Light clusters in nuclei and nuclear matter: Nuclear structure and decay, heavy ion collisions, and astrophysics

Trento, September 02-06, 2019

Main Topics

- Cluster models, structure of light nuclei, cluster quantum phase transition
- Reaction theory, α decay of heavy and superheavy nuclei
- Clustering in nuclear matter and consequences for thermodynamic properties
- Heavy-ion collisions and clustering in nonequilibrium systems, transport codes
- Astrophysical consequences of clustering

Confirmed Speakers

M. Barbui (*TAMU*), R. Bougault (*LPC Caen*), J. Cseh (*INR Debrecen*), D.-S. Delion (*NIPNE Bucharest*), B. Doenigus (*U Frankfurt*), T. Fischer (*U Wroclaw*), Y. Funaki (*Kanto Gakuin University*), F. Iachello (*Yale*), M. Ito (*Kansai University*), M. Itoh (*Tohoku University*), Y. Kanada-En'yo (*Kyoto University*), K. Kato (*U Sapporo*), T. Kawabata (*Osaka University*), T. Kokalova (*U Birmingham*), M. Lyu (*Osaka University*), M. Mirea (*IFIN-HH*), S. Mrowczynski (*NCBJ Warsaw*), J. Natowicz (*TAMU*), T. Neff (*GSI Darmstadt*), H. Pais (*U Coimbra*), C. Providencia (*U Coimbra), Z. Ren (Tongji Shangai), S. Shlomo (TAMU), M. Szala (Goethe University Frankfurt), A. Tohsaki (RCNP Osaka), S. Typel (TU Darmstadt), D. Vretenar (University of Zagreb), H. Wolter (LMU Munich), C. Xu (Nanjing University), T. Yamada (Kanto Gakuin University), P. Zarubin (JINR Dubna), B. Zhou (Hokkaido University)*

Organizers

Gerd Roepke (*Universität Rostock)*, Peter Schuck (*Université Paris-Sud - IN2P3/CNRS - Orsay*), David Blaschke (*University of Wroclaw and JINR Dubna*), Masaaki Kimura *(Hokkaido University, Sapporo),* Hisashi Horiuchi (*RCNP - Osaka University*)

Director of the ECT*: Professor Jochen Wambach (ECT*)

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Tel.:(+39-0461) 314722 Fax:(+39-0461) 314750, E-mail: **driessen@ectstar.eu or visit http://www.ectstar.eu**

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(through the FBK, the Bruno Kessler Foundation)

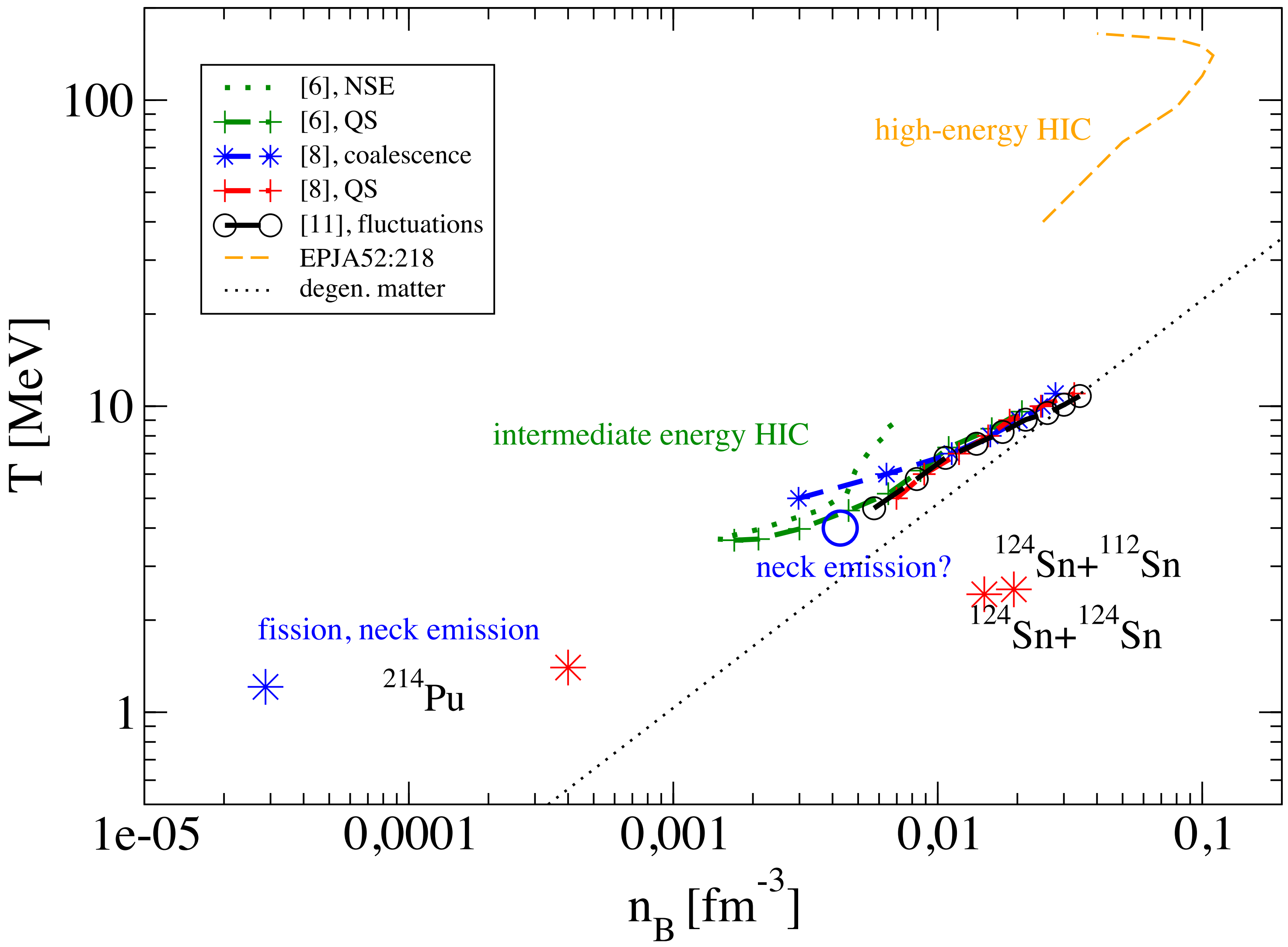
and from the European project Strong-2020.
More information on Strong-2020 can be found on the website: http://ectstar.fbk.eu/node/4486.

