Critical Stability Problems

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Contents

Background for Critical Stability

Thanks to the organizers for inviting me. I am sure this is the beginning of a beautiful week, as all previous Critical Stability Workshops have been. I am very pleased to be here, back again. These series of workshops started here in 1997, when Ben Mottelson was ECT* director, with organizers J.-M. Richard, A. Martin and me. Roughly each three years afterwards again gathered people for these workshops.
The idea was triggered by the previous decade of discoveries related to the special structure of very weakly bound systems, first observed in nuclei, where the ^{11}Li nucleus was realized to be exceptionally large [1]. Very soon after, the exceptional size was related to its small two-neutron binding energy [2]. This explanation was not obvious for the three-body system of two neutrons and the ^{9}Li-core, but the authors bravely considered the two neutrons as one particle, the di-neutron and continued to describe the emerging two-body system, ^{9}Li plus a di-neutron.

They used the large-distance limit for a weakly bound two-body system:

$$< r^2 >= \frac{\hbar^2}{4\mu B} \ ,$$

which was well-known and applies relatively well to the deuteron. This insight was immediately seen to be at least as relevant in atomic and molecular physics. The delicate exotic structure and the derived universal properties are applicable in many subfield of physics, mathematics and in conceptually close lying fields of chemistry and perhaps biology.
Borromean systems, halo states, and Efimov-physics were perhaps the beginning, but soon broader developments into continuum strutures, lower dimensions, condensates, dynamics, decays, properties of weakly bound states in general, mostly all are few-body physics problems.
All this continued into the important notion of universality.

Crucial Trivialities

Often not empasized, often not necessary, but always crucial.
Degrees-of-freedom must be chosen.
Examples could be quarks towards chemical reaction.
More subtle are halos versus core degrees-of-freedom.
Quickly few-body physics problems are in focus.

Dennis method on nuclei

First, divide nucleons into groups, core and valence nucleons.
Each group is intended to be treated individually.
This is one necessary simplification of the N-body problem.
Numerous examples like the cluster philosophy.
HF into core + valence parts. Now superfluous.
Formulated and applied in [3, 4, 5, 6].
Driplines and Efimov investigations.

Applying for 2 valence particles outside a many-nucleon core.
The hamiltonian for the Skyrme zero-range interaction becomes:

$$H = H_c + H_3$$

$$H_c = \sum_{i=1}^{A} T_i - T_c^{(cm)} + \frac{1}{2}\sum_{i,j=1}^{A} V_{ij} \ ,$$

$$H_3 = T_c^{(cm)} + T_{v_1} + T_{v_2} - T_{cm} + V_{v_1 v_2} + \sum_{i=1}^{A} (V_{iv_1} + V_{iv_2}) + V_3 \ ,$$

where v_1 and v_2 refers to the two valence nucleons.
The wave function can be written:

$$\Psi = \mathcal{A}\left[\psi_c(\mathrm{r}_1, \ldots, \mathrm{r}_A)\psi_{3b}(\mathrm{r}_{cv1}, \mathrm{r}_{cv2})\right] ,$$

The core wave function, $\psi_c = det(\{\psi_i\})$, is a Slater determinant, since Skyrme interactions are adjusted to Slater determinants.
ψ_{3b} is the three-body wave function.

The energy is:

$$E = \langle \Psi \,|\, H \,|\, \Psi \rangle = \langle \Psi \,|\, H_c \,|\, \Psi \rangle + \langle \Psi \,|\, H_3 \,|\, \Psi \rangle \,.$$

The Lagrange multipliers, ϵ_i and E_3,
for normalization constraints can be introduced by

$$\left\langle \Psi \,\middle|\, H' \,\middle|\, \Psi \right\rangle = E - \sum_{i=1}^{A} \epsilon_i \int |\psi_i(\mathrm{r})|^2 \, d\mathrm{r} - E_3 \int |\psi_{3b}(\mathrm{r}_{cv1}, \mathrm{r}_{cv2})|^2 \, d\mathrm{r}_{cv_1} d\mathrm{r}_{cv_2}$$

To minimize the energy, ψ_i^* and ψ_{3b}^*, are varied

$$\frac{\delta}{\delta \psi_i^*} \left\langle \Psi \,\middle|\, H' \,\middle|\, \Psi \right\rangle = 0 \quad , \quad \frac{\delta}{\delta \psi_{3b}^*} \left\langle \Psi \,\middle|\, H' \,\middle|\, \Psi \right\rangle = 0.$$

The variation is rather lengthy, but conceptually simple.
The variations lead to core and three-body coupled equation.

