Approach to neutron-neutron correlation functions with partial coherent emissions of Borromean halo nuclei

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Support: Brazilian funding agencies FAPESP and CNPq

International Nuclear Physics Conference INPC 2007 TOKYO, JAPAN

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Introduction

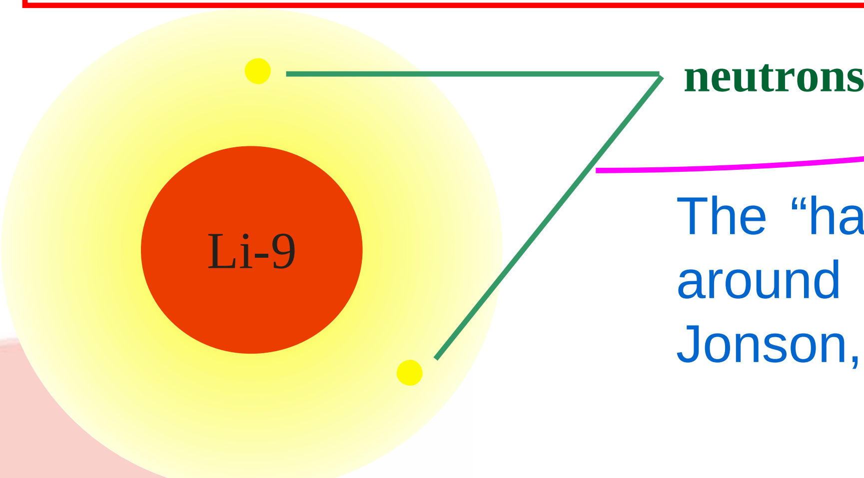
Experimental status of Borromean halo nuclei structure investigation

First observation

^{6}He T. Bjerge, *Nature* 138, 400 (1936)

^{11}Li colliding with some targets → growth of the cross section

Tanihata et al., Phys .Lett. 160 B 380 (1985) and Phys. Rev. Lett. 55 (1985) 2676



The "halo" designation for the low density matter around the core was introduced by Hansen and Jonson, in Europhys. Lett. 4 409 (1987).

T. Kobayashi et al. Phys. Lett. B 232, 51 (1989)

- **The correlation function $C_{nn}(q)$**

Powerful tool in space-time proximity investigation of emissions from nuclei.

- **In Borromean halo nuclei, the neutrons are emitted in very fast processes (10^{-23} s) as Coulomb dissociation or pre-emission in nuclear field.**
- **The space proximity is dominant as it is characterized by final state interaction (FSI) much larger than quantum statistical symmetry (QSS) - one should expect n-n correlation strengths much larger than neutron evaporation processes dominated by QSS.**
- **First C_{nn} measurement for ^{11}Li has been reported by K. Ieki et al. [Phys.Rev.Lett. 70(1993) 730]. The corresponding rms radius was about 13 fm, much larger than the experimental value reported in Tanihata et al. [Phys. Lett. B 287 (1992) 307].**
- **The last reported measurement is in Petrascu et al. [Phys. Rev. C 69 (2004) 011602]. With the C_{nn} denominator built by single neutron product technique, rms is close to the value reported by Ieki et al. With event mixing denominator, rms is much smaller.**
- **A new experiment to obtain C_{nn} for ^{11}Li and for ^{14}Be beams, avoiding residual correlation, and to improve the statistics of n-n coincidence, was recently proposed in Petrascu et al., Phys. Rev. C 73 (2006) 057601.**
- **The measured C_{nn} for ^{11}Li appears to be rather low.**
- **The low value of the correlation strength was considered by Marques et al [Phys. Lett. B 476 (2000) 219] as due to residual correlation. However, it was used a theory of C_{nn} based on independent particle model of Lednicky and Lyuboshits [Sov.J.Nucl.Phys.35(1982)770].**

