QUO VADIS - HALO?

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Abstract

Two decades have elapsed since the discovery of nuclear halos by Tanihata and his team at Berkeley. The field has been driven by remarkable experimental progress and discoveries, and more is to come with new and upgraded facilities, like FAIR here in Europe. From finding adequate phenomenological ways to describe the physics of the halo ground state, ambitions have grown to also understand the halo continuum, also for three–body Borromean halos. Theory has gradually become a useful partner for experiment, also concerning predictions, although reaction theory remains a challenge, in particular at lower energies, as has been demonstrated during this workshop. This has however not prevented theory from having ambitions to go further, to also understand the self-organization of halo systems in an *ab initio* manner, i.e. starting out from nucleon constituents and their interactions. This contributions is a reminder on how the road has been made along the way - while we go.

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This being the last day of our workshop, allows me to make some personal reflections on what we have learned, also about the identity and status of our field. Thus the title of my talk, which is different from the one in the original programme. The original topic was covered in depth by Boris Danilin, and I refer to his instructive pictorial exposition of physics of the Borromean continuum.

My programme for this talk has seven points.

1. Ability to discover underlying structures
2. Identity of our field - unity of approaches
3. From poor man's recipes to more educated ones
4. Pictures of halo dynamics filtered by the reaction process
5. Hyperon glue for beyond dripline nuclei
6. Show shortcomings, not only successes!
7. Outreach - general lessons

I. ABILITY TO DISCOVER UNDERLYING STRUCTURES

This takes me back to the early days of ECT*. The place is just outside the Duomo - the object is a sportcar (Ferrari?), a wedding present wrapped in white paper - attention is on the groom - who cannot get a ribbon (suspended by balloons) with the names of the happy couple

FRANCESCA et RENZO

to fly, because of lack of sufficient updrift. The banner has to fly before the gift can be unveiled!

This was where I got convinced that RENZO knew what he was doing; Getting hold of a scissors, having discovered the underlying structure, he cut the ribbon after the two first letters in Francesca,

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and Francesca and Renzo could fly up in the air. The car was unwrapped ... (you may ask me what is was..).

II. IDENTITY OF OUR FIELD - UNITY OF APPROACHES

Our field is physics of transient phenomena, forms of matter like QGP that exist within the reaction zone or in flight within the accelerator. Thus the field intertwines structure and reactions more than ever before. Halo physics has in recent years, as this workshop has shown, taken further steps to explore the nature of Borromean continua, in fact the major part of the spectrum since halo nuclei support only one or a few bound states. Since 3→3 scattering is prohibitively difficult to perform, the halo continuum has so far been excited in binary collisions, proceeding via the exotic ground state, which to various degrees puts its imprint on the result. It is a challenge to disentangle continuum structures, a topic which was discussed in detail by Boris Danilin.

Historically our theoretical understanding of halos was derived from cluster models, originally suggested by the experimentalists themselves (Gregers Hansen and Björn Jonson, Fig. 1), and subsequently improved by theorists to encompass the true inherent few-body degrees of freedom that contained the leading physics. Thus emerged the famous spatial correlation plot of the ground state of ^{6}He with its dineutron and cigar peaks (Fig. 2). This gross structure simply reflects the Pauli principle, which prevents the halo neutrons from entering the s-motion already occupied in the alpha cluster. The finer details of the landscape given in the plot, essential for quantitatively correct halo physics, are caused by the interactions and dynamics of the three-body system. During this workshop we have had a number of informative reports on progress with *ab initio* approaches, having the ambition to *produce* the self organized halo structures i.e. not putting clustering in by hand as is done in the few-body cluster models. In spite of impressive techniques to handle enormous matrices (billionxbillion) a remaining challenge is to obtain the large widths of most halo continuum structures and a description of the multitude of reaction scenarios which contain ingoing and outgoing clusters, i.e. nuclei. Reactions obviously favor cluster formulations, and the most advanced current reaction theory is within this picture. True ab initio approaches have some way to go: Interesting perspectives toward such ends were described by Hans Feldmeier.