Table: The three-body energy has been adjusted to the experimental value of 0.018 MeV using the three-body interaction strength V_0, but keeping the range constant at $r_0 = 6$ fm. Included is the energy of the first $d_{3/2}$ resonance state in ^{25}O computed using our method and compared to the result of traditional HF calculations. The experimental value is 0.749(10) MeV [7]. The half-life $T_{1/2}$ is from a WKB approximation for the tunneling probability, and harmonic oscillator approximation for the knocking rate. The experimental value from Ref. [7] is $\sim 0.01 - 1$ fs. Energies are in MeV and lengths are in fm.

	SLy4	Sk3	SkM*
V_0	-5.71	-7.71	-5.72
$E_{d_{3/2}}(Our)$	0.85	1.23	0.83
$E_{d_{3/2}}(HF)$	-0.96	-0.53	-1.15
$T_{1/2}$ [fs]	0.4	0.6	0.2

Ordinary mean-field Skyrme calculations with the same parameterizations yield predictions that are not only far from the experimental value, but also clearly bound. The two-body core potential produces the $d_{3/2}$ resonance. This indicates that the present combination of the three-body approach and the self-consistent core mean-field calculation provides a small, but crucial change to the effective potential. The half-life (last row) of ^{26}O calculated using a WKB approximation for the tunneling probability, and a harmonic oscillator approximation for the knocking rate is in the middle of the experimental interval. Exponential dependence show that barrier height and thickness must be remarkably good.

Some conclusions and results

All interactions are the same, that is
between core-nucleons, core-valence, and valence-valence.
Then only the three-body interaction is free for fine tuning.

The core treatment can be improved, the interaction between valence particles and core-valence pairs may be changed.

Less freedom to parametrize interactions
Good for more more unique predictions
Bad for more precise predictions

Illustrations:
First the dripline nucleus, ^{26}O(^{24}O+n+n), as three-body system.
It has the two subsystems, ^{25}O(^{24}O+n), and $n-n$
The ^{26}O 0^+ ground state is fixed at 0.018 MeV
Then the $d_{3/2}$ resonance state in ^{25}O(^{24}O+n) is calculated.

Halo or Efimov in ^{70}Ca+$n+n$ on neutron dripline

To look for Efimov possibilities in nuclei:
^{70}Ca+$n+n$ is a promising case,
being tha last nucleus before the neutron dripline (maybe),
$g9/2$ is full, $s1/2$ (and $d5/2$) above are empty.
No present interaction can provide the Efimov required accuray.
Fine tuning is necessary, even for reliable halo properties.
The usual conditions can be obtained by tuning.
Almost degeneray of $s1/2$ and $d5/2$ leads to valence
sd-wave mixture showing that an extended s-wave halo may
appear even for short-range dominating d-wave.
Calculations of observables, like properties of decay products,
decay mechanism, etc. are possible if required.