Spatial characteristics of halo nuclei in a 3 body model

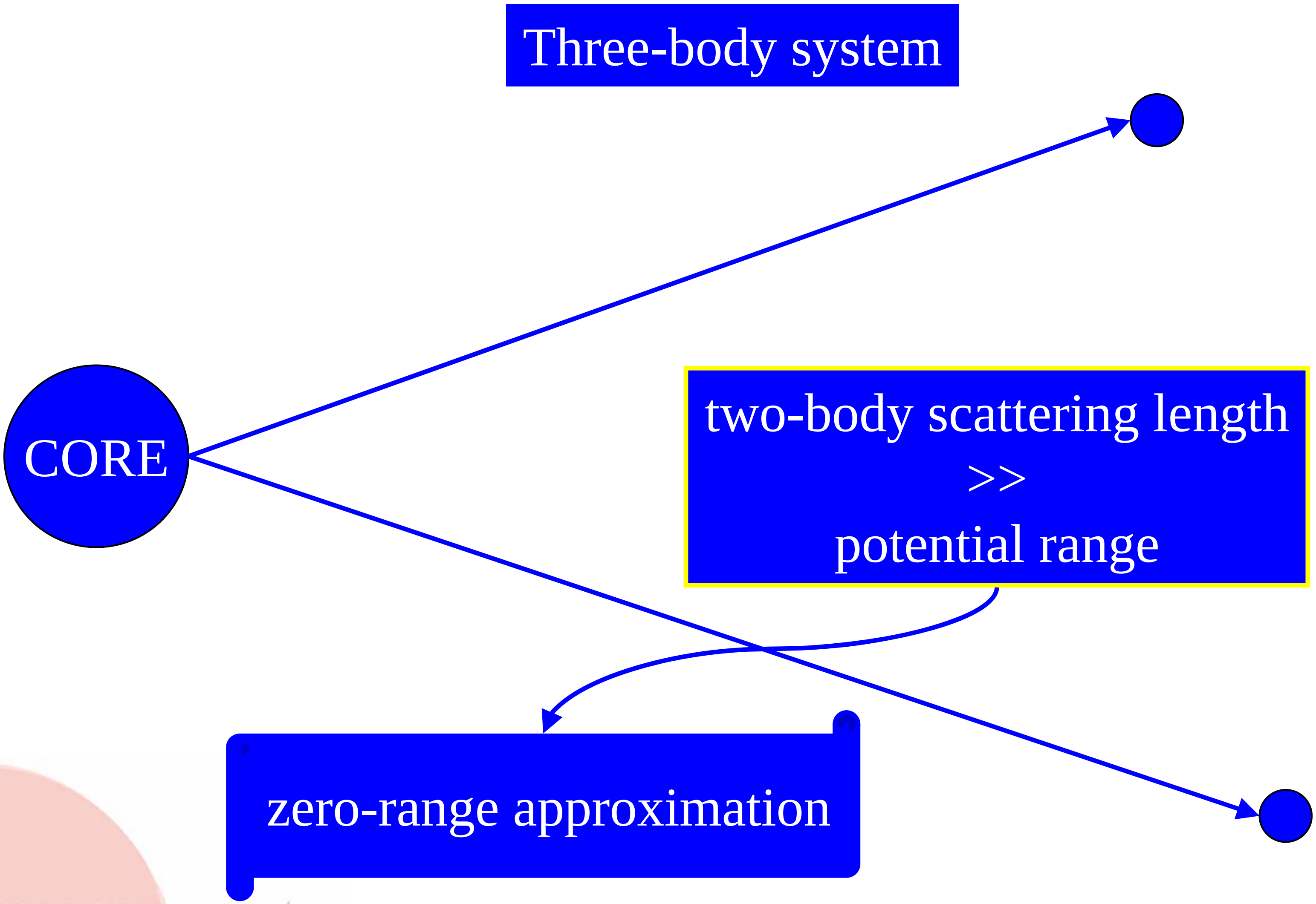
•We consider the independent particle model not appropriate for Borromean halo nuclei, as also recognized by Petrascu et al. [Nucl. Phys. A (2007) to appear].

In the last few years, we have studied [see Yamashita et al, *Phys. Rev* A68, 012506 (2003), *Nucl. Phys.* A735, 40 (2004), and Phys.Rev.C 72, 011601R (2005)] light halo-nuclei systems using a model for weakly bound three-body systems, considering the solution of Faddeev equations with renormalized zero-range two body interaction.

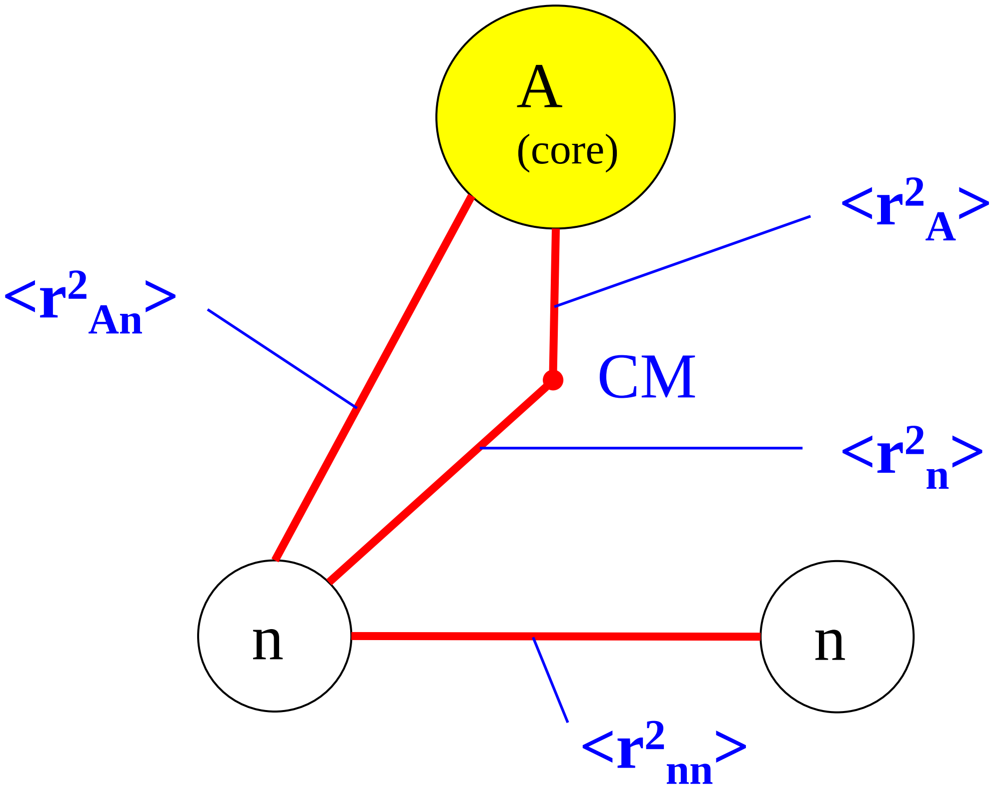
In light halo nuclei, the model was successfully used to study the spatial characteristics and the neutron-neutron correlation (Cnn) in the halo dissociation.

Coherent emission of neutrons was assumed in the halo dissociation.