The three Borromean rings can be used to describe the identity of our field, (i) one ring emphasizing a field driven by experiment, (ii) one the role of emergent degrees of freedom carrying central physics and cluster aspects, the artist's fingertip feeling and recipes, and (iii) the third ring the role of the younger generation - computational physicists - invoking fundamental constituents and an ambition to understand exotic self organization, including resonant structures and reactions. The Borromean connectiveness symbolizes the identity of our field and also that only a unity of action will bring the field truly forwards.

Thus we will need the interplay between the few-body modeling and the many-body ab initio formulations, the former also serving as a guide for the latter to observables which are hard to get at in the more ambitious approach. This does not say that the few-body formulations do not have their own basic challenges, four-body problems have only recently been addressed with success. Historically few-body problems were considered as prohibitively difficult. Antonio Fonseca demonstrated the power of a few-body approach for scattering. Among the many-body formulations the Hill-Wheeler type of approach described by Robert Roth and Hans Feldmeier forms a kind of bridge between the few-body and many-body worlds. Extending this approach to reactions would be a true break-through.

III. FROM POOR MAN'S RECIPES TO MORE EDUCATED ONES

Progress in nuclear physics has to a large extent been due to recipes cooked up by the experimentalists themselves to understand their own data. Theorists must only welcome their frequent success in feeling the heart-beat of the underlying physics. For binary phenomena this procedure is simpler than for interplay between more than two constituents, as demonstrated by the early models for ^{11}Be compared with the Borromean halo nuclei like ^{11}Li and ^{6}He. Still it is of interest to derive recipes also for more complex systems, which can help us in our understanding of the important physics.

As an example I like to derive a relation between the mass radius of a Borromean $A = C+n+n$ system, like ^{6}He, and the charge radius of A and the charge and mass radii for the core nucleus C. The choice of this example here at Halo06 is sparked off by the extensive ab initio calculation reported by Petr Navratil. Details can be found in our recent paper [16].

Here I only include a few main steps.

To estimate the mass radius of the ground state of the three-body halo nucleus $A = C + n + n$, we assume a separable intrinsic wave function

$$\Psi(A) = \Phi(C)\ \psi(h)$$

where $\psi(h)$ describes the relative internal three-body motion between the halo neutrons and the core C, say in hypercoordinates ρ and α. Thus there is no coupling between the relative motion and the internal motion $\Phi(C)$ in the core. Simple geometrical considerations [16] give the relations

$$R_m^2(A) = \frac{C}{A}\ R_m^2(C) + \frac{1}{A}\ R_m^2(h) \tag{1}$$

$$R_c^2(A) = R_c^2(C) + \langle r_C^2 \rangle_\psi \tag{2}$$

where $R_m(h) = \sqrt{\langle \rho^2 \rangle_\psi}$ measures the size of the halo system while $\sqrt{\langle r_C^2 \rangle_\psi}$ describes the average position of the core (C) CM with respect to the CM of the total system A. We can express this latter separation as

$$\langle r_C^2 \rangle_\psi \ = \ \left\{ \frac{1}{C}\ (1+\Delta) \right\}\ \frac{1}{A}\ R_m^2(h)$$

where $\Delta = \langle \rho^2\ \cos 2\alpha \rangle / \langle \rho^2 \rangle$. From eq. 2 now follows an expression for $R_m(h)$ in terms of charge radii, which inserted in eq. 1 gives

$$R_m^2(A) = \frac{C}{A}\ R_m^2(C) + \frac{C}{1+\Delta}\ \left\{ R_c^2(A) - R_c^2(C) \right\}$$

Knowing $R_m(C)$, $R_c(C)$ and $R_c(A)$, say from experiment, the only quantity which needs to be theoretically estimated is Δ. For ^{6}He ρ - α separability is well satisfied giving $\Delta = \langle \cos 2\alpha \rangle \simeq 0.16$. Using the measured quantities for ^{6}He we derive a mass radius of 2.5fm, i.e. just that derive from hadronic experiments when the reaction theory (say Glauber) takes the granularity of the halo system into account.

