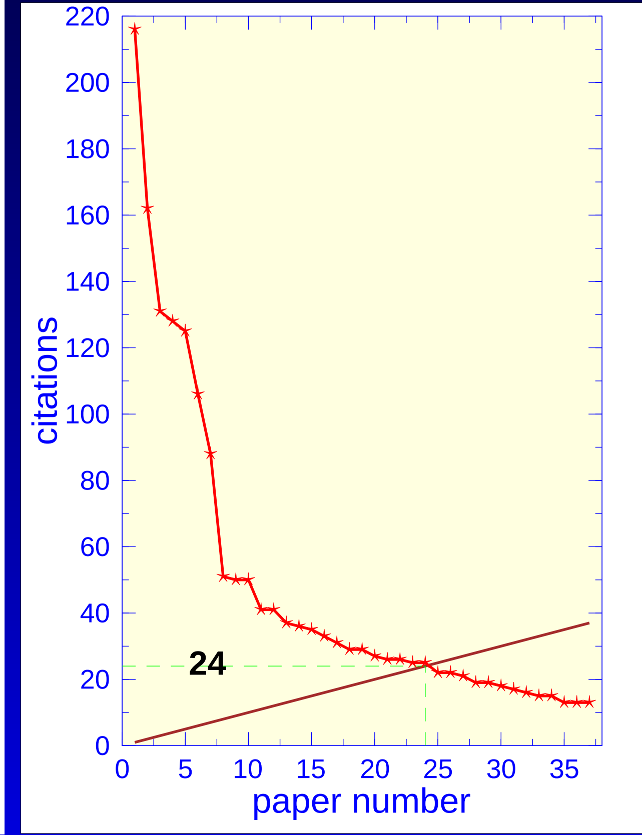
D. N. Poenaru together with A. Sandulescu and W. Greiner are mentioned in Encyclopaedia Britannica for calculations predicting a new type of nuclear decay: "heavy-ion radioactivity". The following types of radioactivities have been experimentally confirmed worldwide: ^{14}C, ^{20}O, ^{23}F, $^{22,24-26}$Ne, ^{28,30}Mg and ^{32,34}Si.

In 2009 the Emanuil Gojdu National College, Oradea, decided to give the name Dorin Poenaru to the Laboratory of Physics.

Dorin Poenaru won in 2009 the title of DFG MERCATOR Gastprofessur, the highest award granted by Deutsche Forschungsgemeinschaft yeach year to few prestigious foreign scientists. In this quality he has been working at the Frankfurt Institute for Advanced Studies, with Dr. R. A. Gherghescu, the founder director Prof. Dr. Dr.h.c.mult. Walter Greiner and the Theoretical MesoBioNano Science Group coordinated by Prof. Dr. Andrey Solov'yov. Through this contact the Romanian researchers contributed to the network of excellence EXCELL of the European Commision.

Other results obtained (II)





D. N. Poenaru's scientific publications were cited more than 2110 times by other authors (see the above figure). He has a Hirsch factor of 24.

Other results obtained (III)

On the web sites http://www.theory.nipne.ro/˜poenaru and http://fias.uni-frankfurt.de/˜poenaru/ 7 presentations are accessible, among which:

1. Macroscopic-Microscopic Method for Atomic Cluster Physics, Special Lecture MesoBioNano Sci, FIAS, 2008
2. Hemispheroidal single-particle Shell Model, Seminar talk, DFT, IFIN-HH, 2009
3. Charged Metallic Clusters, ISACC09 Symposium, Ann Arbor, MI, USA, 2009

External coworker: Dr. Ileana Hania Plonski, CS1

International cooperation (Project DFG, Bonn, project EXCELL of EC, Bruxelles):

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PhD student Veronika Dick, Frankfurt Graduate School for Science, Frankfurt Institute for Advanced Studies

Dr Andrey Lyalin, former member of the Theoretical MesoBioNano Science Group, FIAS, presently at Hokkaido University, Japan