Nonstatistical fluctuations for deep inelastic processes

in $^{27}Al + ^{27}Al$ collision

- **Introduction**

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- **Cross section excitation functions (EFs)**

  1. Statistical analysis

  (a) Energy autocorrelation function (EAF): experimental results and discussion

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- **Conclusions**

Introduction

• **Ericson (Statistical) Fluctuations in the region $\Gamma >> D$**

(due to random interferences between resonances) (T. Ericson, Ann. Phys.,1963)

- channel uncorrelated
- Lorentzian pattern of the energy autocorrelation function: $C(\varepsilon) = \frac{1}{N_{eff}} \frac{\Gamma^2}{\Gamma^2 + \varepsilon^2}, \ \tau = \frac{\hbar}{\Gamma}$

N_{eff} - number of the independently microchannels contributing to the cross section

Γ - correlation width of the fluctuations

• **Types of structures (fluctuations) in the Efs:** gross ($\tau \sim 10^{-22}$ sec), intermediate (nonstatisical) ($\tau \sim 10^{-21}$ sec), CN (statistical) ($\tau > 10^{-19}$ sec)

$\hbar = 6.582\ 10^{-22}$ Mev sec,

$\Gamma \sim$ MeV, hundreds of keV, keV – tens of keV for gross, intermediate, CN structures

• **Fluctuation phenomenon unexpected for deep inelastic processes (DIP):**

amplitude of the fluctuations $\sim 1/N_{eff}$, N_{eff} very large for DIP

However evidence of the fluctuations in EFs of the DIP of the $^{28}Si + ^{64}Ni$ system with nonstatistical features *(A. De Rosa et al, Phys. Lett., 1985)*:

- **Γ** of hundreds of keV
- channel correlated

\+ non Lorentzian pattern of the energy autocorrelation function

- **Other studied systems: medium mass or light α-nuclei**

$^{12}C + ^{24}Mg$	*(A. Glaesner et al, Phys. Lett B, 1986)*
$^{19}F + ^{89}Y$	*(T. Suomijavri et al, PRC, 1987)*
$^{28}Si + ^{48}Ti$	*(A. De Rosa et al, PRC, 1988; F. Rizzo et al, Z. Phys. A, 1994)*
$^{19}F + ^{63}Cu$	*(G. Cardella et al, Z. Phys. A, 1990)*
$^{28}Si + ^{28}Si$	*(M. Papa et al, Z. Phys. A,1995)*
$^{19}F + ^{51}V$	*(Wang Qi et al, Phys. Lett. B, 1996)*

- **Models supposing angular momentum coherence**

Ericson's theory generalized to deep inelastic reaction (*D. M. Brink, K.Dietrich, Z. Phys., 1987),* Kun Model *(S. Yu. Kun, Phys. Lett. B, 1991)*

+ **Partial Overlapping of Molecular Levels** ($\Gamma > D$) POMLM *(G. Pappalardo et al, 1991)* **explain the persistence and the main features of the fluctuations in the EF of deep inelastic processes.**

- **Models for nonstatistical fluctuations from elastic and inelastic scattering of heavy ion as** Orbiting Cluster Model (OCM) *(N. Cindro, 1980)*, Number of Open Channels (NOC) Model *(Y. Abe, F. Haas, 1981)* **predict intermediate structures in light heavy ion systems where both partners are α-nuclei**