IV. PICTURES OF HALO DYNAMICS FILTERED BY THE REACTION PROCESS

Boris Danilin (Fig. 3) has discussed this extensively in his presentation, supplying the experimentalists with dream material (nightmares). Here I only want to remind you of the huge and wavy ocean we disclose when we study correlation plots: spatial-, energy(momentum)- and angular. To extract information from such plots more clearly, we have to subtract in some way the wavy background due to the free (NoFSI - No Final State Interaction) three body motion in the continuum, (Bessel functions for multipoles of the spatial correlations). The physical nature of the continuum structures is what we try to get at, and the diagnostics are more complex for three bodies moving with respect to each other than for what we are more used to - binary motion. What still simplifies the situation for Borromean systems though is that, in hypercoordinates, aspects of the behavior in the hyperradius for three bodies resemble that for two bodies in their relative binary coordinate. For non-Borromean systems with lower binary break-up thresholds, the situation is quite different and often even more complex. As illustrations for the Borromean case, we show again (see Danilin) (i) spatial correlations for ^{6}He monopole motion (Fig. 4), including the famous ground state (Fig. 2) and (ii) spatial (Fig. 5) and (iii) energy correlations for the well defined quadrupole three-body resonance (Fig. 6).

V. HYPERON GLUE FOR BEYOND DRIPLINE NUCLEI

Although our RNBT team in recent years has mainly worked on dripline problems, it has also some pre-history in the physics of hypernuclei [1]. It is interesting to notice that the two fields are approaching each other. Thus hyperon glue (say Λs) may be used in our field for tugging beyond-dripline nuclei back to the dripline, and vice versa, (ii) structurally well understood light dripline nuclei may be used as laboratory for exploring fundamental YN and YY interactions. Such possibilities are addressed in papers by Hiyama and her collaborators, see [2] and references therein. See also the coming proceedings from SNP2006 (Strangeness Nuclear Physics).

VI. SHOW SHORTCOMINGS, NOT ONLY SUCCESSES.

We are all happy when our theories seem to be supported by experiment - less outgoing when there is disagreement. In our minds we even question the data. This is OK, but we should first ask if we compare truly corresponding quantities. In halo physics this was a challenge from the very beginning, and it is not less important nowadays when correlated quantities are extracted. Thus it is often an advantage to sit down with our experimental colleagues and step-by-step find out what has been done. This is also important for finding out what can be done in the future! It is also the essence behind the grant for theory within the EURONS project that we discussed yesterday.

Thus my final example shows how we were rewarded with both happiness and unhappiness when we tried to calculate energy and angular correlation for GSI data [3] for ^{6}He + ^{208}Pb at E/A = 240 MeV. Our four-body reaction model agrees rather well (Fig. 7) with the GSI data for a bin of continuum energies between 1 and 3 MeV. For higher energies (Fig. 8) the situation is however, more perplexing. The angular correlation in the Jacobi T system and the energy correlation in the Y system now deviate strongly from experiment. We have not succeeded in attempts to improve the theoretical description, say by modifying the effective pair-wise interactions, without destroying the good agreement obtained for excitations near threshold. The problem remains open.

VII. OUTREACH -GENERAL LESSONS

The observation and interpretation of nuclear halos has been a strong driving force for dripline physics and many groups have tried to become Masters of the Rings. Visions about Borromean structures or related Efimov states [4], have also been described in other fields, in particular by Macek [5]. From our field Dima Fedorov and Aksel Jensen among others have contributed to the more general discussion of these outstanding quantum physics phenomena - existence in classically forbidden regions. Recently evidence for Efimov states was found in ultracold (10nK) gas of Caesium atoms [6]. A couple of years ago molecular Borromean ring structures (literally!) were addressed in Science [7] as an upcoming nanotech field. And the low density of the halos make them a unique testing ground for fundamental neutron matter under extreme conditions, also of astrophysics relevance.

With upcoming new facilities like FAIR we will certainly make new discoveries, important for our nuclear paradigm. It is however important that we reach out beyond what is only interesting for nuclear physics. Hence it is essential that we appreciate success and even fame that colleagues may obtain - nuclear science much become a field where we collectively celebrate progress and speak well about each other. This does not mean that we should not have hot internal discussions, which we have certainly had at Halo06.

Some selected RNBT papers, relevant for continuum studies are given below [8] - [18].

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[1] B.V. Danilin and A.A. Korsheninnikov, *Sov. J. Nucl. Phys.*, **50**, 703 (1990).

[2] E. Hiyama, Y. Kino and M. Kamimura, *Progr. Part. Nucl. Phys.* **51**, 223 (2003).