Preliminary Program
(status: 22.08.2019)

	Monday, 2.9.	Tuesday, 3.9.	Wednesday, 4.9.	Thursday, 5.9.	Friday, 6.9.
9:00 – 9:45	Registr. 8:30-9:30 Opening 9:30-9:45	Delion	Natowitz	Doenigus	Typel
9:45 – 10:30	Kanada-En'yo	Ren	Wolter	Mrowczynski	Fischer
10:30 – 11:00	Coffee Break				
11:00 – 11:30	Ito	Iachello	Gauthier	Szala	Shlomo
11:30 – 12:00	Lyu	Xu	Barbui	Pysz	Bastian
12:00 – 12:30	Vretenar	Bai	Pais	Cseh	Samarin/Closing
12:30 – 14:30	Lunch Break				
14:30 – 15:15	Neff	Funaki	Zarubin/Zarubina	Mirea	
15:15 – 16:00	Kokalova	Kawabata	Zhou	Itoh (30') Baran (30')	
16:00 – 16:30	Coffee Break				
16:30 – 17:00	Han	Santa Rita	Yamada	Dumitrescu	
17:00 – 17:30	Fujikawa	Shneydman	Gallmeister	Lasseri	
17:30 – 18:00	Kimura	Liu	Kozhevnikova	Discussion (Blaschke)	
18:00 – 18:30	Discussion (Kimura)	Discussion (Schuck)	Discussion (Röpke)		
18:30 – ...	Welcome dinner				
19:30 – ...				Social Dinner	

1	Bai	Some Progress on the New Double-Folding Potential and Alpha-Alpha Elastic Scattering
2	Baran	Description of nuclei in terms of pairs and quartets
3	Barbui	Experimental search for states analogous to the ^{12}C Hoyle state in heavier nuclei
4	Bastian	From nuclear clusters to composite hadrons
5	**Blaschke**	Discussion; Clusters in HIC and astrophysics
7	Delion	Alpha decay versus alpha clustering
8	Dönigus	Cluster production in HIC at ALICE and STAR
9	Dumitrescu	Investigation of α-like Quasimolecules in Heavy Nuclei
10	Fischer	Weak reactions with light clusters in simulations of core-collapse supernovae
11	Fujikawa	Search for alpha-condensed state in 20Ne
12	Funaki	Alpha cluster condensates and dynamics of cluster formation
13	Gallmeister	Nucleosynthesis in heavy-ion collisions at the LHC via the Saha equation
14	Gauthier	A Nucleation Model Analysis of Neck emission yields in Heavy Ion-Reactions
49	Han	Investigation of the 14C + α molecular configuration in 18O by means of transfer and sequential decay reaction
15	Iachello	Symmetry approach to clustering in nuclei
16	Ito	Isoscalar transitions and alpha cluster structures
17	Itoh	Measurement of four-alpha decays near the four-alpha threshold energy in 16O
18	Kanada-En'yo	Cluster excited states probed by alpha and proton inelastic scattering
20	Kawabata	Gamma decay width of the 3-1 state in 12C, and recent activities of the Kyoto-Osaka group
21	**Kimura**	Discussion; Shape of light clustered nuclei
22	Kokalova	Theoretical challenges from an experimentalist's point of view.
23	Kozhevnikova	Production of light clusters in generator THESEUS
24	Lasseri	Quantum localisation and dilution effects on clusterisation
25	Liu	Preliminary Experimental Results of the Molecular States in 16C
26	Lyu	Ab initio study of high-momentum physics in s-shell nuclei
27	Mirea	Fine structure of alpha decay from the time dependent pairing equations
28	Mrowczynski	Thermal vs. coalescence model and production of light nuclei in relativistic heavy-ion collisions
29	Natowitz	Laboratory Studies of Dilute Nuclear Matter
30	Neff	The role of clustering in structure and reactions of light nuclei
31	Pais	Light clusters and pasta phases in warm stellar matter
32	Pysz	Production of H and He isotopes in pA collision at a few GeV beam energy
33	Ren	Calculation on alpha-decay half-lives of heavy nuclei
34	**Röpke**	Discussion; Correlations in nuclear systems
35	Samarin	Application of Feynman's Continual Integrals and Hyperspherical Functions to the Cluster Structure of Light Nuclei
36	Santa Rita	Advances towards the measurement of gamma transitions in clustered states of 16O
37	**Schuck**	Discussion;Life time of alpha GDR state in alpha cluster states; family of Hoyle states in 12C
38	Shlomo	Sensitivity of giant resonances energies to nuclear matter properties and the equation of state
39	Shneydman	Nuclear reflection-asymmetry in cluster approach
40	Szala	Light nuclei formation in heavy ion collisions measured with HADES
41	Typel	Clusters in nuclear matter: from nuclei in the laboratory to stars in the cosmos
42	Vretenar	Localization and clustering in atomic nuclei
43	Wolter	Light cluster production in intermediate energy heavy-ion collisions
44	Xu	Alpha-cluster formation and decay in the quartetting wave function approach
45	Yamada	Nuclear matter calculation with the tensor optimized Fermi sphere method
46	Zarubin	Nuclear clustering studied inside fragmentation cone of relativistic nuclei
47	Zarubina	Imaging of dissociation of relativistic nuclei in nuclear track emulsion
48	Zhou	Microscopic description of multi-clusters in light nuclei