Overview of the formalism –
Approaching the halo nuclei by a three-body system



An overview of the formalism – mean-square radii



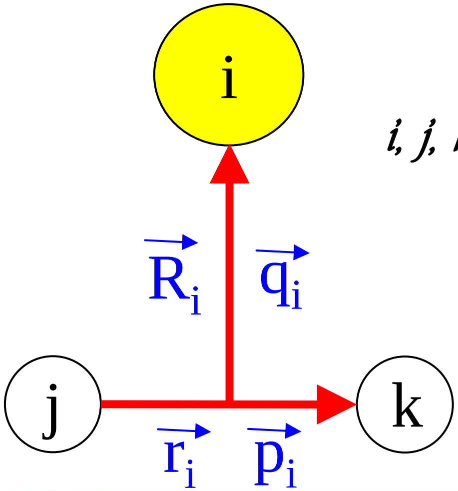
An overview of the formalism – mean-square radii

Renormalized zero-range model: Faddeev Spectator Functions

M.T. Yamashita, L. T. and T. Frederico, *Nucl. Phys.* A735, 40 (2004).

$$\left\langle r_i^2 \right\rangle = \int d^3 r_i r_i^2 \rho_i(r_i) \longrightarrow \rho_i(r_i) = \int d^3 R_i \left| \left\langle \vec{r}_i, \vec{R}_i \middle| \Psi \right\rangle \right|^2$$

$$\rho_i(r_i) = \int d^3 Q F(Q^2) \frac{e^{-i\vec{Q}\cdot\vec{r}_i}}{(2\pi)^3} \longrightarrow F(Q^2) = \int d^3 r_i e^{i\vec{Q}\cdot\vec{r}_i} \rho_i(r_i)$$



i, j, k = n or A

$$\left\langle r_{jk}^2 \right\rangle = -6 \frac{dF_{jk}(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

$$F_{jk}(Q^2) = \int d^3 q_i d^3 p_i \left\langle \vec{q}_i, \vec{p}_i + \frac{\vec{Q}}{2} \middle| \Psi \right\rangle \left\langle \vec{q}_i, \vec{p}_i - \frac{\vec{Q}}{2} \middle| \Psi \right\rangle$$

$$\left\langle \vec{q}_i, \vec{p}_i \middle| \Psi \right\rangle = \frac{f_i(|\vec{q}_i|) + f_j(|\vec{p}_i - \frac{\vec{q}_i}{2}|) + f_k(|\vec{p}_i + \frac{\vec{q}_i}{2}|)}{|E_3| + H_0}$$

Overview of the formalism – Renormalized zero-range model with subtracted Faddeev spectator functions.

$$f_j(\vec{q}) = \left(\frac{A+1}{2A}\right)^{3/2} \frac{1}{\pi} \left(\sqrt{|\varepsilon| + \frac{q^2(A+2)}{2(A+1)}} \pm \sqrt{|\varepsilon_{AB}|} \right)^{-1}$$

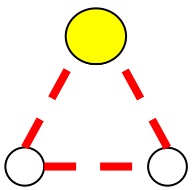
$$\left\{ \int_0^\infty k^2 dk \int_{-1}^{1} dy \left[\frac{1}{|\varepsilon| + q^2 + \frac{A+1}{2A}k^2 + kqy} - \frac{1}{1 + q^2 + \frac{A+1}{2A}k^2 + kqy} \right] f_i(\vec{k}) \right.$$

$$\left. - \int_0^\infty k^2 dk \int_{-1}^{1} dy \left[\frac{1}{|\varepsilon| + \frac{A+1}{2A}q^2 + \frac{A+1}{2A}k^2 + \frac{1}{A}kqy} - \frac{1}{1 + \frac{A+1}{2A}q^2 + \frac{A+1}{2A}k^2 + \frac{1}{A}kqy} \right] f_j(\vec{k}) \right\}$$

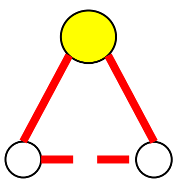
$$f_i(\vec{q}) = \frac{2}{\pi} \left(\sqrt{|\varepsilon| + \frac{(A+2)}{2A} q^2} \pm \sqrt{|\varepsilon_{AA}|} \right)^{-1} \int_0^\infty k^2 dk \int_{-1}^{1} dy \left[\frac{1}{|\varepsilon| + \frac{A+1}{2A} q^2 + k^2 + kqy} - \frac{1}{1 + \frac{A+1}{2A} q^2 + k^2 + kqy} \right] f_j(\vec{k})$$

neutron-neutron root-mean-square radii in halo nuclei

Core (A)	$\|E_3\|$ (MeV)	$\|E_{nA}\|$ (MeV)	$(\langle r_{nn}^2\rangle)^{1/2}$ (fm)	$(\langle r_{nn}^2\rangle)^{1/2}_{exp}$ (fm)
^{4}He	0.973	0	5.1	5.9 ± 1.2
		0.3 (v)	4.6	
		4.0 (v)	3.6	
^{9}Li	0.32	0	9.2	6.6 ± 1.5
		0.8 (v)	5.9	
	0.29	0	9.7	
		0.05 (v)	8.5	
		0.8 (v)	6.7	
	0.37*	0	8.6	
		0.05 (v)	7.7	
		0.8 (v)	6.2	
^{12}Be	1.337	0	4.6	5.4 ± 1.0
		0.2 (v)	4.2	
^{18}C	3.50	0.16	3.0	-
		0.53	4.4	



