Four α correlations in nuclear fragmentation: a game of resonances

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Today, clustering is still a hot topic in nuclear structure for C, O and more complex nuclei [1–4]. This is true in nuclear dynamics as well, for instance in fragmentation reactions [5–10], together with the possibility of observing a Bose Einstein Condensate (BEC) and Efimov states [3,11]. Following Ref. [12], we can identify the HS as an Efimov State (ES) [11, 13-14] because of its 100% decay into ^{8}Be+α, i.e, with the lowest relative energy of two αs equal to 92 keV. The mechanism at play is that an α particle is exchanged between the other two αs. The Boson exchange produces an effective field that binds the 3 particles system [15]. This mechanism might be extended to 4 or more Bosons [16] and provide new insight into many body interactions. In particular, if ^{16}O can be described as 4α clusters, we can study the relative energy distributions of all 2α possible combinations. To put this idea on a firm ground, we extend the ^{12}C case to ^{16}O and write its excitation energy as:

$$E^{*} = \frac{1}{2}\sum_{i=1,j<i}^{4} E_{ij} - Q. \qquad (1)$$

where E_{ij} are the two αs relative energies and we have classified the (undistinguishable) particles according to their relative energies in such a way that $E_{ij}^{1} \leq E_{ij}^{2} \leq \cdots E_{ij}^{6}$; Q = -14.44 MeV is the Q-value for the decay into 4α. If the six E_{ij} relative energies combinations equal to 92 keV (the ^{8}Be ground state) then we expect from eq. (1) an excited level at E^{*}=14.72 MeV [16]. Similarly, to the ^{12}C [17-18], we might expect an excited level of ^{16}O, which decays sequentially to ^{12}C(HS)+α with the ^{12}C(HS) decaying into ^{8}Be+α [19–22]. In this case the available excitation energy is not divided democratically (equally) among all the αs. Only the lowest relative energy of two αs is equal to 92 keV (the last ^{8}Be decay).

To study `in medium' 4α correlations and link them to the ‘fission’ of ^{16}O in two ^{8}Be in the ground state or $^{12}C^{*}$(Hoyle State) + α, events with only 4α particles emitted amongst other particles were analyzed at the same time for the system of 35 MeV/nucleon ^{70}Zn+^{70}Zn, ^{64}Zn+^{64}Zn and ^{64}Ni+^{64}Ni measured using the NIMROD array [7,10]. To assign a position to the fragment in the single detector, two possible avenues are commonly followed [10, 23-24]. One is to assign the fragment position at the center of the single detector(CD), the second is to assign a random position on the surface of the single detector (RD). In fact, we can randomly choose the position of the real events N>>1 times (RDN). In this way we can uniformly explore the surface of the detector and, if we normalize the number of events to one, it becomes the probability of finding a fragment at a certain angle and energy. Another detector feature to consider is double hits (DH). Because of the finite granularity it is possible that two fragments hit the same detector in the same event. For α-particles the detector response to DH is quite unique and there is no possibility to confuse those events with other fragments (say $^{6;7}$Li etc.) [24]. This together with the CD method automatically produces a ‘resonance’ for relative energies E_{ij}(DH)=0 MeV. The RD(N) method, on the other hand, might give non-zero relative energy since the positions of the two particles in the single detector are randomly chosen. The next step in the data analysis is to generate mixing events for each assumption discussed above. This is achieved by choosing four different α-particles from four different events. This procedure can be repeated many times (more than the number of real events) in order to get a smooth paving of the available phase space. As for the real events, we normalize the total number of mixing events to 1. A four-body correlation function can be defined as:

$$1 + R_4 = \frac{Y_R}{Y_M} \tag{2}$$

where Y_R is the yield of real events and Y_M is the yield of mixing events. Similarly, the three-body ($1+R_3$) or the two-body ($1+R_2$) correlation functions can be obtained. The ratio can be performed as function of the ^{16}O excitation energy defined in eq. (1) or other relevant physical quantities

In Fig. 1, we plot the correlation function as function of the ^{16}O excitation energy. In the left panel, the $E_{ij}(DH)$=92 keV is adopted while the $E_{ij}(DH)$=0 keV is given in the center panel. The results without DH are displayed in the right panel. The CD (black full circles) and RD (green open squares)