Freeze-out temperatures and densities

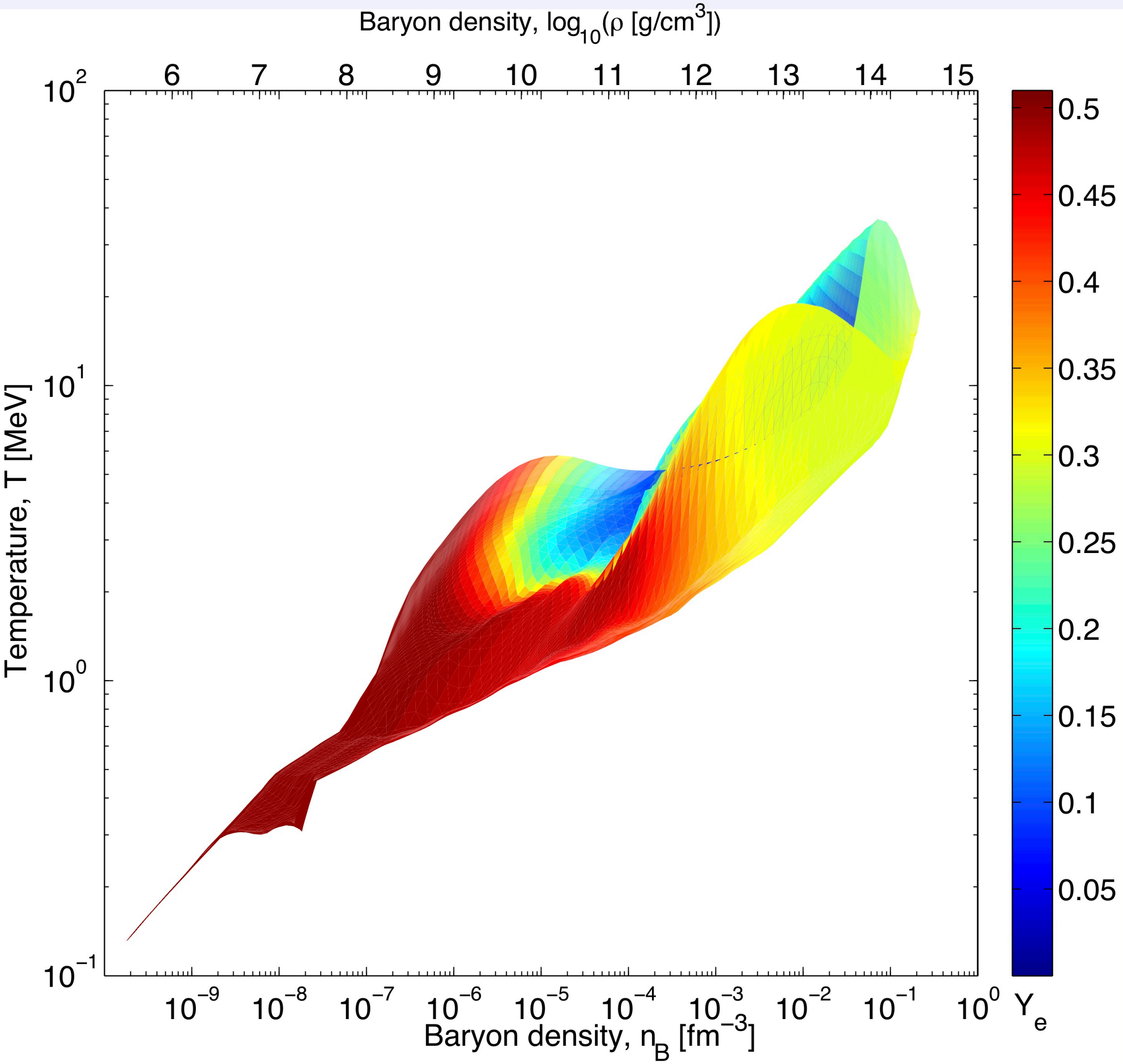


Nuclear matter phase diagram

Core collapse supernovae

Relevant Parameters:

- **density**:
  $10^{-9} \lesssim \varrho/\varrho_{\rm sat} \lesssim 10$
  with nuclear saturation density
  $\varrho_{\rm sat} \approx 2.5 \cdot 10^{14}$ g/cm^3
  ($n_{\rm sat} = \varrho_{\rm sat}/m_n \approx 0.15$ fm^{-3})
- **temperature**:
  0 MeV $\leq k_B T \lesssim 50$ MeV
  ($\hat{=}\ 5.8 \cdot 10^{11}$ K)
- **electron fraction**:
  $0 \leq Y_e \lesssim 0.6$



T. Fischer, GSI Darmstadt

Correlations in nuclear systems

- Kimura: Clusters?
- Correlations in many-particle systems, finite density?
- Classical – quantum: antisymmetrization
- Bound states, continuum correlations
- Spectral function - quasiparticle concept
- Pairing: $n_{up}n_{down}$, $p_{up}p_{down}$, $n_{up}p_{down}$
- Quartetting: $n_{up}n_{down}p_{up}p_{down}$

- Correlations in thermodynamic equilibrium
- Center-of-mass motion, intrinsic motion are separated
- Inhomogeneous systems
- Time-dependent processes

Effective wave equation for the deuteron in matter

In-medium two-particle wave equation in mean-field approximation

$$\left(\frac{p_1^2}{2m_1}+\Delta_1+\frac{p_2^2}{2m_2}+\Delta_2\right)\Psi_{d,P}(p_1,p_2)+\sum_{p_1',p_2'}(1-f_{p_1}-f_{p_2})V(p_1,p_2;p_1',p_2')\Psi_{d,P}(p_1',p_2')$$

$$=E_{d,P}\Psi_{d,P}(p_1,p_2)$$

Add self-energy

Pauli-blocking

Fermi distribution function

$$f_p=\left[e^{(p^2/2m-\mu)/k_BT}+1\right]^{-1}$$

Correlated medium?

Thouless criterion

$$E_d(T,\mu)=2\mu$$

BEC-BCS crossover:
Alm et al.,1993

Few-particle Schrödinger equation in a dense medium

4-particle Schrödinger equation with medium effects

$$\left(\left[E^{HF}(p_1)+E^{HF}(p_2)+E^{HF}(p_3)+E^{HF}(p_4)\right]\right)\Psi_{n,P}(p_1,p_2,p_3,p_4)$$

$$+\sum_{p_1',p_2'}(1-f_{p_1}-f_{p_2})V(p_1,p_2;p_1',p_2')\Psi_{n,P}(p_1',p_2',p_3,p_4)$$

$$+\{permutations\}$$

$$=E_{n,P}\Psi_{n,P}(p_1,p_2,p_3,p_4)$$

Thouless criterion
for quantum condensate:

$E_{n,P=0}(T,\mu) = 4\mu$

Composition of dense nuclear matter

$$n_p(T,\mu_p,\mu_n) = \frac{1}{V}\sum_{A,\nu,K} Z_A f_A\{E_{A,\nu K} - Z_A\mu_p - (A-Z_A)\mu_n\}$$

$$n_n(T,\mu_p,\mu_n) = \frac{1}{V}\sum_{A,\nu,K} (A-Z_A) f_A\{E_{A,\nu K} - Z_A\mu_p - (A-Z_A)\mu_n\}$$

mass number A
charge Z_A
energy $E_{A,\nu,K}$
ν: internal quantum number

$$f_{A(z)} = \frac{1}{\exp(z/T) - (-1)^A}$$

- Medium effects: correct behavior near saturation
  self-energy and Pauli blocking shifts of binding energies,
  Coulomb corrections due to screening (Wigner-Seitz, Debye)

Asymmetric nuclear light clusters in supernova matter

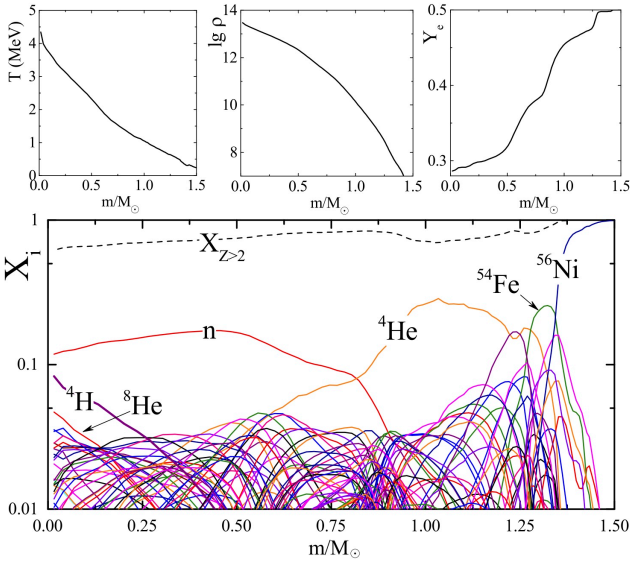


Figure 1. Upper three panels, from left ro right: temperature T (in MeV), log of density ρ (in $\mathrm{g \cdot cm^{-3}}$) and electron fraction Y_e as a functions of mass coordinate m. Lower panel: mass fractions of of nuclei X_i as a function of m. The black dashed line marked $X_{Z>2}$ shows the total mass fraction of elements with $Z>2$. EoS is pure NSE.