Energy distributions

The kinetic energy distribution of the fragments in a three-body decay is the square of the wave function in coordinate space, where the hyper-angles are angles in momentum space [8, 9].
If k_x and k_y are the Jacobi momenta corresponding to the Jacobi coordinates x and y,
then $k_y^2 \propto \cos^2\alpha$ is the energy of the third particle relative to its maximum possible energy, $E_n/E_n^{(max)}$, [8].
Then the energy probability distribution can be expressed as

$$P(\rho, \cos^2\alpha) \propto \sin(2\alpha) \int |\psi_{3b}(\rho, \alpha, \Omega_x, \Omega_y)|^2 d\Omega_x d\Omega_y.$$

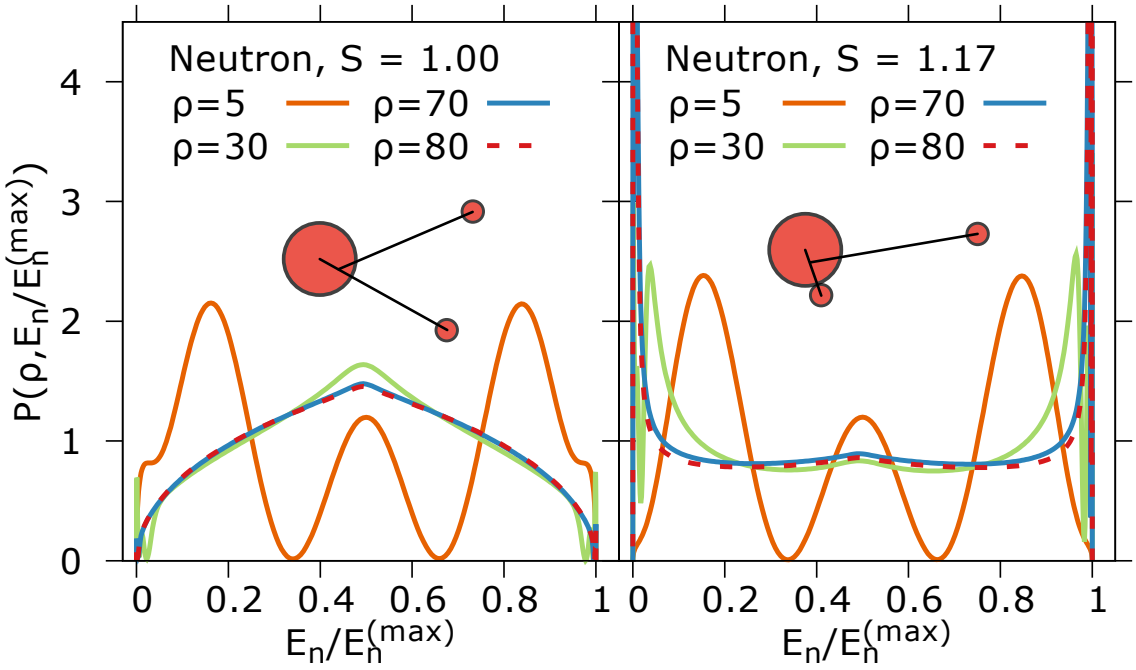


Figure: The single-particle energy distributions for the neutron after decay of ^{70}Ca $+ n + n$ at $\rho = 5$, 30, 70, and 80 fm, for $Z = 1.0$ (left) and $Z = 1.17$ (right). Schematic illustrations of the large distance configurations are also included.

Two slightly different interactions.
The relative energy for short distances are identical.
The evolution to large distances are remarkably different.
One has one central peak, both neutrons are far from the core,
Decay directly into the three-body continuum.
The other interaction gives two peaks at very small and
very large relative energy, one neutron far away, and
one is close to the core, implying sequential decay mechanism.
The interaction difference are very small, observables at large distances must be complemented by theoretical connection to small distance structure.

Astrophysical applications on proton dripline

The usual phenomenology with ordinary three-body investigations makes it difficult to obtain concrete predictions.
The present method has very little arbitrariness,
the interaction is chosen simultaneously for all particles.
Interesting reactions are the two-proton capture reactions,
exemplified by $^{68}\mathrm{Se}+p+p \rightarrow {}^{70}\mathrm{Kr}+\gamma$,
The reaction mechanism could be sequential as

$$\begin{aligned} c+p+p \rightarrow (cp)+p \quad &\rightarrow \quad A^* \rightarrow A+\gamma, \\ c+p+p \rightarrow (cp)+p \quad &\longrightarrow \quad A+\gamma, \end{aligned}$$

where A^* is the well-defined resonance state.