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[4] V.M. Efimov, *Phys. Lett.* **B33**, 563 (1970).

[5] Z.Zhen and J.Macek, *Phys. Rev.* **A38**, 1193 (1988).

[6] T. Kraemer et al., *Nature* **440**, 315 (2006).

[7] K.S.Chichak et al., *Science* **304** (2004).

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[9] B.V. Danilin, M.V. Zhukov, S.N. Ershov et al., Phys. Rev. C **43**, 2835 (1991).

[10] S.N. Ershov, T. Rogde, B.V. Danilin et al., Phys. Rev. C **56**, 1483 (1997).

[11] S.N. Ershov, B.V. Danilin, T. Rogde and J.S. Vaagen, Phys. Rev. Lett. **82**, 908 (1999)

[12] S.N. Ershov, B.V. Danilin, J.S. Vaagen, Phys. Rev. C **62**, 041001(R) (2000).

[13] S.N. Ershov, B.V. Danilin, J.S. Vaagen, Phys. Rev. C **64**, 064609 (2001).

[14] S.N. Ershov, B.V. Danilin, J.S. Vaagen, A.A. Korsheninnikov and I.J. Thompson, Phys. Rev. C **70**, 054608 (2004).

[15] B.V. Danilin, T. Rogde, J.S. Vaagen et al., *Phys. Rev.* **C69**, 024609 (2004).

[16] B.V. Danilin, S.N. Ershov, J.S. Vaagen, Phys. Rev. C **71**, 057301 (2005).

[17] S.N. Ershov, B.V. Danilin, J.S. Vaagen, Phys. Rev. C **72**, 044606 (2005).

[18] S.N. Ershov, B.V. Danilin, J.S. Vaagen, Phys. Rev. C **74**, 014603 (2006).

FIG. 1: In memory of Gregers Hansen and in appreciation of Björn Jonson who is 65 today; pioneers in our field.

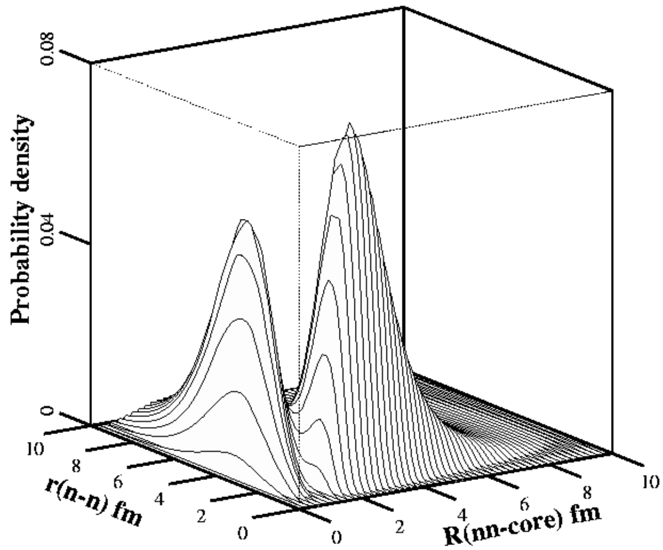

FIG. 2: The cigar and dineutron configurations in the ^{6}He ground state.