BORROMEANS



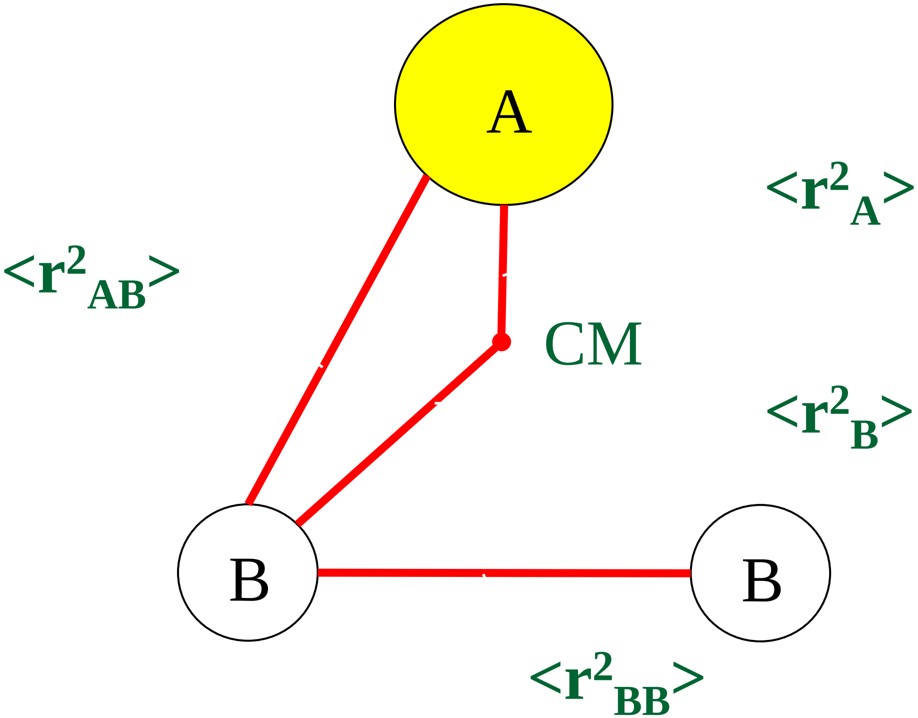
M.T. Yamashita, L T and T. Frederico *Nucl. Phys. A735, 40 (2004).*

Exp. from F.M. Marqués et al. *Phys. Lett. B476, 219 (2000); Phys. Rev. C64, 061301 (2001),*

The virtual states are indicated by (v). The nn virtual state energy was taken as -143 keV.

Flexibility of the formalism: weakly-bound molecules

MTYamashita, R.S. Marques de Carvalho, L.T. and T. Frederico PRA 68, 012506 (2003)



B = ^{4}He

A = ^{4}He, ^{6}Li, ^{7}Li, ^{23}Na

A	E_3 (mK)	E_{BB} (mK)	E_{AB} (mK)	$\sqrt{\langle r_{BB}^2\rangle}$ (Å)	$\sqrt{\langle r_{AB}^2\rangle}$ (Å)	$\sqrt{\langle r_B^2\rangle}$ (Å)	$\sqrt{\langle r_A^2\rangle}$ (Å)
^{4}He	106.0	1.31	1.31	9.45	9.45	5.55	5.55
^{6}Li	31.4	1.31	0.12	16.91	16.38	10.50	8.14
^{7}Li	45.7	1.31	2.16	14.94	13.88	9.34	6.31
^{23}Na	103.1	1.31	28.98	11.66	9.54	8.12	1.94

Neutron-neutron correlation function

Radii are experimentally extracted from

correlation function

R. Hanbury-Brown and R. Q. Twiss (HBT) - NATURE
177, 27 (1956)
178, 1046 (1956)
178, 1447 (1956)

First used in astrophysics

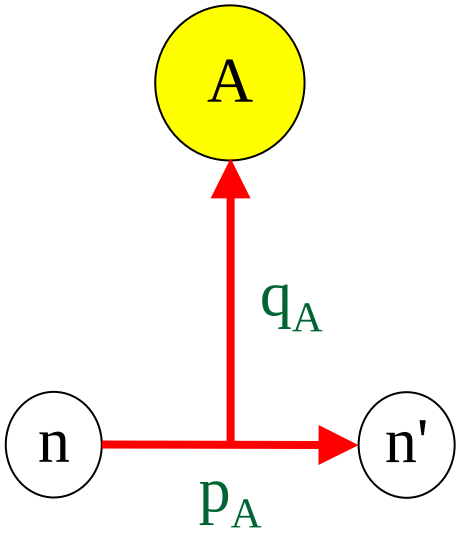
Nuclear Physics

Neutron-neutron Correlation (Cnn) in the halo dissociation of light exotic nuclei

- The 3-body wave function describing the core and the 2 weakly bound neutrons is obtained by solving the Faddeev equations. In order to obtain $C_{nn,}$ the final state interaction is taken into account. The model is parameterized by minimal number of physical inputs which are directly related to known observables S(2n) and the n-n scattering length

Neutron-neutron correlation function

MTYamashita, T. Frederico and LT, PRC 72, 011601(R) (2005)



$$C_{nn}(\vec{p}_A) = \frac{\int d^3 q_A \left|\Phi(\vec{q}_A, \vec{p}_A)\right|^2}{\int d^3 q_A \rho(\vec{q}\,'_n)\rho(\vec{q}_n)}$$

$$\vec{q}_{n'} = \vec{p}_A - \frac{\vec{q}_A}{2} \qquad \vec{q}_n = -\vec{p}_A - \frac{\vec{q}_A}{2}$$