Or the reaction mechanism could be direct as

$$\begin{aligned} c + p + p &\rightarrow A^* \rightarrow A + \gamma, \\ c + p + p &\rightarrow A + \gamma. \end{aligned}$$

These distinctions in practice mostly conceptual, as the actual reaction mechanism would be superpositions of all possibilities, all of which are accounted for in the present formulation.
To pin down specific reaction mechanisms, the angular wave function, integrated over directional angles is revealing

$$P(\alpha, \rho) = \sin^2(\alpha)\cos^2(\alpha) \int |\psi_{3b}(\alpha, \rho, \Omega_x, \Omega_y)|^2 d\Omega_x d\Omega_y, \qquad (1)$$

where $tan(\alpha) = x/y$, and $\alpha = 0, \pi/2$ correspond to one proton close to the core, the other far away.

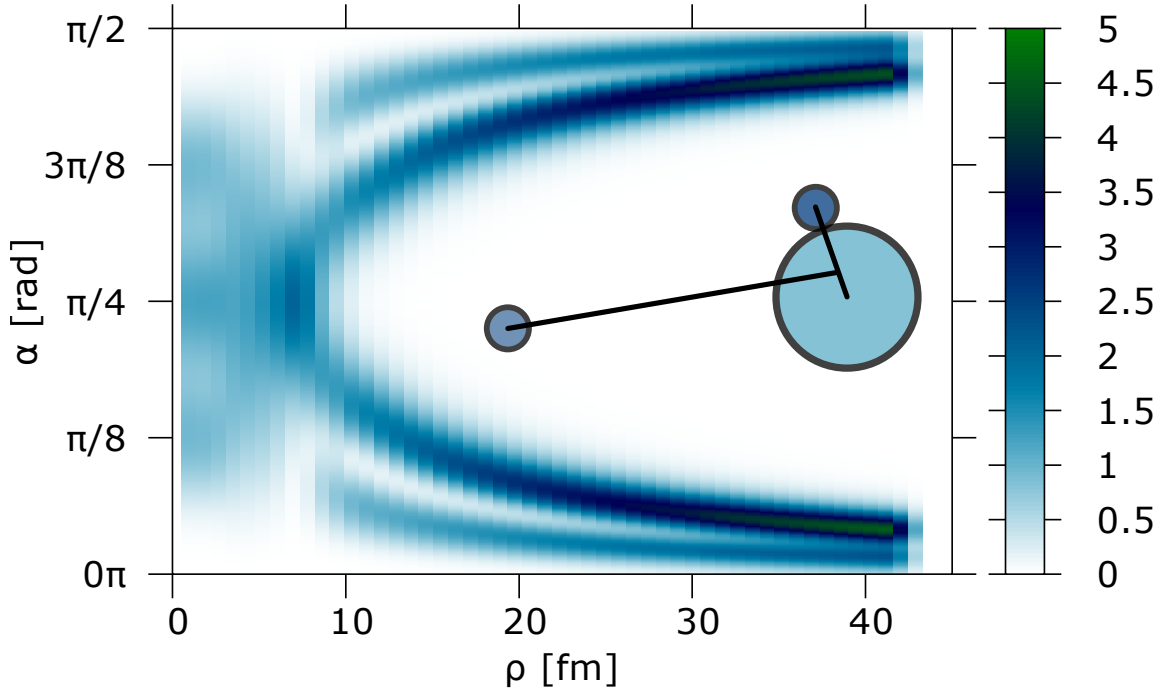


Figure: The probability distribution, as expressed by Eq. (1), of the three-body, ^{68}Se $+ p + p$, wave function for the lowest allowed potential in a 2^+ state. This is given as a function of hyperradius, ρ, and hyperangle, α, related to the Jacobi coordinate system where "x" is between core and proton.