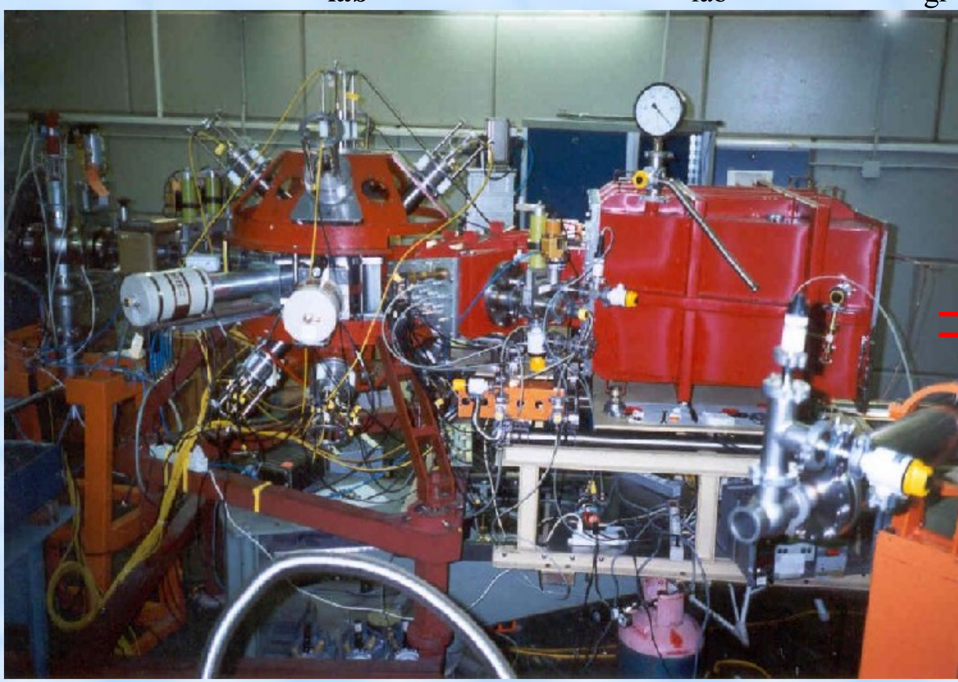
- **Systems studied by us light mass non-□:**

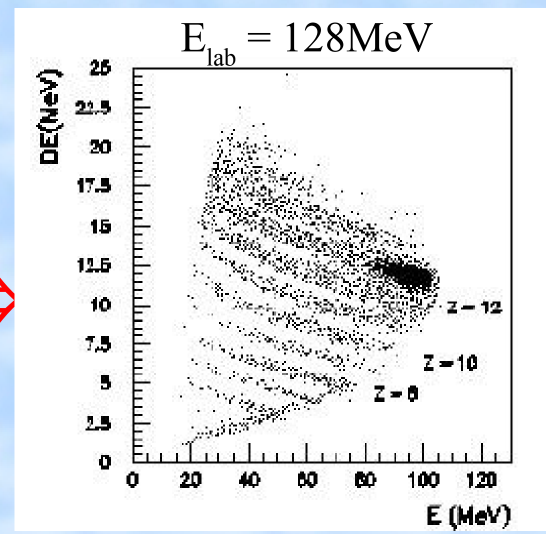
$^{19}F + ^{27}Al$ *(I. Berceanu et al, Phys. Rev. C, 1998)*, **$^{27}Al + ^{27}Al$**