One-body density

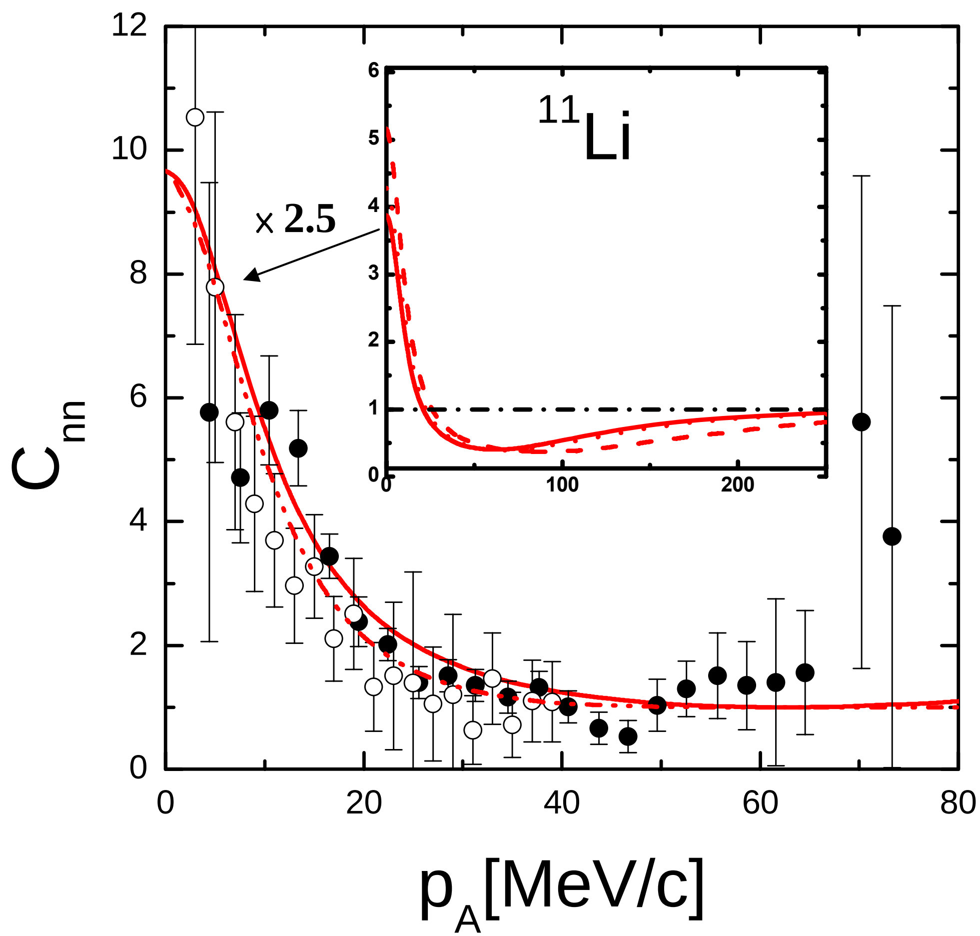
$$\rho(\vec{q}_{nA}) = \int d^3 q_{n'A} \left|\Phi\left(-\vec{q}_{nA} - \vec{q}_{n'A}, \frac{\vec{q}_{nA} - \vec{q}_{n'A}}{2}\right)\right|^2$$

$\Phi \equiv \Phi(\vec{q}_A, \vec{p}_A)$ Breakup amplitude including the FSI between the neutrons

$$\Phi = \Psi(\vec{q}_A, \vec{p}_A) + \frac{1/(2\pi^2)}{\sqrt{E_{nn}} - ip_A} \int d^3 p \frac{\Psi(\vec{q}_A, \vec{p})}{p_A^2 - p^2 + i\varepsilon}$$

Ψ is the three-body wave function

Neutron-neutron Correlation (Cnn) in the halo dissociation of light exotic nuclei



● F. M. Marqués et al. Phys. Rev. C **64**, 061301 (2001)

○ M. Petrascu et al. Nucl. Phys. A **738**, 503 (2004)

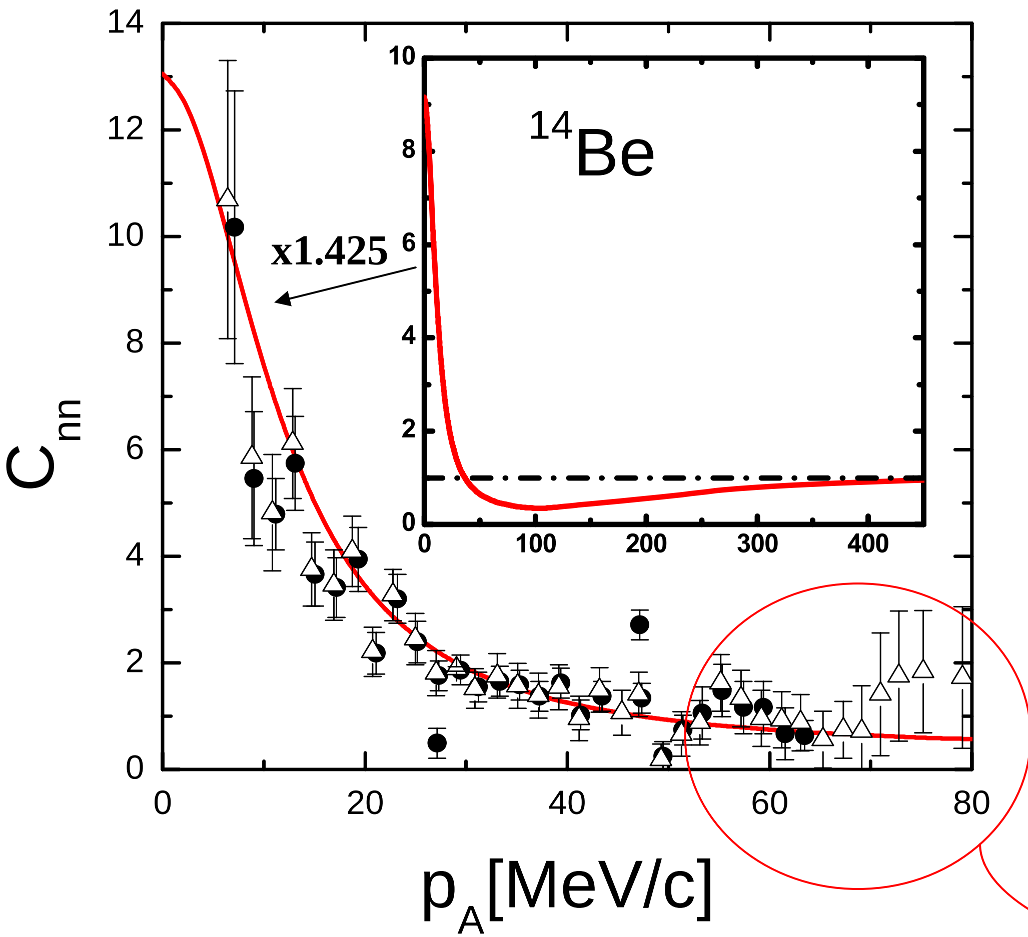
Solid line: E_3 = 0.29 MeV, E_{nA} = 0.05 MeV