One proton moving away from a core-proton resonance state, energy E_{pc}, and outside the strongly attractive region, it would experience a Coulomb potential (Z_c is core charge):

$$V_{seq}(\rho) = \frac{e^2(Z_c + 1)}{\rho} + E_{pc},$$

Both protons move symmetrically away, the potential is

$$V_{dir}(\rho) = \frac{e^2\left(2Z_c + \frac{1}{2}\right)\sqrt{2}}{\rho}.$$

They cross for $Z_c = 34 \gg 1$ and $E_{pc} = 0.6$ MeV for:

$(\rho_{crit}, V_{crit}) \approx (\frac{2.6Z_c}{E_{pc}}, 1.6E_{pc}) \simeq (147 \text{ fm}, 0.94 \text{ MeV})$

Then, $V_{seq}(\rho < \rho_{crit}) < V_{dir}(\rho < \rho_{crit})$
and the reaction is sequential for this low-lying resonance.

Isospin and beta-decay in halo nuclei

Choice of degrees-of-freedom is crucial for structure calculations.
But it is also important for reactions and decay.
Here we look into beta-decaying halo-nuclei.
Strong interactions determine nuclear structure.
Weak interactions determine beta-decay.
Measurements provide incredible precision related to nuclear structure.

The beta-decay operator is of one-body nature, i.e.

$$O_\beta = \sum_{i=1}^{A} O_\beta(i) = O_\beta^{core} + O_\beta^{halo},$$

from the split between halo and core degrees-of-freedom.
The halo-core product wave function,

$$|core; halo\rangle = |core\rangle|halo\rangle$$

then implies that the beta-decay of halo nuclei appears as

$$O_\beta|core; halo\rangle = |halo\rangle O_\beta^{core}|core\rangle + |core\rangle O_\beta^{halo}|halo\rangle$$

An all-important aspect is that the beta operator on a halo state must produce a structure coherently adding two pieces, i.e. one of halo beta-decay and one of core beta-decay.

The leading order beta-decay operators are very simple,
two types are called Fermi and Gamow-Teller.

The **Fermi** operator maintains spin-space wave functions, while changing only one neutron into a proton (or vice versa).

The **Gamow-Teller** operator maintains the spatial wave function, while changing the spin as a vector by one unit,
still changing one neutron into a proton (or vice versa).