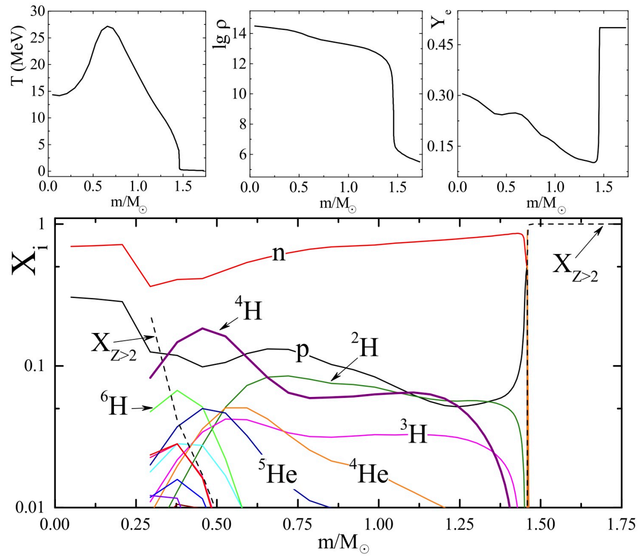
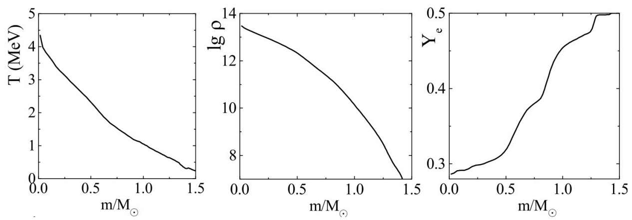
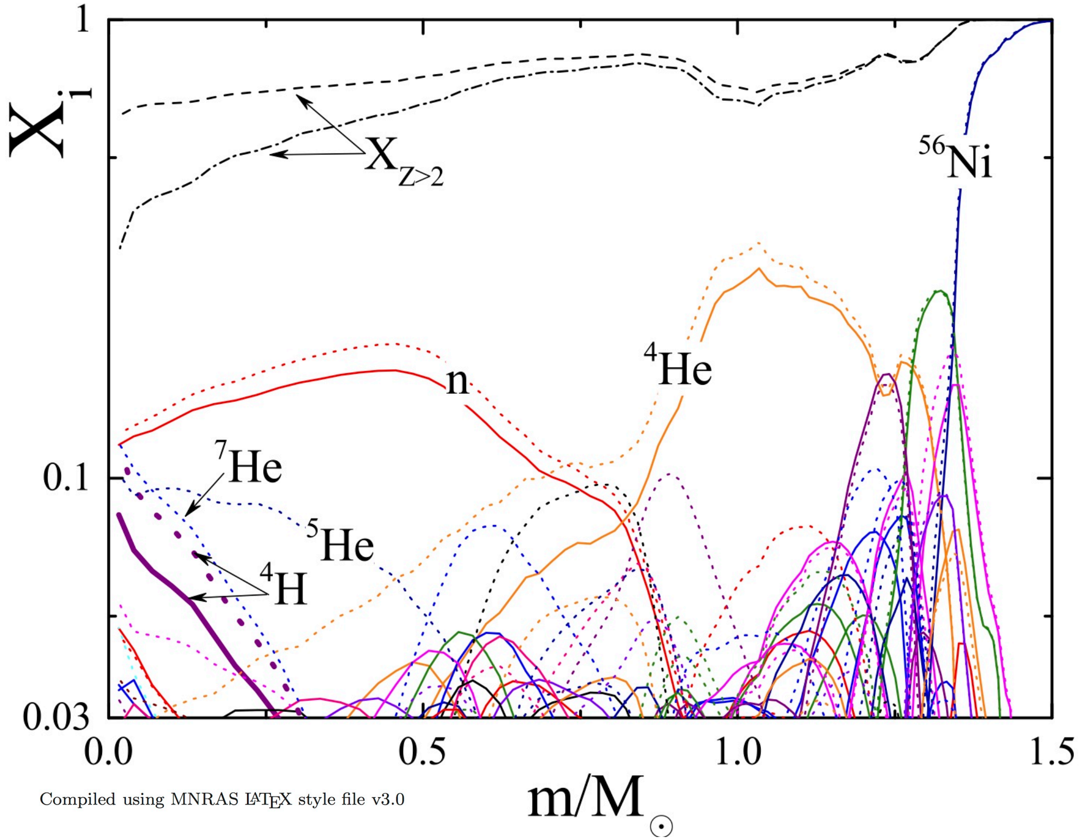


Figure 7. Upper three panels, from left ro right: temperature T (in MeV), log of density ρ (in $\mathrm{g \cdot cm^{-3}}$) and electron fraction Y_e as a functions of mass coordinate m. Lower panel: mass fractions X_i of of hydrogen and helium isotopes as a function of m. The black dashed line marked $X_{Z>2}$ shows the total mass fraction of all rest nuclei. Stellar profile corresponds to 200 ms after bounce approximately, calculations according to modified HS EoS.

A. V. Yudin, M. Hempel, S. I. Blinnikov, D. K. Nadyozhin, I. V. Panov,
Monthly Notices of the Royal Astronomical Society **483**, 5426 (2019)

Light unstable clusters





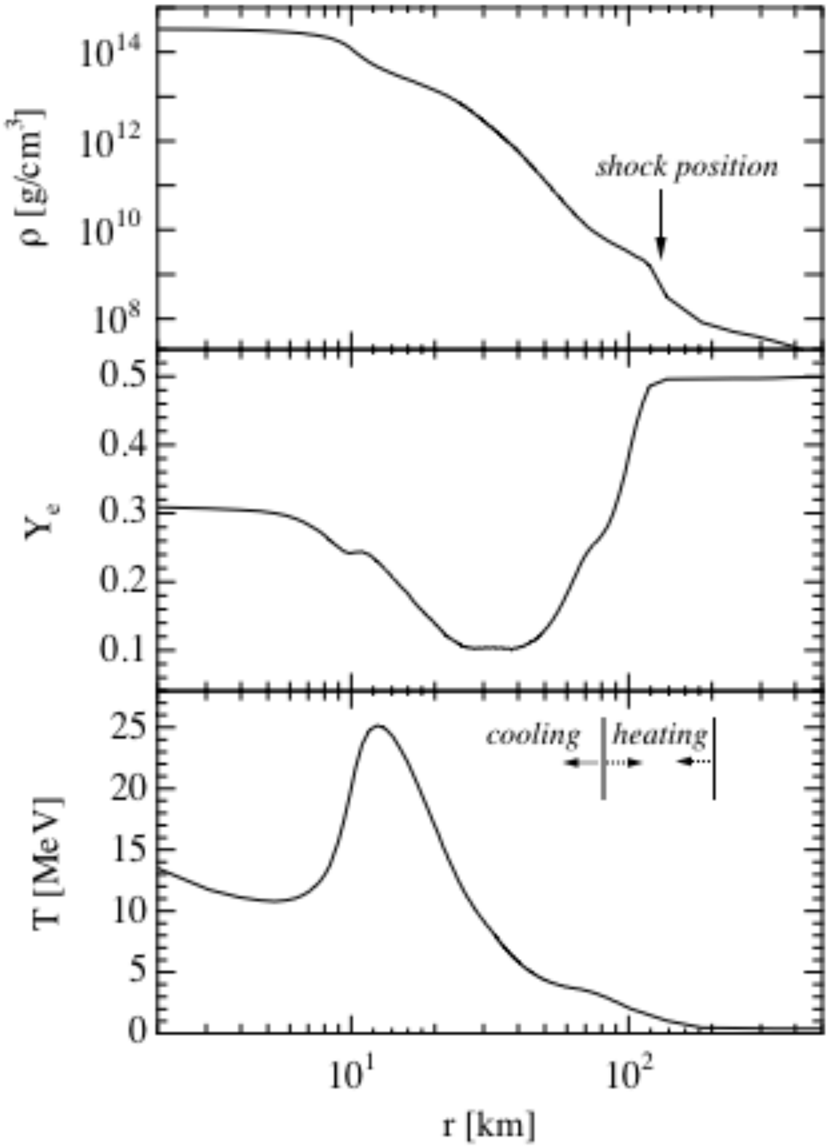
arXiv:1812.09494

MNRAS **000**, 1–9 (2018) Preprint 27 December 2018 Compiled using MNRAS LaTeX style file v3.0