Experimental procedures

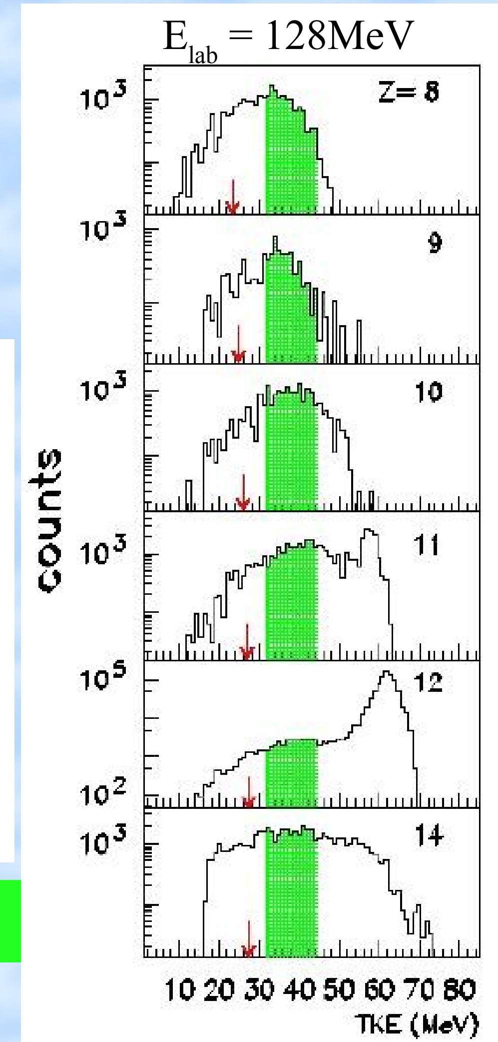
- Incident energy range: E_{lab} = 120 - 132 MeV,
- Energy increment: 250 keV (125 keV in CMS)
- Targets: ^{27}Al of 39, 40 μg/cm^2 (~ 75 keV),
  ^{197}Au of 92 μg/cm^2, ^{12}C of 100 μg/cm^2
- Beam current measured with a tantalum plated Faraday cup provided with an electron suppressing guard ring
- Detection and identification of the reaction products:
  Ionization chambers (ICs) of **DRACULA** Device
  ICs center at $\boldsymbol{\theta_{lab} = 24^o}$; $12^o \leq \theta_{lab} \leq 36^o$; θ_{gr}(132 MeV) = 15^o