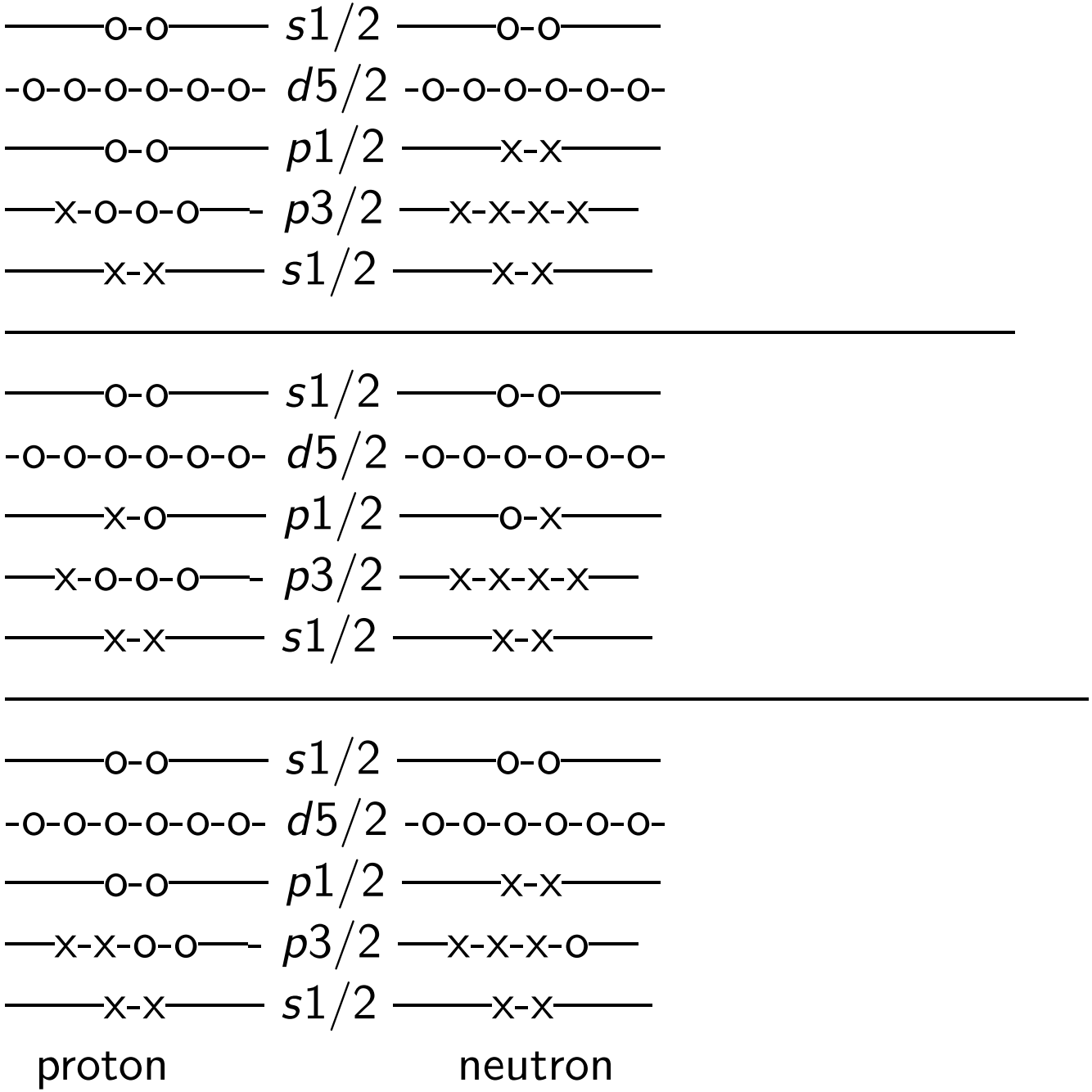
Isospin in nuclei

Neutrons and protons are differently charged,
but otherwise they behave remarkably similar.
Treating neutrons and protons as identical particles lead to
the concept of isospin, which is a fundamental nuclear symmetry,
with implications on structure, reactions and decay.

Isospin, $\vec{t} = (t_1, t_2, t_3)$, for a nucleon is a vector.
The third component, $t_3 = \pm 1/2$ for neutrons and protons.
The length, $< t^2 >= t_1^2 + t_2^2 + t_3^2 = t(t+1)$ is quantizes with
integer or half integer values, t.

The total nuclear isospin is also a vector. Measure of symmetry.
$\vec{T} = \sum \vec{t_i} = (T_1, T_2, T_3)$, $T_3 = (N - Z)/2$ and quantized
$< T^2 >= T_1^2 + T_2^2 + T_3^2 = T(T+1)$, T is interger or half integer.
Measure of symmetry. Small (large) isospin is high (low) symmetry.
The energy $E \simeq 93.6$ MeV $T(T+1)/A$ [11].

Isospin is only made complicated by the Pauli principle



The isobaric analogue state has identical quantum numbers, same isospin, total nucleon, proton and neutron differ by one

$$
\begin{aligned}
|IAS\rangle &= \sqrt{\frac{t_h}{t_h + t_c}} |t_c, t_c^{(3)} = -t_c\rangle \ |t_h, t_h^{(3)} = -t_h + 1\rangle \\
&+ \sqrt{\frac{t_c}{t_h + t_c}} |t_c, t_c^{(3)} = -t_c + 1\rangle \ |t_h, t_h^{(3)} = -t_h\rangle
\end{aligned}
$$

The isobaric anti-analogue state has identical quantum numbers, total nucleon, proton and neutron differ by one,
except one unit lower of the isospin

$$
\begin{aligned}
|AAS\rangle &= \sqrt{\frac{t_c}{t_h + t_c}} |t_c, t_c^{(3)} = -t_c\rangle \ |t_h, t_h^{(3)} = -t_h + 1\rangle \\
&- \sqrt{\frac{t_h}{t_h + t_c}} |t_c, t_c^{(3)} = -t_c + 1\rangle \ |t_h, t_h^{(3)} = -t_h\rangle
\end{aligned}
$$

$|IAS\rangle$ is populated by Fermi decay.
$|IAS\rangle$ has larger size (less binding), and Coulomb push.
The beta decay strength is spread out over more than one states.