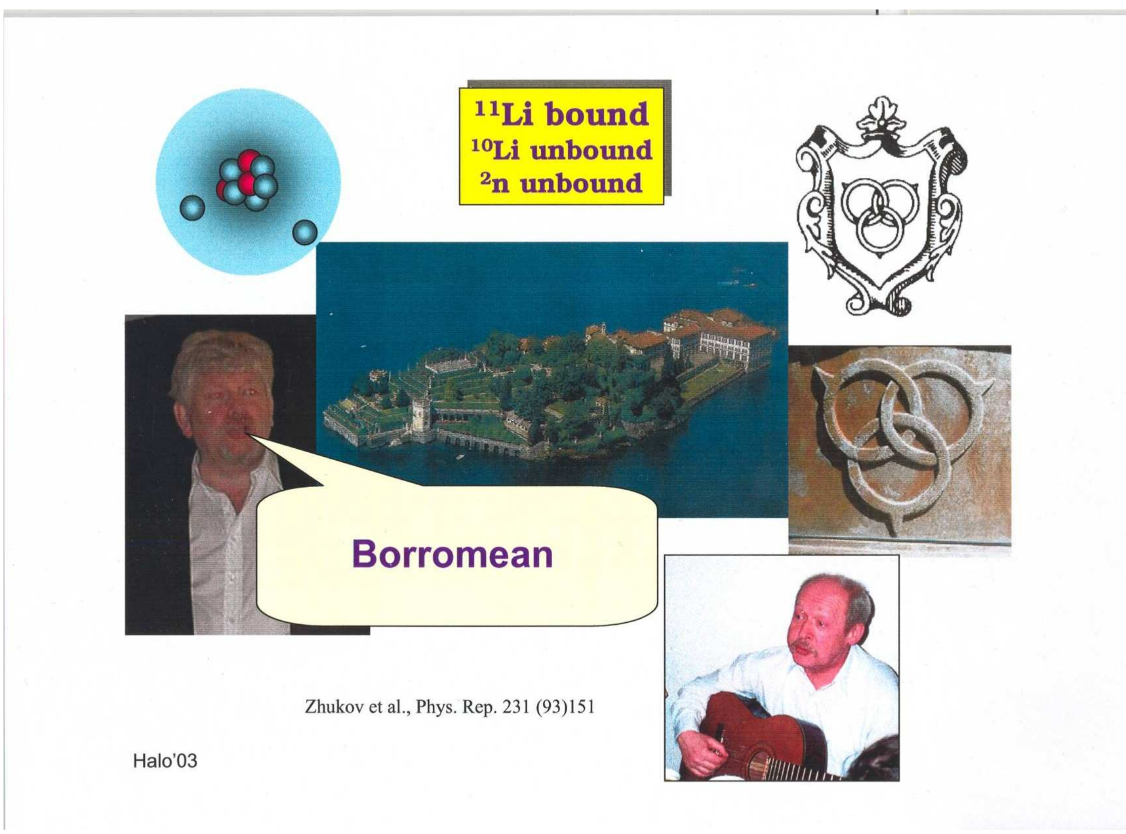

FIG. 3: Aspect of human dimension and plurality in the theory community. A collage made by Björn Jonson.

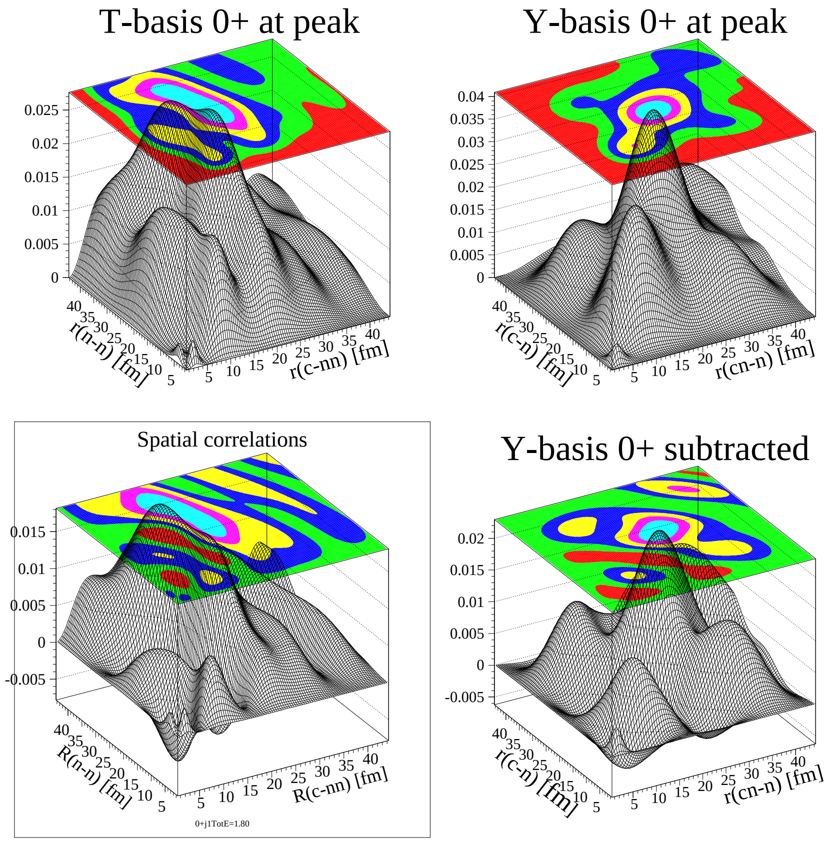

FIG. 4: Spatial correlations for the energy peak position of the 0^+ soft monopole mode (upper row) and after subtraction of the APW density (lower row) in **T** and **Y** systems.