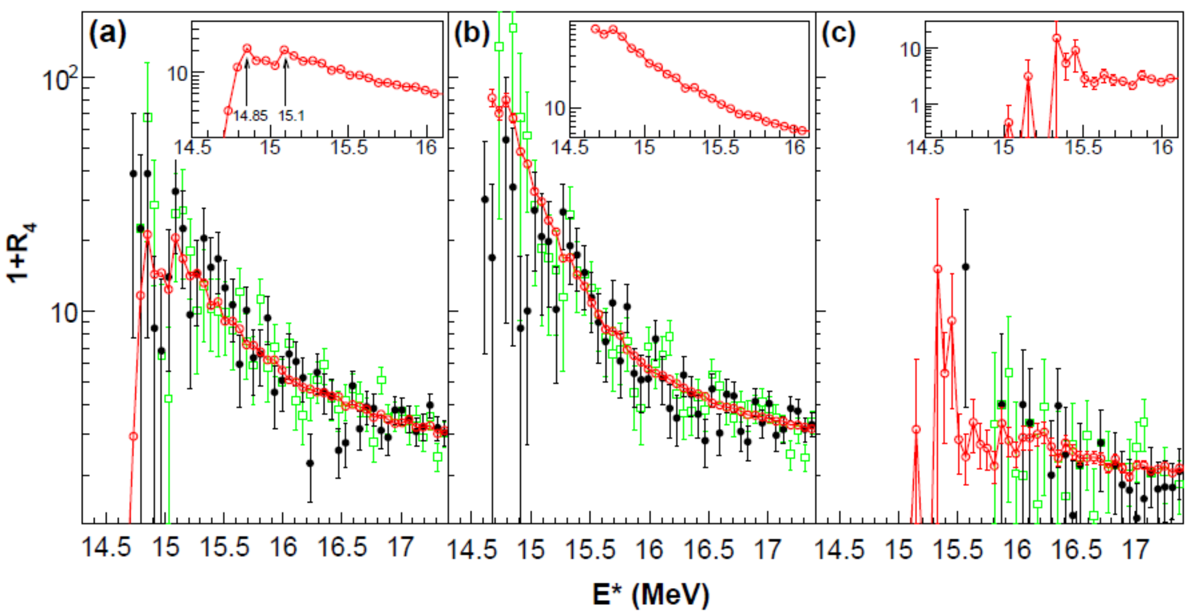

Fig. 1. Four αs energy correlation function of 16O: (a) relative energy for DH is equal to 92 keV and (b) equal to zero. No double hits in panel (c). In all cases, the bin-width is 60 keV. In the insets we display the results for the RDN cases only.

choices give a positive correlation function around 15 MeV. A peak at 15.1 MeV is clearly seen when the $E_{ij}(DH)$=92 keV assumption is adopted. If we generate a large number of RDN events (red open circles) we obtain a smoothing of the RD case (see also the insets). The interesting feature is that two clear peaks appear at 14.85 and 15.1 MeV in the left panel, while the two peaks are smoothed in the middle one. These results confirm the resonance at 15.1 MeV and give some circumstantial evidence for a peak at lower E =14.72 MeV consistent with the decay of ^{16}O into four alpha particles all with energies 92 keV (see eq. (1)), i.e, all combinations of two αs result in the g.s. of ^{8}Be. The right panel (no DH) shows the positive correlation function above 15 MeV but no data points are found for lower energies thus suggesting that DH relevant with the decay of ^{8}Be are crucial to determine the exact position of the resonance(s).

In Fig. 2, we have repeated the analysis of the previous Fig. 1 for different bin-widths ((a),(b),(c),(d) correspond to the bin-widths of 60 keV, 80 keV, 120 keV, 200 keV, and the middle and bottom panels are similar) and for the CD case only. The 15.1 MeV is clearly visible in the two top panels