$|AAS\rangle$ can be populated by Gamow-Teller, not by Fermi decay.
The strength is also spread out.

These states are mixed, isospin is broken.
Less mixing for stable than for halo nuclei

Application to beta-decaying $^{11}\mathrm{Li}(n+n+^{9}\mathrm{Li})$

Fermi beta-operator on upper ^{11}Li gives coherent sum of lower two.
This sum is the isobaric analogue state.
Gamow-Teller change both vectors, spin and isospin, by one unit.
For halo nuclei, valence and core are decoupled.
The beta-decay product is then sparated into two terms,
where one of the halo neutrons is changed into a proton,
while the core is unchanged, $^{11}\mathrm{Li}(n+n+^{9}\mathrm{Li}) \rightarrow ^{11}\mathrm{Be}(p+n+^{9}\mathrm{Li})$,
and one term, the halo neutrons remain and the core beta-decays,
$^{11}\mathrm{Li}(n+n+^{9}\mathrm{Li}) \rightarrow ^{11}\mathrm{Be}(n+n+^{9}\mathrm{Be})$.
These coherent terms give rise to a measured spectrum.
Breakup decay after β-decay to α's and neutrons.
Few-body technique is efficient to investigate these decays.
It is an extension from halo structure studies [10].
The isospin symmetry is mandatory to understand these decays.

Non-integer dimension, d

Take N particles, total mass M,
particle masses m_i and coordinates, r_i,
center of mass coordinate, R_{cm}
The only length coordinate is the hyperradius, ρ, defined

$$mM\rho^2 = M\sum_{i=1}^{N} m_i(\mathrm{r}_i - \mathrm{R}_{cm})^2 = \sum_{i<j} m_i m_j(\mathrm{r}_i - \mathrm{r}_j)^2 \ ,$$

All other coordinates are dimensionless angles, $\{\Omega\}$

For dimension $d = 2, 3$ the reduced (hyper) radial equation is

$$\Big(-\frac{\partial^2}{\partial\rho^2} + \frac{\ell_{d,N}(\ell_{d,N}+1)}{\rho^2} + \frac{D_\Omega^2}{\rho^2} + \frac{2m}{\hbar^2}\Big(\sum_{i<j} V_k(\mathrm{r}_{ij}) - E_{d,N}\Big)\Big) f_{d,N}(\rho) = 0 \ ,$$

where D_Ω^2 contains all angular dependence, $D_\Omega^2 = 0$ for s-waves.

The generalized angular momentum, $\ell_{d,N}$,
and the reduced hyperradial wave function, $f_{d,N}(\rho)$, are

$$\begin{aligned} \ell_{d,N} &= [(N-1)d - 3]/2 \\ f_{d,N}(\rho) &= \rho^{(\ell_{d,N}+1)} F_{d,N}(\rho) \ , \end{aligned}$$

where $F_{d,N}(\rho)$ is the total hyperradial wave function. Then

$$\begin{aligned} (N,d) &= (2,2),(2,3),(3,2),(3,3) \\ \ell_{d,N} &= -1/2, \quad 0 \quad , \quad 1/2 \ , \ 3/2 \end{aligned}$$

The dimension d is so far integer.
But analytic continuation to non-integer values is very tempting.
Previously shown that Efimov is possible for $2.3 < d < 3.8$ [12].
Calculations are then straightforward for only s-waves.
But the physics is obscure until an interpretation is available.
We force the d-method to be equivalent to a $d = 3$ formulation with an external harmonic one-body field.
External fields or constraints are used before [1, 2, 3].
We force the energy for $d = 3$ plus external field, ω_{ho},
to equal the d-result for harmonic two-body interactions, ω_{pp}:

$$\begin{aligned} d &= 2 + \sqrt{1 + \frac{\omega_{ho}^2}{\omega_{pp}^2}} - \frac{\omega_{ho}}{\omega_{pp}} \,, \\ \frac{\omega_{ho}}{\omega_{pp}} &= \frac{(3-d)(d-1)}{2(d-2)} \,. \end{aligned}$$

These expressions are simple and also independent of N.