Dashed line: E_3 = 0.37 MeV, E_{nA} = 0.8 MeV

Dotted line: E_3 = 0.37 MeV, E_{nA} = 0.05 MeV

E_{nn} = 0.143 MeV

Neutron-neutron Correlation (Cnn) in the halo dissociation of light exotic nuclei



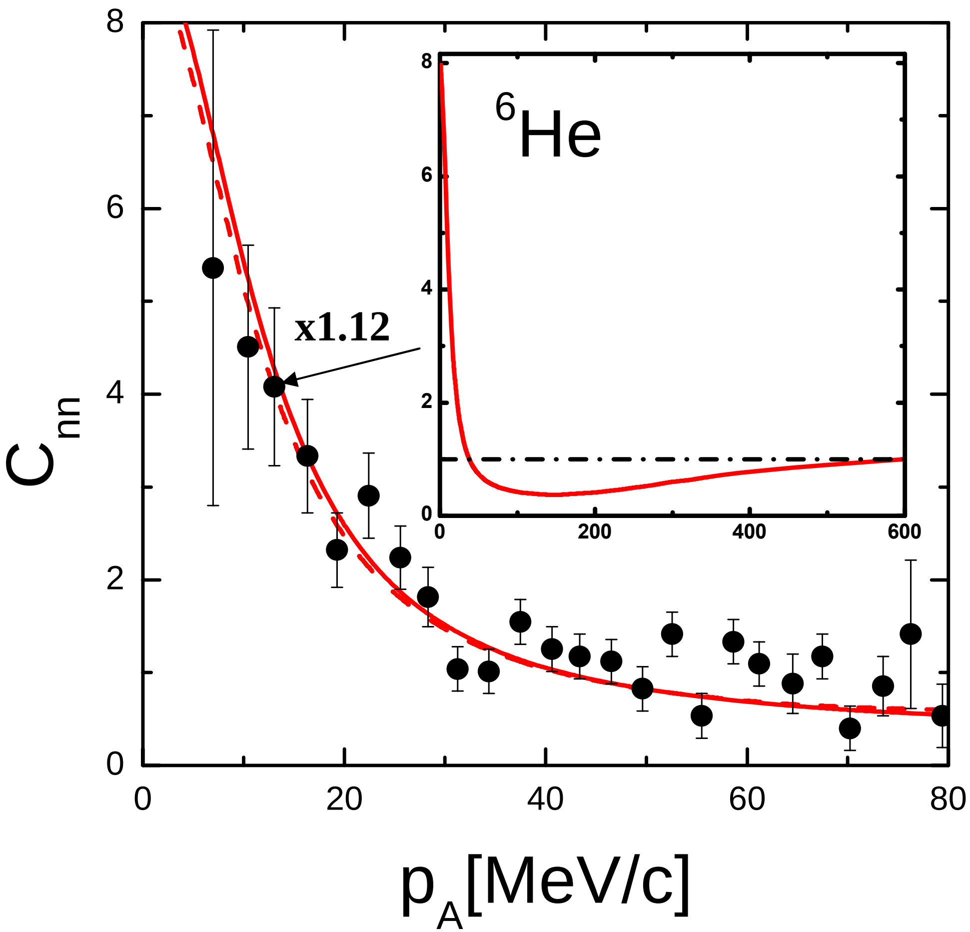
● F. M. Marqués et al. Phys. Rev. C **64**, 061301 (2001)

△ F. M. Marqués et al. Phys. Lett. B **476**, 219 (2000)

E_3 = 1.337 MeV
E_{nA} = 0.2 MeV
E_{nn} = 0.143 MeV

asymptotic region ?

Neutron-neutron Correlation (Cnn) in the halo dissociation of light exotic nuclei



- F. M. Marqués et al. Phys.Rev.C **64**, 061301 (2001)

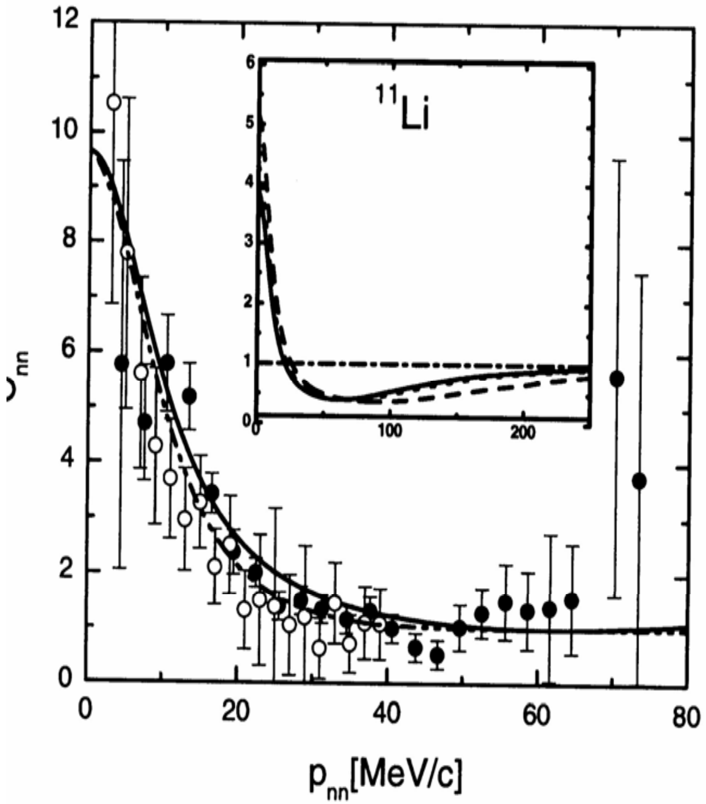
Solid line: E_3 = 0.973 MeV, E_{nA} = 4 MeV