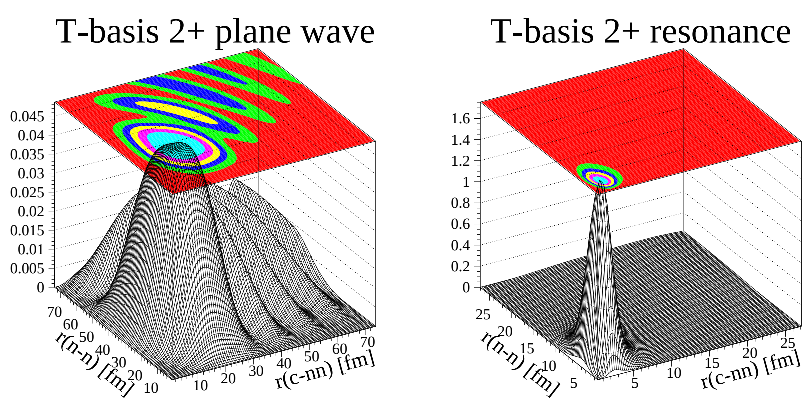

FIG. 5: Spatial correlations for the 2^+ partial component of an APW (left) and the 2_1^+ resonance calculated at resonant energy in **T** coordinate system. Very similar correlations are in the translation invariant 'shell model' **Y** coordinate system.

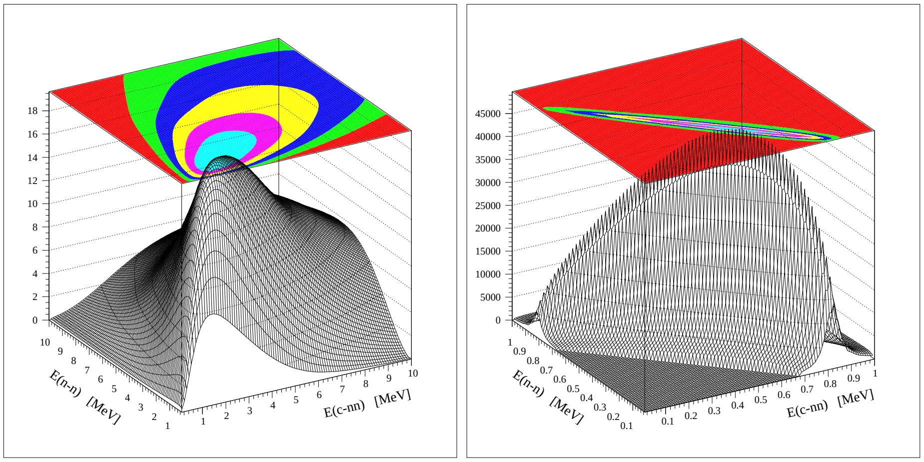

FIG. 6: Energy correlation plot for 2^+ states in cluster **T** basis: left - NoFSI, right - with FSI (2_1^+ resonance).