To make it useful, the trick is to require that ω_{pp} is found by producing the same three-body root-mean-square radius as the realistic short-range interaction in dimension $d = 2$.
The wave function with external field can now be approximately reproduced by the d-method by identifying wave function from the two methods.
The wave function from the d-method

$$F_{d,N}(\rho) = N_F \exp(-0.5\rho^2/b_{int}^2) \ ,$$

equals the $d = 3$ oscillator wave function by deforming ρ:

$$\rho^2 \to \rho_\perp^2 + \rho_z^2 s^2 \ ,$$

$$s^2 = \frac{b_{int}^2}{b_{ext}^2} = \sqrt{1 + \frac{\omega_{ho}^2}{\omega_{pp}^2}},$$

$$b_{ext}^2 = \hbar/(m_i\sqrt{\omega_{ho}^2 + \omega_{pp}^2}) \ \ , \ \ b_{int}^2 = \hbar/(m_i\omega_{pp}) \ .$$

Thus, the d-method can be translated to physical $d = 3$-space. The Efimov condition can be worked out as function of d, detected by an infinitly large scattering length or for zero s-wave energy. Then when no bound two-body state exist in $d = 3$, squeezing towards $d = 2$ must at some point produce a bound state. Conclusion is that Efimov structure can be induced by squeezing with an external field, but found with the d-method.

Curvature correction

An external field constraining the particles has an effect.
to be incorporated, which is called curvature correction.
It was first formulated in 1971 by Jensen and Koppe [4].
They expressed that the Lagrange-d'Alembert principle is not valid in general, that is one cannot just assume the constraint produce no force on the constraining particles.
This can be made mathematical as suggested by Schrödinger by basically introducing corresponding generalized coordinates, and the metric tensor corresponding to the geometry.
This means to stay completely within the confined space.
But this is also in general not correct.
It is fun to read the Jensen-Koppe formulation where they refer to prominent mathematicians and physicists Lagrange, d'Alembert, Schrödinger as being incorrect in their basic assumption.

The potential, U, acting on a particle constrained to be on a surface (two dimensions) can to lowest order be expressed as

$$\frac{\hbar^2}{2m}U = -\frac{\hbar^2}{8m}\left(\frac{1}{R_1} - \frac{1}{R_2}\right)^2 ,$$

m is the particle mass, R_1 and R_2 are the curvature radii.
For a sphere, $R_1 = R_2$ and the potential is zero as expected.
All different geometries result in an attractive potential.
The potential on a particle on a curve (dimension one) is

$$\frac{\hbar^2}{2m}U = -\frac{\hbar^2}{8mR^2} ,$$

where R is the curvature radius of the curve in its own direction.
Thus, an attractive potential, constant for a circle,
but for an ellipse the attraction is largest where the
radius is smallest, or for the largest curvature.
A particle can be stuck in a bound quantum state when confined to an ellipse already by this external confining potential.

Points to emphasise

My emphasis today: The very trivial but extremely crucial.
The choice of degrees-of freedom determines the physics.
Bohr and Mottelson philosophy from my youth at NBI/Nordita
First the largest contribution, then address the smaller.
Few-body is in this way subtle, brute force may be nice
but require no thinking and little understanding.
Few-body physics techinques and concepts keep extending,
Developing with perhaps small steps towards bridging
the gap to the full many-body problem.

The work basically done by: Dennis Hove, Eduardo Garrido,
Dmitri Fedorov, Karsten Riisager, Hans Fynbo.

I am looking forward to your contributions this week.
Thank you all for your patience now, and the years before.

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