Asymmetric Nuclear Light Clusters In Supernova Matter

A. V. Yudin,[1⋆] M. Hempel,[2] S. I. Blinnikov,[1] D. K. Nadyozhin,[1,3] I. V. Panov[1,3]

Core-collapse supernovae



Density,

electron fraction, and

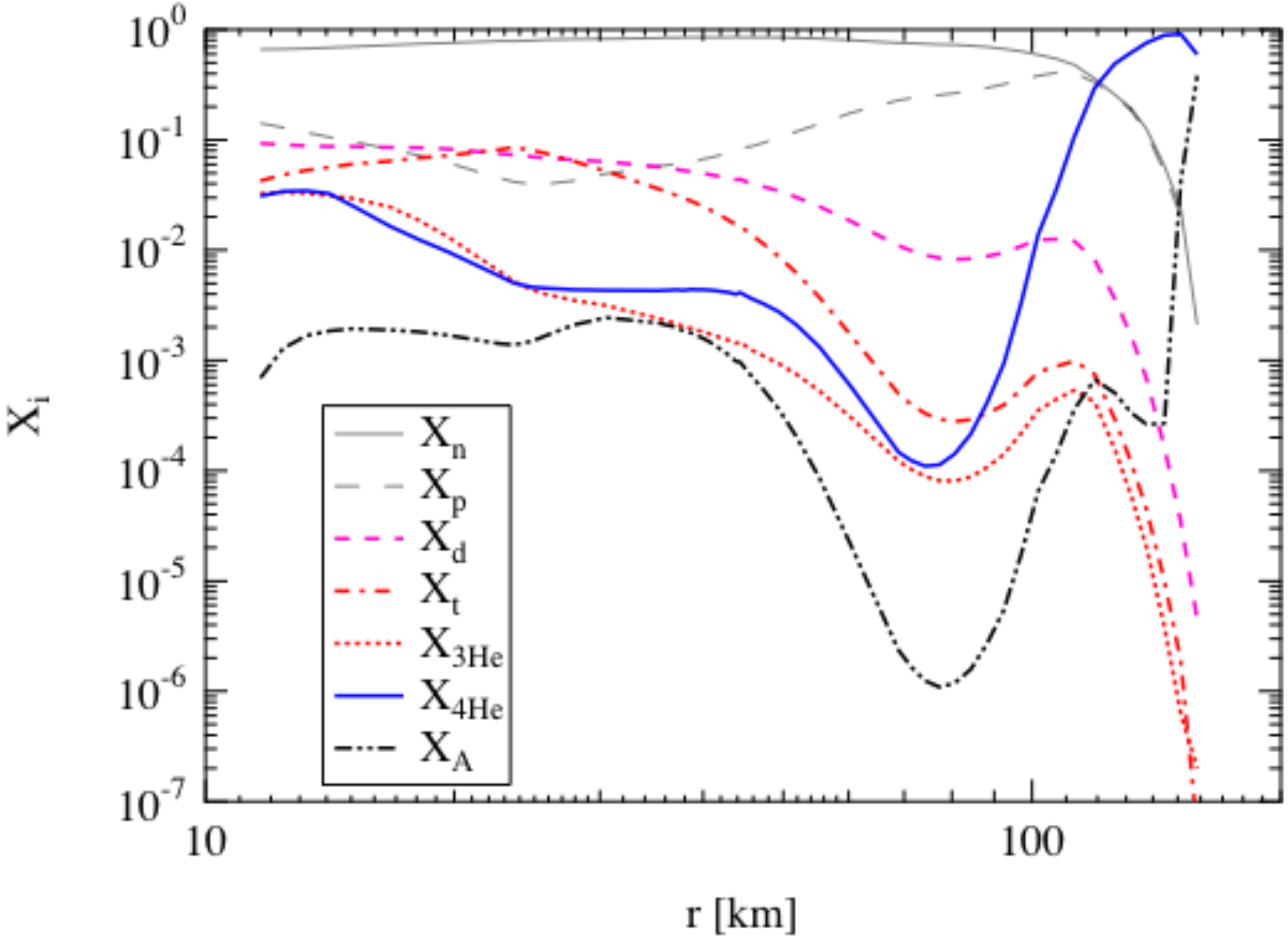
temperature profile

of a 15 solar mass supernova at 150 ms after core bounce as function of the radius.

Influence of cluster formation on neutrino emission in the cooling region and on neutrino absorption in the heating region ?

K.Sumiyoshi et al., Astrophys.J. **629**, 922 (2005)

Composition of supernova core



Mass fraction X
of light clusters
for a post-bounce
supernova core

K.Sumiyoshi,
G. R.,
PRC **77**,
055804 (2008)

EOS: continuum contributions

Partial density of channel A,c at P (for instance, $^3S_1$= d):

$$z_{A,c}^{\rm part}(\mathbf{P};T,\mu_n,\mu_p)=e^{(N\mu_n+Z\mu_p)/T}\left\{\sum_{\nu_c}^{\rm bound} g_{A,\nu_c}\, e^{-E_{A,\nu_c}(\mathbf{P})/T}\,\Theta\left[-E_{A,\nu_c}(\mathbf{P})+E_{A,c}^{\rm cont}(\mathbf{P})\right]+z_{A,c}^{\rm cont}(\mathbf{P})\right\}$$

separation: bound state part – continuum part ?

$$z_c^{\rm part}(\mathbf{P};T,n_B,Y_p)=e^{[N\mu_n+Z\mu_p-NE_n(\mathbf{P}/A;T,n_B,Y_p)-ZE_p(\mathbf{P}/A;T,n_B,Y_p)]/T}$$
$$\times g_c\left\{\left[e^{-E_c^{\rm intr}(\mathbf{P};T,n_B,Y_p)/T}-1\right]\Theta\left[-E_c^{\rm intr}(\mathbf{P};T,n_B,Y_p)\right]+v_c(\mathbf{P};T,n_B,Y_p)\right\}$$

parametrization (d – like):

