What Interferometry May Bring to the Study of High Density Symmetry Energy?

- The history of interferometry
- \(nn, np\) and \(pp\) correlations measured simultaneously
- Heavier particles
- What did we learn about the symmetry term in experiments at energy \(< 100\text{A}\ \text{MeV}\)?
- Theory – at these energies,,,,,,and higher.
- A comment about chronology
- Perspectives for ASY-EOS
Interferometry has a long history ........

in optics ......., in astrophysics ..., in particle .. and nuclear physics .....
and then came simultaneous pp, np and nn correlation experiments

This experiment was outlined at the Jackson Hole meeting 1992

... and proposed to the SARA PAC at ISN Grenoble, that rejected it with the argument that it should be more "safe to focus on pp correlations"!

After a convincing performance by Ö. Skeppstedt about our ability to handle liquid scintillators, the next PAC accepted it

and the size of these experiments changed...

p: 20 CsI(Tl) [EMRIC]
n: 48 liq. scint [EDEN]
P: 36 phoswich [ARGOS]

experiments performed at SARA, RIKEN, AGOR, LNS
and the result was ...... 

.... where we plot

\[ C(q) = \frac{N_c(q)}{N_{nc}(q)}, \quad \text{where} \quad q = \mu \cdot |\vec{p}_1 - \vec{p}_2| \]

and compare it to the two-particle correlation formalism of Koonin/Pratt including (anti)symmetrization of the two-particle wave function and final state interactions (attractive strong interaction and for pp Coulomb int.)

\[
C(q, P) = \int d^3r \frac{\int d^3\bar{R} \cdot f(\bar{P}, \bar{r}_1, t_e) \cdot f(\bar{P}, \bar{r}_2, t_e)}{\left| d^3\bar{r}_1 \cdot f(\bar{P}, \bar{r}, t_e) \right|^2} |\Psi_{12}(q, \bar{R})|^2 
\]

where \( \bar{P} = \frac{1}{2} \cdot (\vec{p}_1 + \vec{p}_2), \quad \bar{r} = \bar{r}_1 + \bar{r}_2, \quad \bar{R} = \frac{\bar{r}}{2} \) and \( t_e \) is the emission time for both particles at which the Wigner functions in space and phase – space are introduced

\[ f(\bar{P}, \bar{R}, t_e) = \int_{-\infty}^{t_e} dt \cdot g(\bar{P}, \bar{R} - \vec{v}_p(t_e - t), t) \]

g is now the emission model of your choice

curves right: \( \Delta t = 0 \), Gaussian in r and p (- - - -)

Evaporative (———)
isospin effects - easier to observe for heavier particles?

Data: CHIC Collaboration + S. Kopecky, V. Kravchuk, H. Wilschut, KVI, Groningen

- anticorrelations in nd due to t formation
- nt function contains $^4$H unbound states
- pd (and pt) are dominated by Coulomb
- and pt shows also decay of exc. $^4$He
- isospin effects obvious for nd, nt, pt

$61\text{A MeV} \, ^{36}\text{Ar} + ^{112,124}\text{Sn}$

- $30 - 45^\circ$
- $60 - 120^\circ$

Relative Momentum, $q$ (MeV/c)
Isospin effects ……in \( p_{\text{tot}} = p_1 + p_2 \) gated correlations

Source analysis gives velocity 0.02c for TLS and 0.18c for IS

Gates to probe IS are:
- \( \Theta = 30 - 42^\circ \)
- high \( P_{\text{tot}} \) (early emission)
- interm. \( P_{\text{tot}} \) (late emission)
- TLS:
  - low \( P_{\text{tot}} \)
  - \( \Theta = 54 - 120^\circ \)

Observations
- progressively weaker correlations from left to right \( \rightarrow \) longer emission times
- higher correlation peaks for the n-rich isotope

Bo Jakobsson, Zagreb, Oct. 2009
Interferometry - calculations

1. Comb. of Evaporation and $\Delta t = 0$ Gaussian in $r$ and $p$ (old data) [Jakobsson, Pratt]

2. Expanding fireball + Evaporation, Gaussian in space, Boltzmann in energy, successive cooling (LNS and KVI data, see figure to the right) [Czörgö, Helgesson]

3. BUU (Bao-An Li), isospin dependent and momentum-independent, Skyrme potential $U = A u + B u^\sigma + C z u^\gamma \delta^2$ NN collisions with Pauli blocking. Freeze-out density $\rho_o/8$ (so far KVI pp and np data) [Helgesson]

....all convoluted to the Koonin-Pratt two-particle relative wave functions

Data where singles spectra are used to set source velocities and version 2 then is introduced in the correlation plots are from:

LNS Catania, 45A MeV $^{58}$Ni + $^{27}$Al, nat$^{197}$Au [xxx]

KVI Groningen, 61A MeV $^{36}$Ar + $^{27}$Al (see right), $^{112,124}$Sn
Isospin effects calculations vs data

Calculations, model 3, (J Helgesson, BUU – Bao-an Li)

no isospin soft stiff e.o.s

The overall agreement is quite good (BUU stopped at 110 fm/c)
Isospin dependent potential gives better agreement
The stiff eos describes the differences better
pn data does not fit into this scheme!
As chronometer............

Classical picture of .......

\[ E_p > E_n \]

\[ E_n > E_p \]

The Lednicky prescription on how to utilize the asymmetry of the unlike-particle wavefunction

For beam/target residues: \( t_d < t_p < t_n \)

For dynamic (IE) sources: \( t_n < t_d < t_p \)

But IE source at 45A MeV: \( t_p < t_d < t_n \)
Perspectives for ASY-EOS

Detectors:

Some of those detector systems that are proposed for ASY-EOS are well suited as c.p. Interferometers (see next slides)

Neutron detectors (LAND, NEULAND, Liq. scint. Walls) must be carefully evaluated as nn and part of np interferometers

Parts of CHIMERA well suited for PFs. What about time and energy resolution now for the use as interferometer?

Electronics: Trigger electronics well known (see last slide).

DAQ: No extreme requirements (slow count rates)

Physics: Extrapolations of BUU + evaporation

and QMD + evaporation to 400 – 800A MeV needed
Produced by Monocrystal, Kharkov

Assembled and bench tested in Lund and Santiago de C.

Tested in 180 MeV proton beams at TSL, Uppsala

final choice of readout device to be made soon (normal PDs work very well for protons and light fragments but unfortunately not for photons at 100 keV, noise level too high)

*) USC design
TSL test with 179 MeV protons show small differences in the energy resolution between:

- 20x20x110 mm³
- 10x30x100/130 mm³ two-truncated pyramide (USC) type

$$\delta E/E, \ 0.4 - 0.7 \%$$

$$\delta E/E, \ 0.5 - 0.9\%$$
Trigger electronics in NIM/CAMAC standard for typical nn-np-pp interferometer
J. Pluta et al., Nucl. Instr. Meth, A 411 417