Integration window:
TKEL = (20 - 32) MeV
TKEL = E_{cm} – TKE



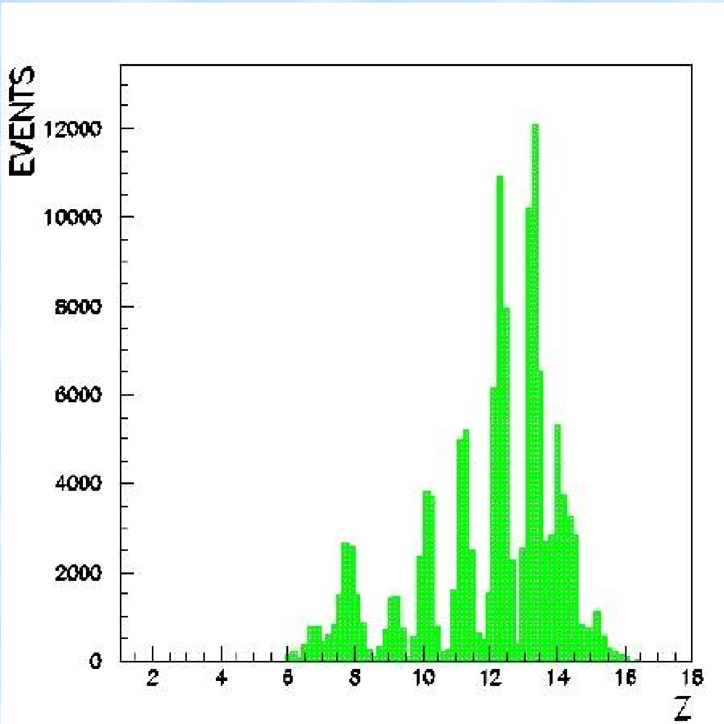


ΔE/E = 2.5%; Δθ=0.5^o; ΔZ=0.3

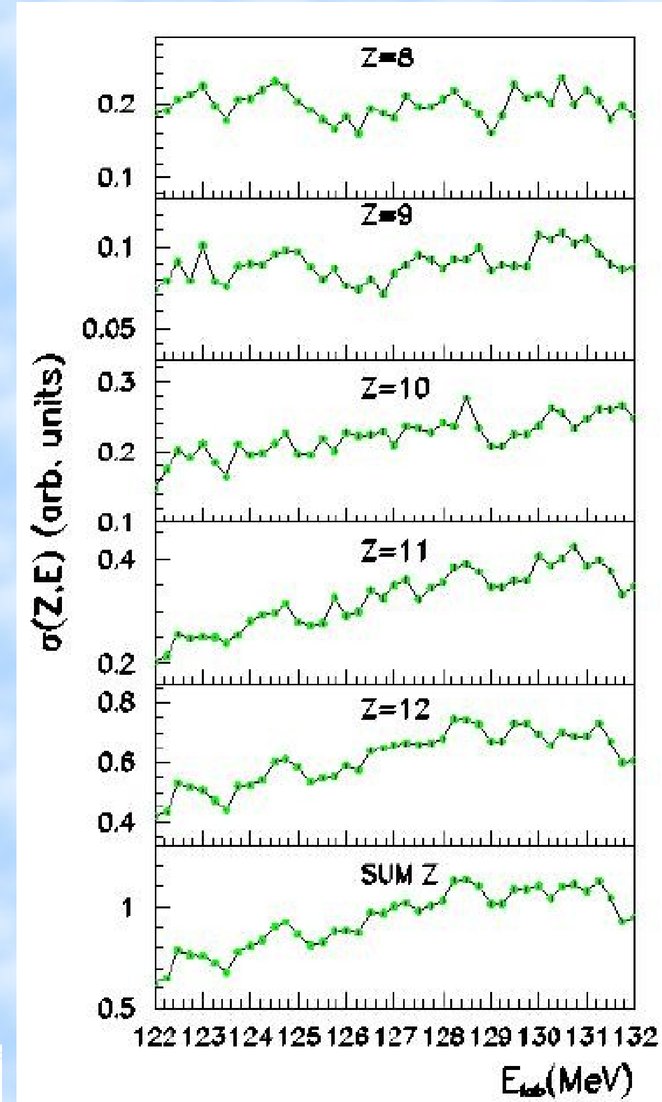


Carbon deposition on Al target = 6 μg/cm^2
The effect on the yield of the Z ≠ 13 products < 1%

Cross section excitation functions



$$\sigma(Z,E) = N_{ev}/N_{beam}$$



1. Statistical analysis

- **Cross Correlation Coefficients (CCC)**

$$C_{Z_iZ_j} = \left\langle \left(\frac{\sigma(Z_i,E)}{\overline{\sigma}(Z_i,E)} - 1\right)\left(\frac{\sigma(Z_j,E)}{\overline{\sigma}(Z_j,E)} - 1\right)\right\rangle$$

$\langle\ ,\ \rangle$ - average on energy

$\overline{\sigma}(Z_{i,j},E)$ - energy averged cross section

Z	8	9	10	11	12
8	1	0.865	0.702	0.356	0.467
9		1	0.482	0.671	0.554
10			1	0.831	0.977
11				1	0.703
12					1

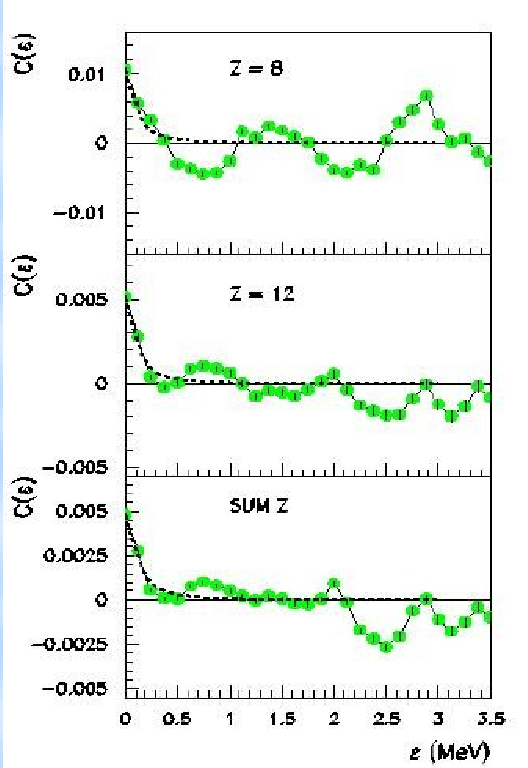
Large CCC → nonstatistical fluctuations

- **Energy autocorrelation function (EAF)**

$$C(\varepsilon) = \left\langle \left(\frac{\sigma(Z,E)}{\overline{\sigma}(Z,E)} - 1 \right) \left(\frac{\sigma(Z,E+\varepsilon)}{\overline{\sigma}(Z,E+\varepsilon)} - 1 \right) \right\rangle,$$