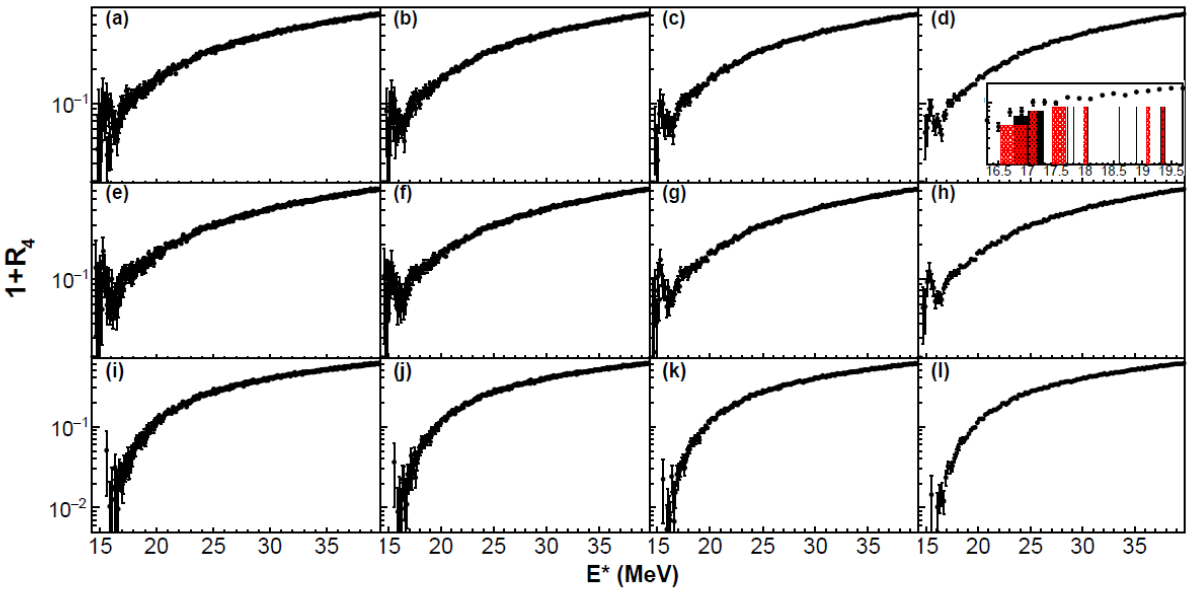

Fig. 2. Excitation energy distribution for the CD choice: (top) Eij(DH)=92 keV, (middle) Eij(DH)=0 keV and (bottom) no double hits.The (a),(b),(c),(d) correspond to the bin-widths of 60 keV, 80 keV, 120 keV, 200 keV, and the middle and bottom panels are similar. In the inset of (d), the positions and widths of known resonances are indicated as well, see text.

with some hint in the bottom panel where DH are not included. Some data points are also present near the 14.85 MeV excitation energy but error bars are too large. In the inset of figure 2(d) we have indicated the positions and widths of some observed excited levels coming from the decays into ^{8}Be+^{8}Be (black full lines) and α+^{12}C*(HS) (red dashed lines) [19–22]. We notice the large bump below 16 MeV which might be dominated by the suggested resonances plus the detector acceptance. For larger excitation energies, resonances are embedded into the BEC thus are not clearly distinguishable [5, 8-9]. Of course repeating the experiment with an improved detector granularity might shed more light on these in medium levels. In such a scenario the RDN method proposed in this work might be crucial.

[1] D.J. Marín-Lámbarri *et al.*, Phys. Rev. Lett. **113**, 012502(2014).

[2] T. Ichikawa *et al.*, Phys. Rev. Lett. **107**, 112501(2011).

[3] J. Bishop *et al.*, Phys. Rev. C **100**, 034320 (2019).

[4] M. Barbui *et al.*, Phys. Rev. C **98**, 044601 (2018).

[5] G. Giuliani, H. Zheng, and A. Bonasera, Progress in Particle and Nuclear Physics **76**, 116 (2014).

[6] A. Bonasera, F. Gulminelli, and J. Molitoris, Phys. Rep. **243**, 1 (1994).

[7] K. Schmidt *et al.*, Phys. Rev. C **95**, 054618 (2017).

[8] J. Mabiala, H. Zheng, A. Bonasera, Z. Kohley, and S. J. Yennello, Phys. Rev. C **94**, 064617 (2016).

[9] P. Marini *et al.* [INDRA Collaboration], Phys. Lett. B **756**, 194 (2016).

[10] Z. Kholey, PhD Thesis, Texas A&M University, 2010.
[11] V. Efimov, Phys. Lett. B **33**, 563 (1970).
[12] H. Zheng and A. Bonasera, arXiv:1811.10412.
[13] V. Efimov, Nat. Phys. **5**, 533 (2009).
[14] A.Tumino, A.Bonasera, G.Giuliani *et al.*, Phys. Lett. B **750**, 59 (2015).
[15] L.H. Thomas, Phys. Rev. **47** 903 (1935).
[16] C.H. Greene, Phys. Today **63** (3), 40 (2010).
[17] S. Zhang, A. Bonasera, M. Huang *et al.*, Phys. Rev. C **99**, 044605 (2019).
[18] S. Zhang, J.C. Wang, A. Bonasera *et al.*, Chinese Phys. C **43**, 064102 (2019).
[19] P. Chevallier *et al.*, Phys. Rev. **160** (4), 827 (1967).
[20] F. Brochard *et al*., Phys. Rev. C **13** (3), 967 (1976).
[21] M. Freer *et al.*, Phys. Rev. C **51**, 1682 (1995).
[22] M. Freer *et al.*, Phys. Rev. C **70**, 064311 (2004).
[23] Ad. R. Raduta *et al.*, Phys. Lett. B **705**, 65 (2011).
[24] R. Wada *et al.*, Phys. Rev. C **69**, 044610 (2004).