Dashed line: E_3 = 0.973 MeV, E_{nA} = 0

Enn = 0.143 MeV

Neutron-neutron Correlation (Cnn) in the halo dissociation of light exotic nuclei

The most interesting result of the model is shown in the inset in which one can see the interference minimum of C_{nn} around p_{nn}= 50 MeV/c. The normalization of the function was set to 1 in order to compare with experimental points. The open circles are from: M. Petrascu et al. Nucl. Phys A738, 503 (2004). The solid circles are from: F. M. Marques et al., Phys. Lett. B476, 219 (2000)

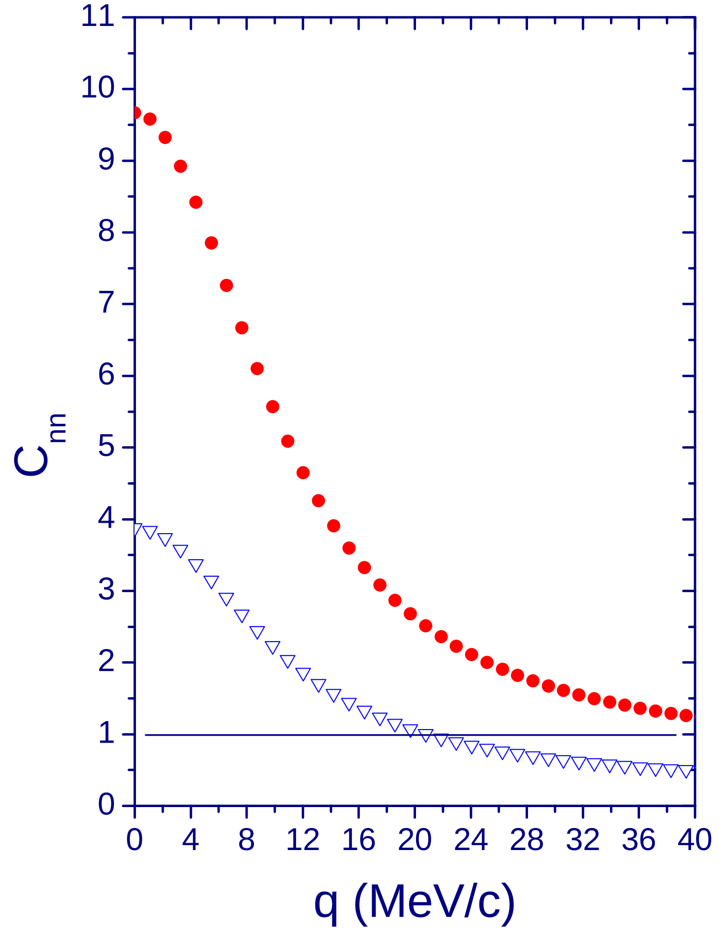


Possibility to test the model

(See Petrascu et al., Phys. Rev. C 69, 011602(R) (2004); and in Nucl. Phys. A (2007), to appear.

In this Figure is shown in more detail the model results for Lithium, with C_{nn} normalized asymptotically (in blue) and at the minimum (in red). One can see that C_{nn} becomes smaller than one at q~20 MeV/c.

The possibility to verify the model experimentally depends on the errors that can be attained in this region.



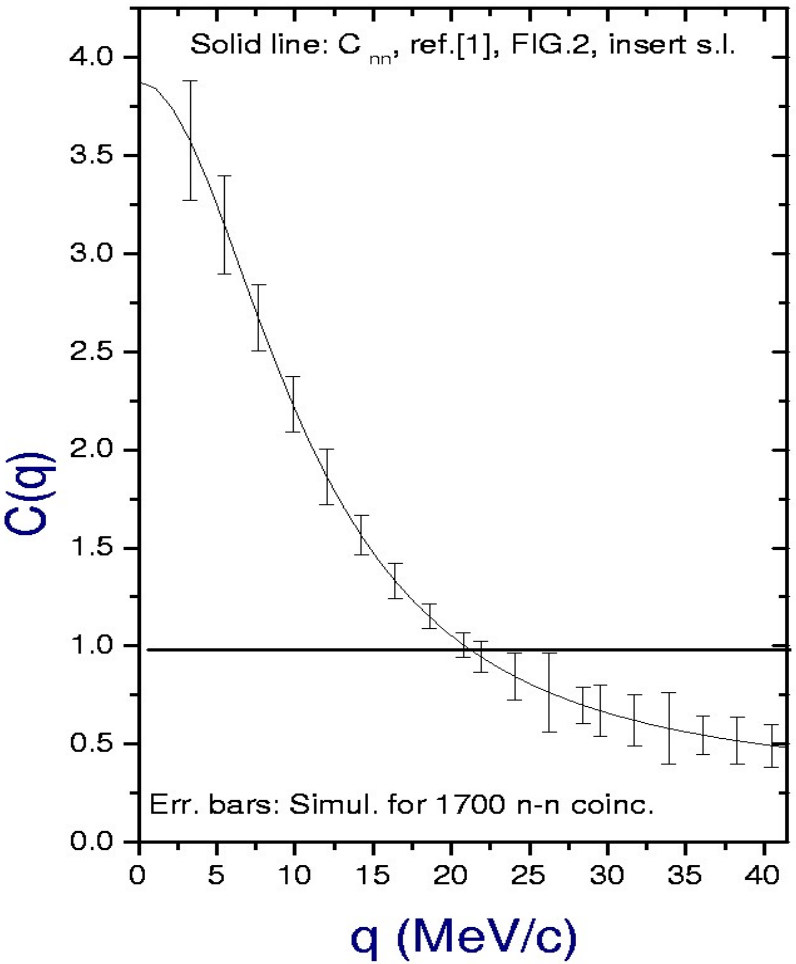
C_{nn} = 2.4 C_{nn}

Possibility to test the model

(See Petrascu et al., Phys. Rev. C 69, 011602(R) (2004); and in Nucl. Phys. A (2007), to appear.