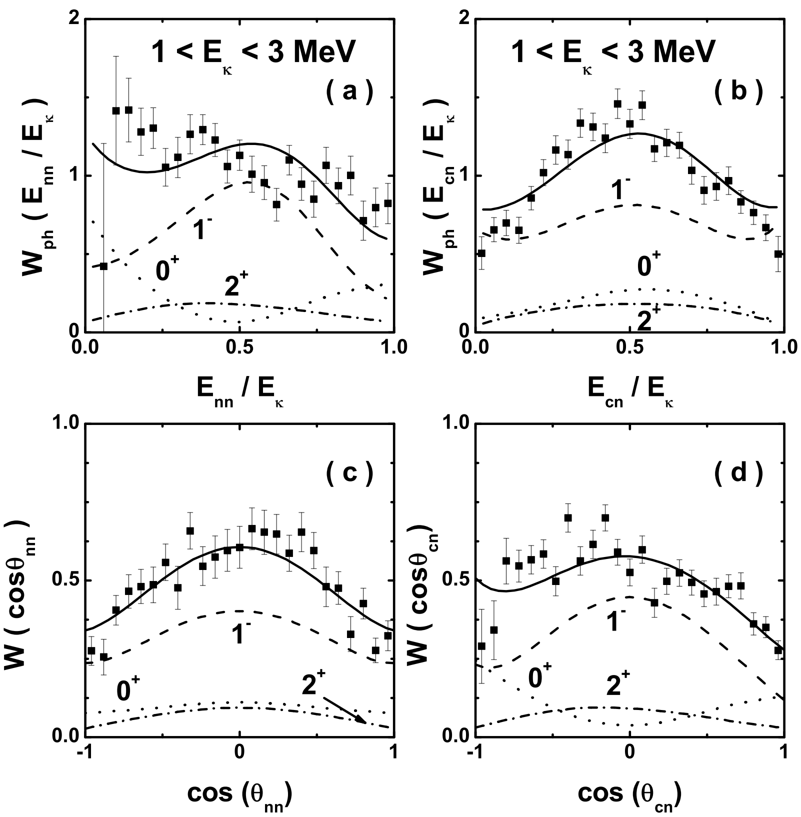

FIG. 7: Energy ((a) and (b)) and angular ((c) and (d)) fragment correlations (solid line) in the ^{6}He + ^{208}Pb breakup at 240 MeV/nucleon for continuum energy region $1 < E_\kappa < 3$ MeV. (a) and (c) are shown in Jacobi configuration **T**, (b) and (d) in configuration **Y**. The dashed, dotted and dash-dotted lines show the dipole 1^-, monopole 0^+, and quadrupole 2^+ contributions, respectively.

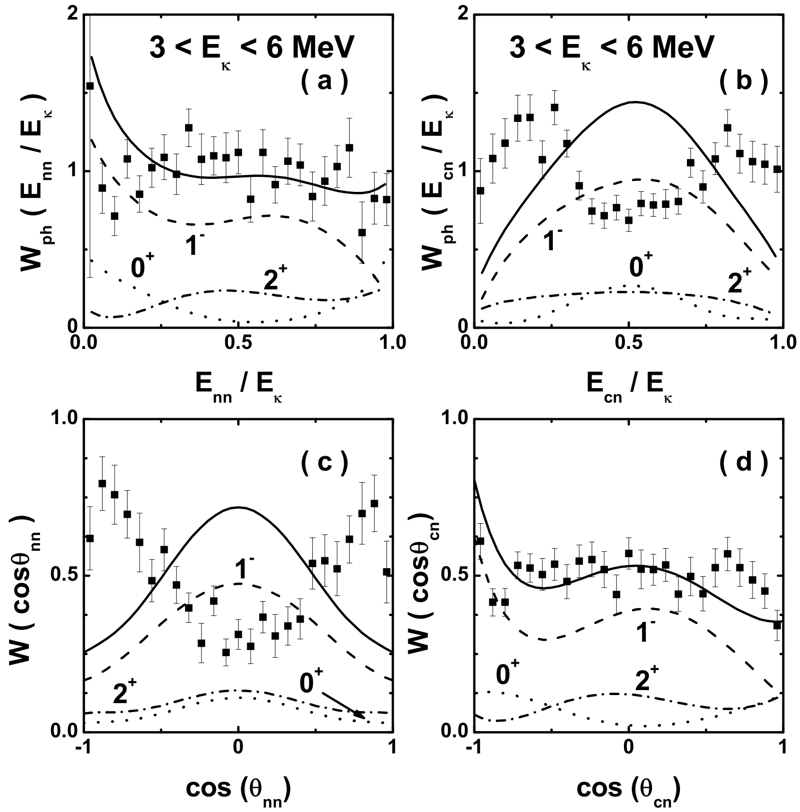

FIG. 8: Energy and angular fragment correlations in ^{6}He + ^{208}Pb breakup at 240 MeV/nucleon for excitation energy region $3 < E_\kappa < 6$ MeV.