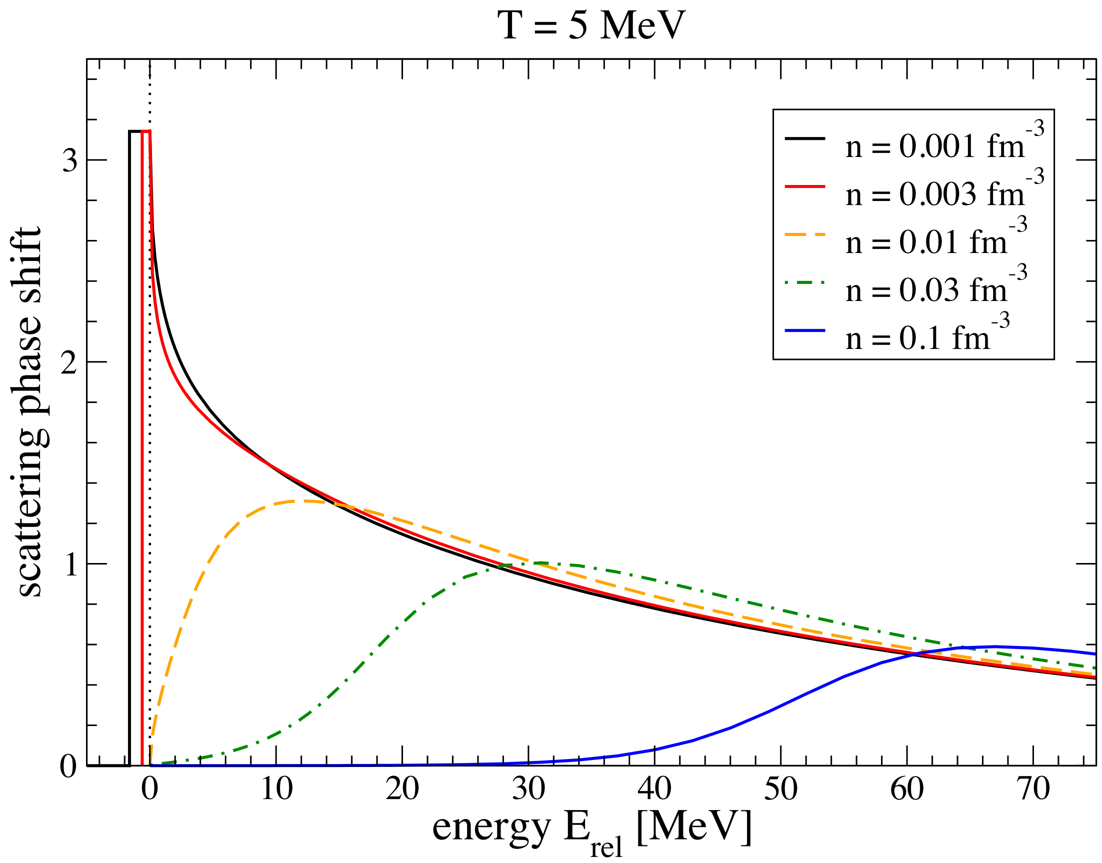
$$v_c(\mathbf{P}=0;T,n_B,Y_p)\approx\left[1.24+\left(\frac{1}{v_{T_I=0}(T)}-1.24\right)e^{\gamma_c n_B/T}\right]^{-1}.$$

$$v_d^0(T)=v_{T_I=0}^0(T)\approx 0.30857+0.65327\;e^{-0.102424\;T/{\rm MeV}}$$

G. Roepke, PRC 92,054001 (2015)

Deuteron-like scattering phase shifts

Virial coeff. $\propto e^{-E_d^0/T} - 1 + \frac{1}{\pi T}\int_0^\infty dE\, e^{-E/T}\left\{\delta_c(E) - \frac{1}{2}\sin[2\delta_c(E)]\right\}$



Tamm-Dancoff

deuteron bound state -2.2 MeV

G. Roepke, J. Phys.: Conf. Series 569, 012031 (2014)
Phys. Part. Nucl. 46, 772 (2015) [arXiv:1408.2654]

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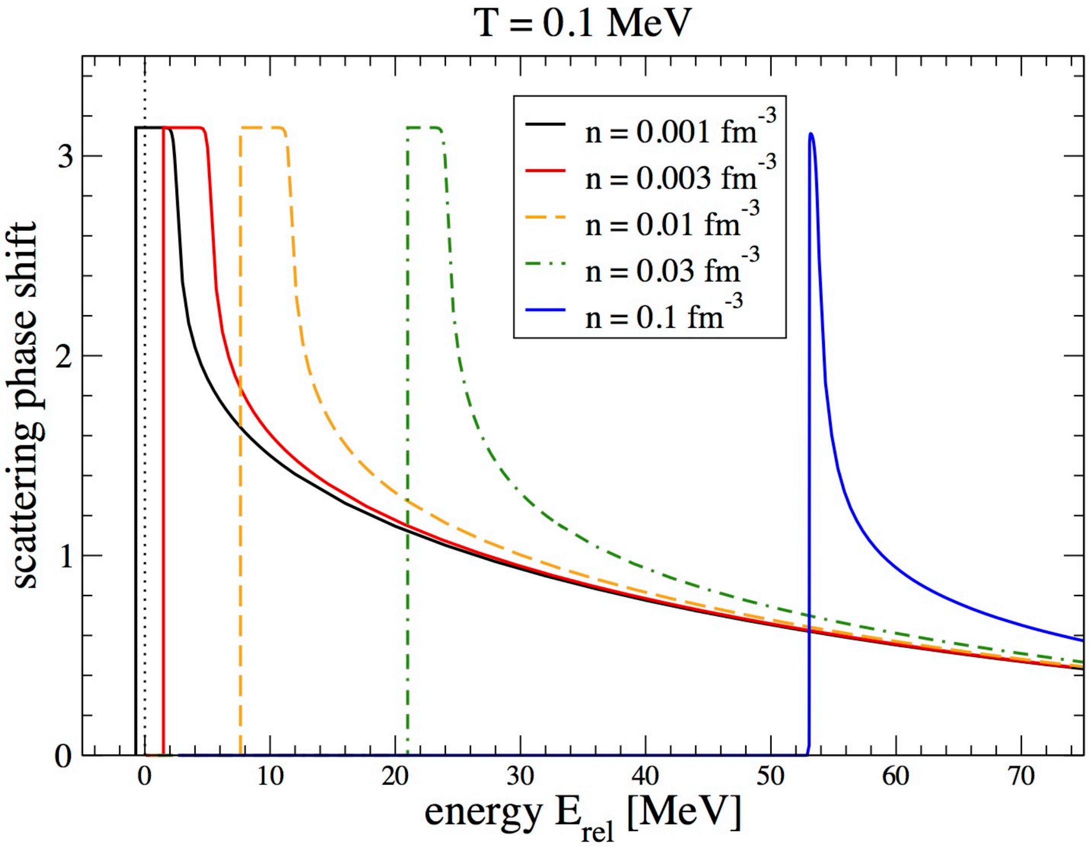

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G. Roepke, J. Phys.: Conf. Series 569, 012031 (2014)
Phys. Part. Nucl. 46, 772 (2015) [arXiv:1408.2654]