$\varepsilon = (0, (E^{f}_{cm} - E^{i}_{cm}))$ - energy increment in CMS

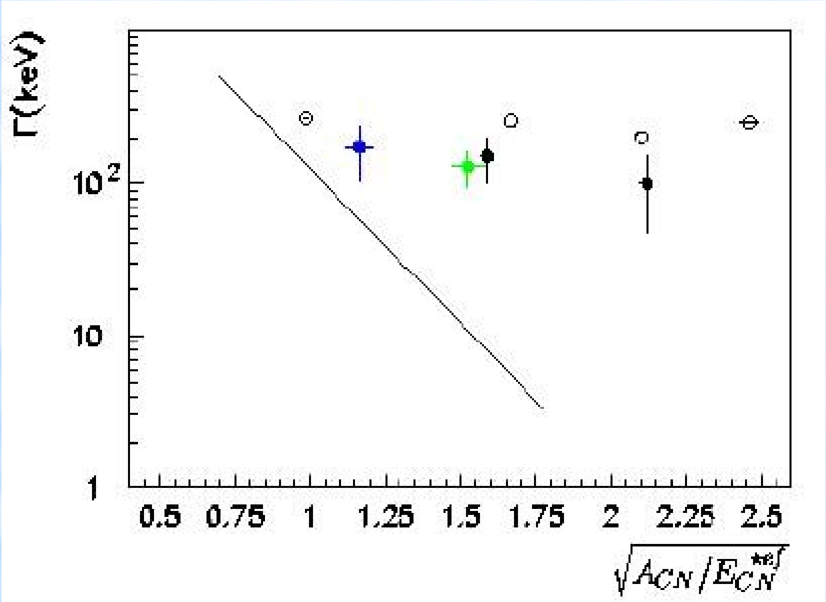
$$C(\varepsilon) = \frac{1}{N_{eff}} \frac{\Gamma^2}{\Gamma^2 + \varepsilon^2}, \quad \tau_{DNS} = \frac{\hbar}{\Gamma}$$



$\Gamma = (128 \pm 32)$ keV, $\tau_{DNS} = (5.1 \pm 1.1) 10^{-21}$sec

$\Gamma = (150 \pm 75)$ keV, *(M.Papa et al, Phys. Rev. C, 2000)*

Points on figure (from the left to the right):



- $^{19}F + ^{27}Al$, $^{27}Al + ^{27}Al$, $^{27}Al + ^{27}Al$, $^{28}Si + ^{28}Si$

o $^{19}F + ^{63}Cu$, $^{19}F + ^{51}V$, $^{19}F + ^{89}Y$, $^{28}Si + ^{48}Ti$

$\Gamma = (170 \pm 65)$ keV, $\tau_{DNS} = (3.9 \pm 2.1) 10^{-21}$sec

Thin line on figure:

$$\Gamma_{CN} = 14\, exp\left(-4.69 \sqrt{\frac{A_{CN}}{E^{*ef}_{CN}}} \right) MeV,$$

(D. Shapira et al, Phys Rev. C, 1974)