As discussed recently by Petrascu in a contribution to Few-Body 18 [see Nucl. Phys. A (2007), to appear], there are already some indications in favor of the present model.

The possibility to verify the model experimentally depends on the errors that can be attained in the high momentum region.
From a recent analysis (see Fig), the error bars were simulated for a statistics of 1700 detected neutron pairs, calculated by taking into account the target screening effect [Petrascu et al., Phys. Rev. C 73 (2006) 057601] (the solid line is from our model).



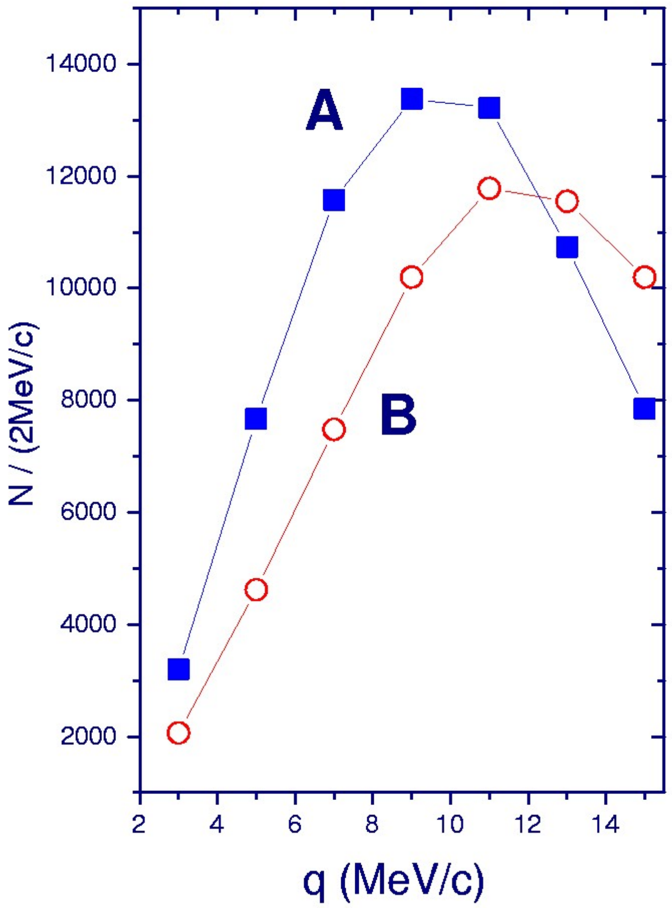
Possibility to test the model

Another possible indication:

The figure was obtained from data of Phys. Rev. C {69} (2004) 011602. The solid square data (A) are obtained from the denominator of the correlation function built from single detected neutrons; and the open circles data (B) from the denominator built by event mixing. The using of denominator of the type (B) has been criticized in R. Ghetti et al. [Nucl. Phys. A 660 20 (1999) 20]:

"In the event mixing the denominator is generated by randomly mixing the neutrons from the coincidence sample. This method has the advantage that the uncorrelated distribution corresponds to the same class of collisions as in the case of the numerator, but has the disadvantage that it may distort the correlation one wants to measure - because it may not succeed to decorrelate completely the events. In the single product technique the denominator is constructed by the product of single neutron distribution."

This is puzzling, as noted by Petrascu et al. The denominator type (B) should be higher than the denominator type (A), because the denominator (B) is not able to decorrelate completely the events! In a single case denominator type (B) could be lower than denominator type (A). The conclusion of Petrascu et al. is that such **result is consistent with a sink in the data, in agreement with the minimum predicted by the present model for the C_{nn}.**



Conclusions and Perspectives

- Main different approach of the present model in comparison with the previous model analysis of halo-nuclei correlation functions was to consider that **in the halo dissociation we have coherent emission of neutrons and include final state interactions between the neutrons in the breakup amplitude.**
- As a result, **the correlation function presents a minimum near ~ 50 MeV/c**, with the asymptotic momentum region pushed to much higher values. The result affects the corresponding $\mathbf{C_{nn}}$ normalization.
- Another relevant result of the model is the root-mean-square radius. For the separation between the halo neutrons inside ^{11}Li we found **8.5 fm** (when the binding energy is 0.29 MeV) which is very close to the result given by $COSMA_1$ model (**8.3 fm**) [Zhukov et al., Phys. Rep. 231 (1993) 151]. Consequently, the finding of a correlation function as given by our model implies in confirmation of the ^{11}Li halo structure predicted by $COSMA_1$ model.

- In order to improve the model, we are also considering the effect of partial coherence between the emitted particles.

- But, for the present analysis of halo-neutrons, a significative coherence between the neutrons is expected. A preliminary analysis already shows that an interpolating model cannot change this picture.

- The experimental verification of a minimum is expected in the plot of $\mathbf{C_{nn}}$ as a function of the momentum, implying in a rescaling of the $\mathbf{C_{nn}}$ normalization.

- Inclusion of higher partial waves in the calculations of radii and correlation functions can also improve analysis of other 3body systems.

Thanks!

- for your attention

- to the INPC2007 local organizers for selecting this talk

- Brazilian funding agencies FAPESP and CNPq, for partial support