α-n scattering phase shifts

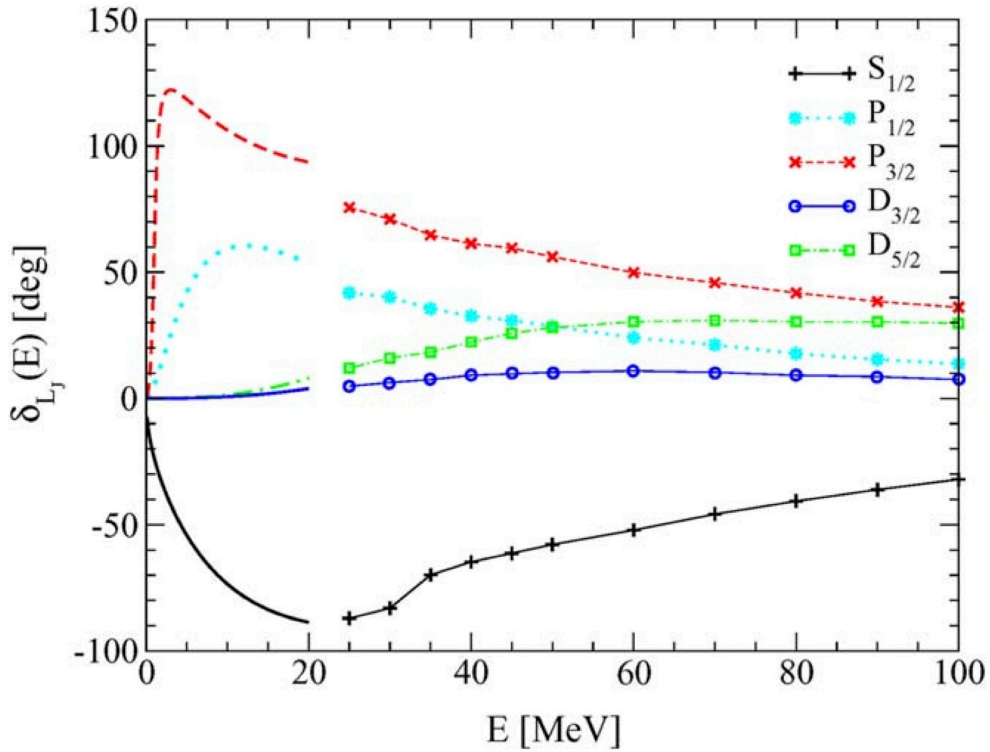
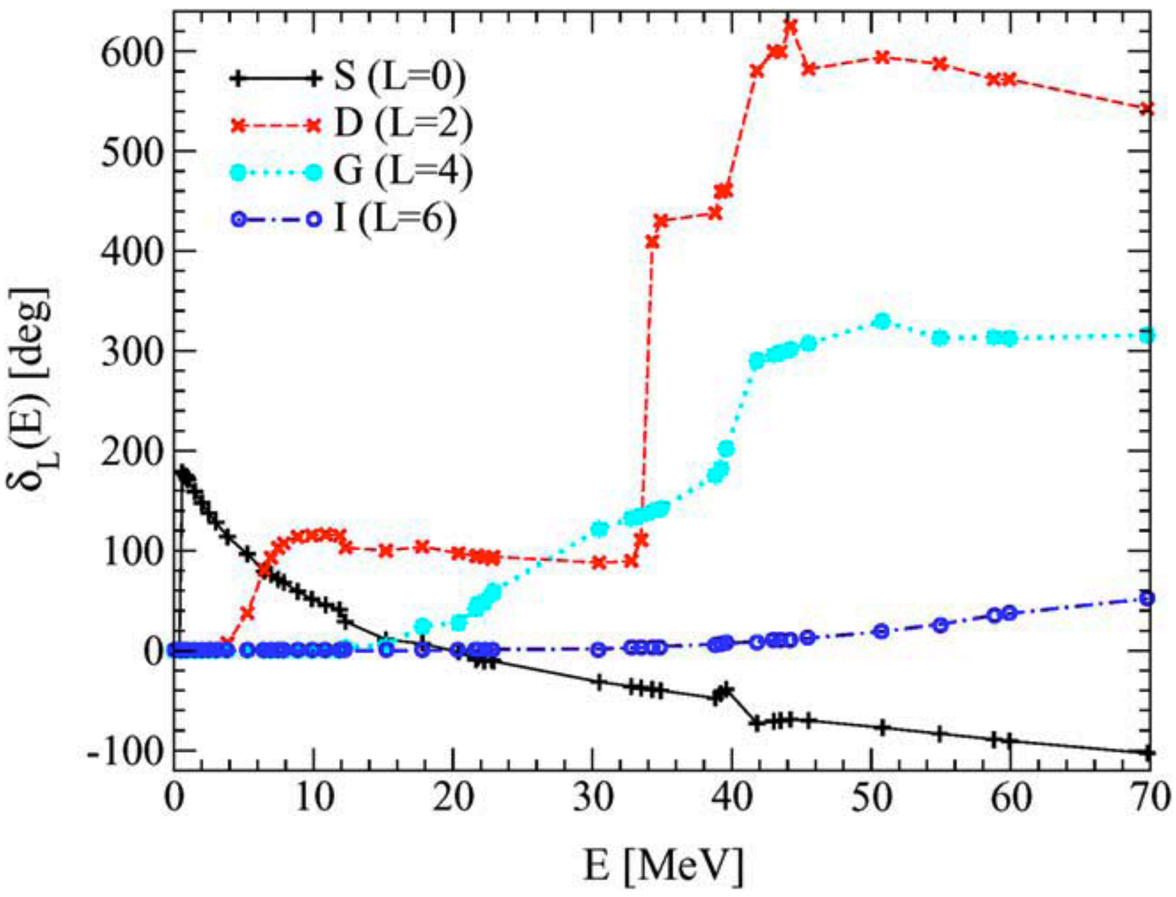


Fig. 2. (Color online.) The phase shifts for elastic neutron-alpha scattering $\delta_{L_J}(E)$ versus laboratory energy E. As discussed in the text, the solid lines are from Arndt and Roper [37] and the symbols are from Amos and Karataglidis [38]. For clarity, we do not show the F-waves included in our results for $b_{\alpha n}$.

C.J.Horowitz, A.Schwenk, Nucl. Phys. A **776**, 55 (2006)