$E^{*ef}_{CN} = E^{*}_{CN} - E_B$, $E_B = V_{CB} + E_{rot}$,

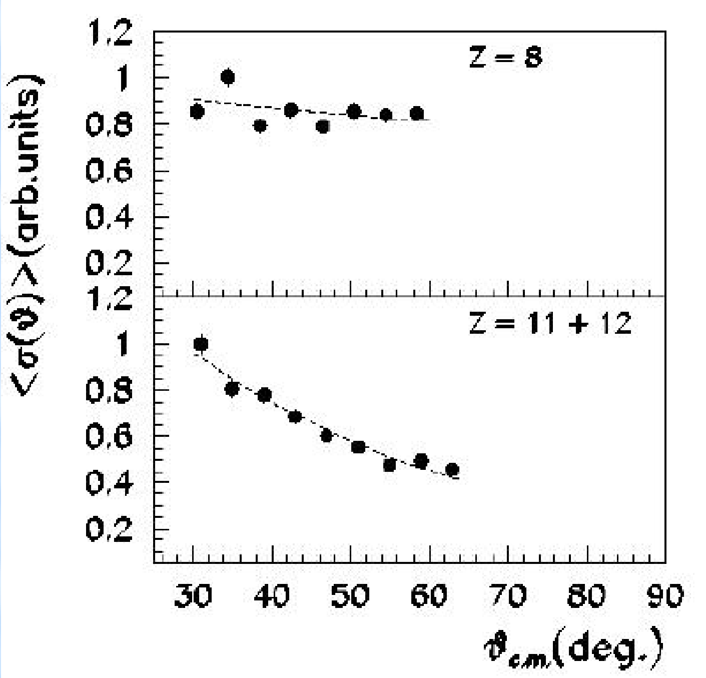
V_{CB} - the Coulomb barrier,

E_{rot} - the energy of the rotational level sequence

• Angular analysis

Average angular distribution

$$d\sigma/d\vartheta_{cm} \propto exp(-\vartheta_{cm}/\omega\cdot\tau) + exp(-(2\pi-\vartheta_{cm})/\omega\cdot\tau)$$



$\tau_{ang} = 5.5\ 10^{-22}$ sec, $\theta_{cm} < 50^o$

$\tau_{ang} = 1.4\ 10^{-21}$ sec, $\theta_{cm} > 50^o$ Z = 11+12

$\tau_{ang} = 1.8\ 10^{-21}$ sec, Z = 8

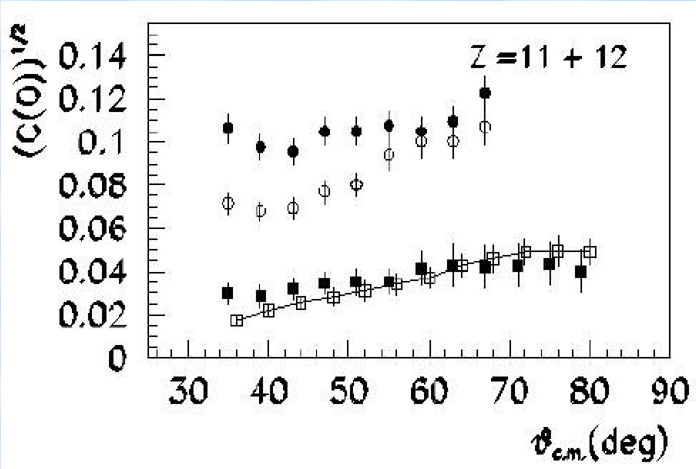
$\tau_{EAF} = (5.1 \pm 1.1)\ 10^{-21}$ sec

$\rightarrow \tau_{EAF}$ more consistent with τ_{ang} for slower processes

Normalized Variance C(0)

Relationship between V = $(C(0))^{1/2}$ and the level density in the framework of POMLM:

$$V = 1.5\cdot(\Delta)^{-\frac{1}{1+\gamma}}\frac{\sigma_S}{\sigma_F+\sigma_S}\sqrt{\frac{D}{\Gamma}},$$



Δ- the angular momentum window,

$\gamma = \Gamma/\hbar\omega$ - the degree of the angular momentum coherence

σ_s, σ_F - cross sections for slow and fast processes

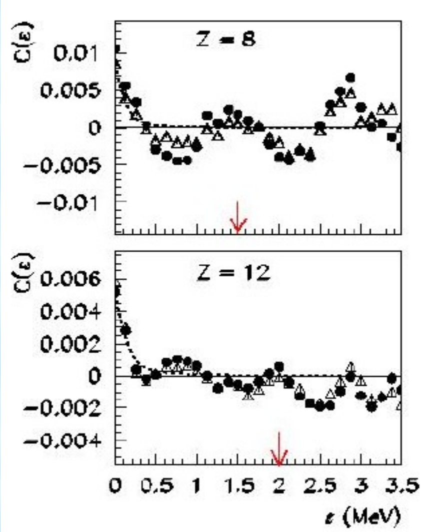
$\gamma = 0.128$ MeV/1 MeV ~ 0.13

$\sigma_S/(\sigma_S + \sigma_F) = 0.5$, $\Delta = 2$

$\Gamma/D \sim 16$, $\rho \sim 125\ MeV^{-1}$

• Deformation of the di-nuclear system

For $\tau_{DNS} \geq T$ **secondary structures** in the EAF of the symmetric systems with period *(S. Yu. Kun, Z. Phys. A, 1993)*:



$$\varepsilon_c = 2n\hbar\omega \quad (1)$$

T - rotation period of DNS, **n** – number of DNS revolutions

$\omega = \hbar l / J$ - angular velocity of the di-nucleus, $J = J_{rel} + J_{int}$,

$J_{rel} = 1.044\ \mu r^2\ 10^{-46}$ MeVsec^{-2}- the relative momentum of inertia

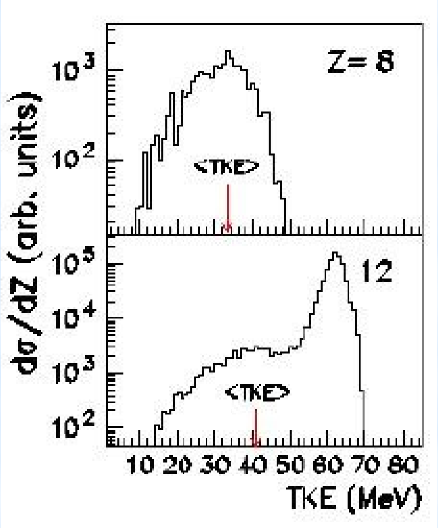
$J_{int} = 1.044\ (2/5)\ r_o^2 (A_3^{5/3} + A_4^{5/3})\ 10^{-46}$ MeVsec^{-2} - the intrinsic momentum of inertia

... n final channel

$\tau_{DNS} = 5.1\ 10^{-21}$sec, $T = 4.9\ 10^{-21}$ sec

The **most probable total kinetic energy**:

$$\langle TKE \rangle = 1.44 \frac{Z_3 Z_4}{r} + \frac{\hbar^2 l(l+1)}{2\mathcal{J}_{rel}}.$$



$l_i = (l_{gr} + l_{cr})/2 = (47.8 + 43.7)/2 = 45.8\hbar$

$l_{st} = l_i(1 - J_{int} / J_{tot})\ \hbar$

Z = 8, <TKE> = 33 MeV, l_{st} = 29.6 r = 10.9 fm

ε_c = 1.7 MeV   to compare with ε_{EAF} = 1.5MeV

Z = 12 , <TKE> = 41 MeV, l_{st} = 32.5 r = 10.0 fm

ε_c = 2.0 MeV   to compare with $\varepsilon_{EAF} \sim$ 2.0 MeV

l_{cr} for light heavy-ion systems has a large spreading: (27ħ – 42ħ)

l_{cr} = 35ħ, r = 10.3 (9.5) fm, ε_d = 1.4 (1.6) MeV for O + Ar (Mg + Si)

→ a lower value of l_{cr} should be more appropriate to describe the long range oscillations from Z = 8 EAF, while they are quite well reproduced with l_{cr} = 43.7ħ for the fragments with atomic number close to the projectile one

- Large deformation of the DNS: $J_{rel}(r) = 1.97\, J_{rel}(R_{int})$, for $r \sim 10.9$ fm