α-α scattering phase shifts



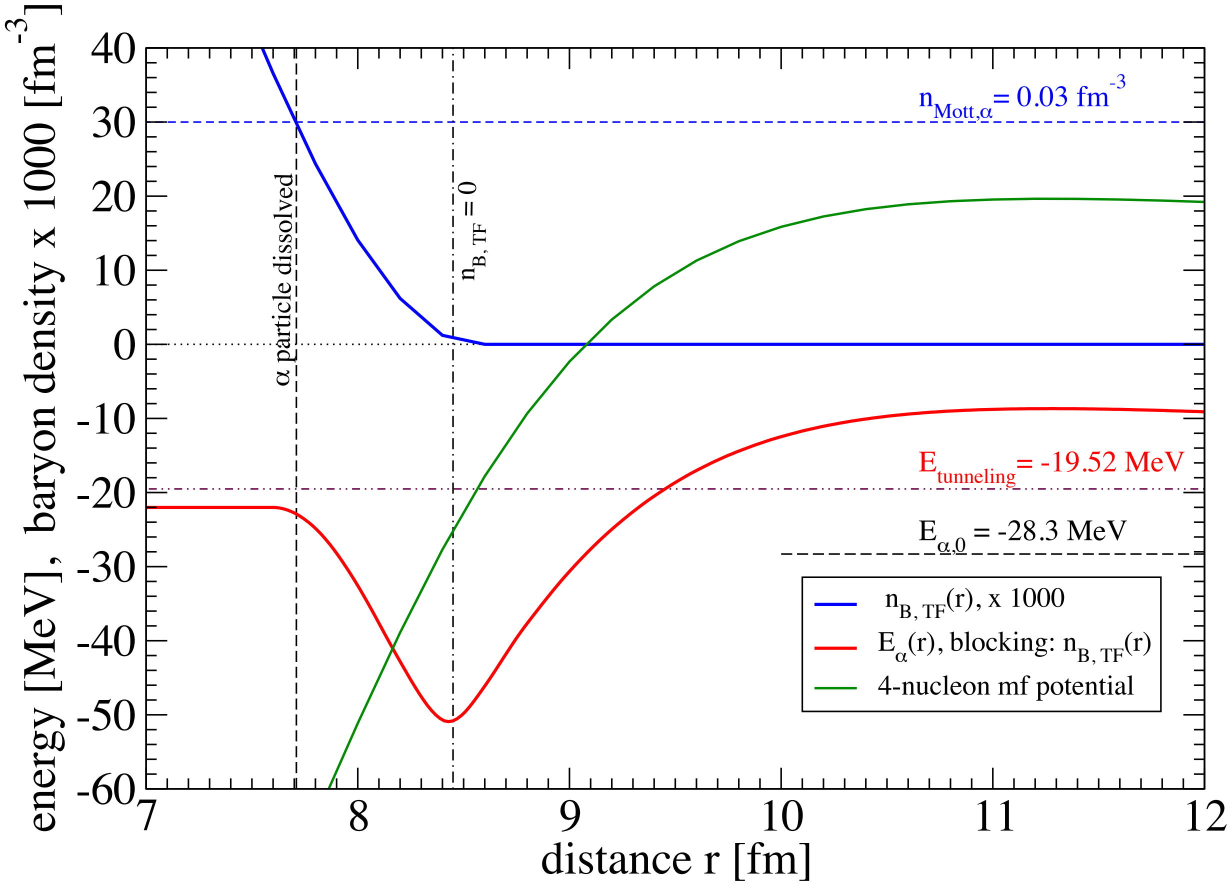
C.J.Horowitz, A.Schwenk, Nucl. Phys. A **776**, 55 (2006)

^{212}Po: α on top of ^{208}Pb

Problem:
decay half-life too short

Finite system:
discrete spectrum
of energy levels.
Relax the
Thomas-Fermi rule
$\mu_4 = E_{tunneling}$

Discrete spectrum:
shell effects



G. R., Chang Xu, et al., PRC **90**, 034304 (2014)

Clusters in an external potential

c. o. m. coordinate R, relative coordinates s_j

$$\Psi(\mathbf{R}, \mathbf{s}_j) = \varphi^{\rm intr}(\mathbf{s}_j, \mathbf{R})\, \Phi(\mathbf{R})$$

normalization

$$\int dR\, |\Phi(\mathbf{R})|^2 = 1 \qquad \int ds_j |\varphi^{\rm intr}(\mathbf{s}_j, \mathbf{R})|^2 = 1$$

Wave equation for the c.o.m. motion

$$-\frac{\hbar^2}{2Am}\nabla_R^2\Phi(\mathbf{R}) - \frac{\hbar^2}{Am}\int ds_j \varphi^{\rm intr,*}(\mathbf{s}_j, \mathbf{R})[\nabla_R \varphi^{\rm intr}(\mathbf{s}_j, \mathbf{R})][\nabla_R \Phi(\mathbf{R})]$$
$$-\frac{\hbar^2}{2Am}\int ds_j \varphi^{\rm intr,*}(\mathbf{s}_j, \mathbf{R})[\nabla_R^2 \varphi^{\rm intr}(\mathbf{s}_j, \mathbf{R})]\Phi(\mathbf{R}) + \int dR'\, W(\mathbf{R}, \mathbf{R}')\Phi(\mathbf{R}') = E\,\Phi(\mathbf{R})$$

c.o.m. effective potential

$$W(\mathbf{R}, \mathbf{R}') = \int ds_j\, ds'_j\, \varphi^{\rm intr,*}(\mathbf{s}_j, \mathbf{R})\, [T[\nabla_{s_j}]\delta(\mathbf{R}-\mathbf{R}')\delta(\mathbf{s}_j - \mathbf{s}'_j) + V(\mathbf{R}, \mathbf{s}_j; \mathbf{R}', \mathbf{s}'_j)]\, \varphi^{\rm intr}(\mathbf{s}'_j, \mathbf{R}')$$

Wave equation for the intrinsic motion

$$-\frac{\hbar^2}{Am}\Phi^*(\mathbf{R})[\nabla_R \Phi(\mathbf{R})][\nabla_R \varphi^{\rm intr}(\mathbf{s}_j, \mathbf{R})] - \frac{\hbar^2}{2Am}|\Phi(\mathbf{R})|^2\nabla_R^2 \varphi^{\rm intr}(\mathbf{s}_j, \mathbf{R})$$
$$+\int dR'\, ds'_j\, \Phi^*(\mathbf{R})\, [T[\nabla_{s_j}]\delta(\mathbf{R}-\mathbf{R}')\delta(\mathbf{s}_j - \mathbf{s}'_j) + V(\mathbf{R}, \mathbf{s}_j; \mathbf{R}', \mathbf{s}'_j)]\, \Phi(\mathbf{R}')\varphi^{\rm intr}(\mathbf{s}'_j, \mathbf{R}') = F(\mathbf{R})\varphi^{\rm intr}(\mathbf{s}_j, \mathbf{R})$$

G. Roepke et al., PRC **90**, 034304 (2014)

Quantum condensate: quartetting

Ideal Bose condensate : $|0\rangle = b_0^\dagger b_0^\dagger \cdots b_0^\dagger |vac\rangle$

α-particle condensate : $|\Phi_{\alpha C}\rangle = C_\alpha^\dagger C_\alpha^\dagger \cdots C_\alpha^\dagger |vac\rangle$

In r-space :

$$\langle \vec{r}_1, \vec{r}_2, \cdots, \vec{r}_{4n} | \Phi_{\alpha C} \rangle = \mathcal{A}\{\Phi(\vec{r}_1, \vec{r}_2, \vec{r}_3, \vec{r}_4)\Phi(\vec{r}_5, \vec{r}_6, \vec{r}_7, \vec{r}_8)\cdots\Phi(\vec{r}_{4n-3}, \vec{r}_{4n-2}, \vec{r}_{4n-1}, \vec{r}_{4n})\}$$

In comparison with pairing :

$$\langle \vec{r}_1, \vec{r}_2, \cdots | \mathrm{BCS} \rangle = \mathcal{A}\{\Phi(\vec{r}_1, \vec{r}_2)\Phi(\vec{r}_3, \vec{r}_4)\cdots\}$$

A. Tohsaki et al., PRL **87**, 192501 (2001)