  $R_{int} = r_o(A_3^{1/3} + A_4^{1/3})$ - interaction radius for spherical nuclei

For system ^{19}F + ^{27}Al we obtained $r \sim 11$ fm *(1998)*

- **Comparison** with results from the EAF analysis for other systems

S. Yu. Kun: ^{19}F + ^{89}Y *(Phys. Lett. B, 1991)*, ^{58}Ni + ^{46}Ti *(Z. Phys. A, 1997)* no deformation

^{12}C + ^{24}Mg *(PRC, 1999)*, ^{24}Mg + ^{24}Mg, ^{28}Si + ^{28}Si *(PRL, 1999)* deformation

- RLDM: in **mass region 40-100** "it should be possible to form super-deformed nuclei" (*S. Cohen, F. Plasil, W. J. Swiatecki, 1974)*

E. g.: triaxial ^{54}Fe and ^{46}Ti CNs for l > 33.6ħ and 29ħ, respectively

- **Intensive experiments studing deformation in mass region 40-60**

For systems with mass close to that of the **^{27}Al + ^{27} Al**

Light charged particle spectra emitted by ^{55}Co, ^{56}Ni and ^{59}Cu CNs formed in the reactions ^{28}Si + ^{27}Al *(D. K. Agnihotri et al, Phys. Lett., 1993*), ^{28}Si + ^{28}Si *(C. Bhattcharya et al, Phys. Rev. C, 2001)* and ^{35}Cl + ^{24}Mg (*D. Mahoub et al, Phys. Rev. C, 2004)* could be described by calculating the yrast line with an effective moment of inertia:

$J_{eff} = J_{sphere}(1 + \delta_1 l^2 + \delta_2 l^4)$, δ_1, δ_2 - the deformability parameters;

J_{sphere} - rigid body momentum of inertia

$J_{eff} \sim 1.5\, J_{sphere}$ for δ_1, δ_2 from experiment

For systems with mass close to that of the **^{19}F + ^{27}Al**

Experiments at IReS, Strasbourg

^{16}O + ^{28}Si: the α spectral shape at three incident energies indicate large deformation of the ^{44}Ti CN (axis ratio a/b ~ 2) *(P. Papka et al, Acta Phys. Pol., 2003)*

^{18}O + ^{28}Si: the shape of γ-ray spectrum from the decay of GDR built in hot ^{46}Ti could be described supposing an elongated 3-axial equilibrium shape at $l = 30\,\hbar$ *(A. Maj et al, Nucl. Phys. A, 2004)*

^{27}Al + ^{19}F: α-particle spectra also suggests very elongated shapes around this value of the angular momentum *(M. Brekiesz et al, Acta Phys. Pol., 2005)*

Conclusions

Large fluctuations have been evidenced in the EF for deep inelastic processes in the $^{27}Al+^{27}Al$ interaction on the incident energy interval (122 - 132) MeV. The large channel cross correlation coefficients and non-Lorentzian pattern of the EAF show the nonstatistical origin of the fluctuations.

The correlation width extracted from the EF is equal to (128±32) keV to which corresponds a DNS lifetime of $(5.1 \pm 1.1)\ 10^{-21}$ sec. This lifetime is in good agreement with the DNS lifetime extracted from the average angular distribution.

From the analysis of the EAF structure at $\varepsilon > 0$ a separation distance value of 10.0 – 10.9 fm has been obtained indicating a large deformation of the excited rotational states as in the case of the previously system $^{19}F + ^{27}Al$ studied by us.

The low value of the Γ/D estimated in the POMLM framework is physically supported by the excitation of the deformed DNS levels in a region at ~ 27 MeV above yrast line.

The experimental evidence from the present paper supports a reaction mechanism where special states of rotational (molecular) nature play the role of doorway configurations toward a regime characterized by stochastic exchange of nucleons between interacting nuclei as the main mechanism behind the dissipative phenomena in light heavy ion collisions.

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