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Broad resonances in light nuclei studied with β- and γ-spectroscopy

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Abstract. Recent work on broad nuclear resonances in ^{12}C are discussed. An attempt is made to formulate pressing currently open questions, which should be adressed in future studies. A new method for identifying and studying broad resonances is presented, and first results discussed.

1 Introduction

In the past decade there has been an impressive progress in the experimental understanding of cluster resonances in ^{12}C. The lowest energy resonance is the famous 7.654 MeV 0^+ Hoyle state discovered already in the 1950s [1], see also [2] for a discussion of the background and history of this discovery. Although it was quickly suggested that this resonance could be highly deformed [3], experimental backup of this conjecture has been slow to come. For a long time it was believed [4] that a broad structure seen in the β-decay of ^{12}B [5] was the first rotational (2^+) excitation of the Hoyle state. However, in 2005 the β-decays of both ^{12}B and ^{12}N were used to show that this structure is dominated by a broad 0^+ resonance [6], see also [7] for a discussion of this and later measurements using the same approach. Backup of this conclusion has come from scattering experiments off ^{12}C using beams of both protons [8, 10] and α-particles [9]. However, these experiments also find evidence for a 2^+ resonance in the same energy region as the broad 0^+ resonance. A common analysis of the evidence for a 2^+ resonance from the proton- and α-particle scattering data is given in [11], and a discussion of the impact of these measurements is given in [12]. In the latest analysis of the β-decay data [13], there is also indications for the existence of 2^+ resonances, but the lowest one is about an MeV above the resonance found in the scattering experiments. Yet, a search for a resonance at that energy in the ^{11}B(^{3}He,d)^{12}C reaction was unsuccessful [14]. The existence of the 2^+ resonance seen in the proton- and α-particle scattering experiments recently received support from a measurement of the ^{12}C(γ,3α) reaction at the HIγS facility [15]. This experiment, importantly, in addition provides a value of 0.45(8) W.u. for the electromagnetic transition rate between the ground state and the 2^+ resonance, which can be used to test models of its structure. It would be good to see data points at higher energy from this approach to better understand if one of more resonances contribute to the data. Evidence is also emerging for the existence of a 4^+ resonance in the neighborhood of the well-known 4^+ resonance at 14.2 MeV [16] (a finding which is supported by a preliminary report [17]), and at INPC 2013 first evidence for a resonance with even higher spin was presented by the Birmingham group [18].

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Although of primary interest for nuclear structure, the elucidation of the resonance structure of ^{12}C also impacts on other fields. The implications for the nuclear synthesis of ^{12}C for various astrophysical processes is discussed in [7, 19–21], and references therein.

2 Theoretical status

It is impossible to do justice to the wast body of theoretical work on the nuclear structure of ^{12}C, and the following therefore only provides a biased selection af mainly recent works.

At INPC 2013 it was impressive to see the impact of ab-initio calculations to many regions of the nuclear physics landscape. Also for the long standing challenge of nuclear structure in general, and for ^{12}C in particular this was the case. The nuclear lattice approach finds the Hoyle state with a binding energy of 85(3) MeV [22], impressively close to the experimental value (84.51MeV). Also of significance is that the theoretical number now come with an error bar. The same approach also finds an excited 2^+ resonance 2(3) MeV above the Hoyle state [23], with a structure of a bent arm, while the bound states are predicted to have a compact triangular configuration. Those predicted structures are not directly observable, but Epelbaum *et al.* also give predictions for other observables such as electromagnetic transition rates. E.g. the above mentioned rate between the ground state and first 2^+ resonance comes out a factor 3 larger than the experimental value, but with a large error bar of 100%.

There are also recent results for ^{12}C from the quantum Monte-Carlo (VMC and GTMC) on form factors for electron scattering, which probe the ground state wave function. Here the binding energy is determined with about an order of magnitude smaller error bar [25]. It will be interesting to see the continuation of this line of work to the exited states of ^{12}C.

Since the 1970s a large number of microscopical cluster models based on more effective interactions using e.g. the resonating group (RGM) or generator coordinate (GCM) methods have been studied, see e.g. [26] for an early example. These calculations predict several still unobserved resonances of both positive and negative parity, including several 0^+ and 2^+ resonances. The related antisymmetrised molecular dynamics and fermionic molecular dynamics methods confirm these early predictions [27, 28], and therefore is seems the prediction of these states is a generic feature of the microscopical cluster models. It is a challenge to both experiment and ab-initio theory to test this prediction.

The RGM and GCM results from the 1970s have been analysed in a series of recent works where it has been demonstrated that these wavefunctions can be described by a parameterisation inspired by Bose-Einstein condensation of atoms [29]. Zinner and Jensen have recently compared and contrasted atomic nuclei with cold gases [30] including a detailed discussion of the possible meaning of the concept of nuclear bose-condensed states.

The nature and cause of nuclear clustering is discussed in [31, 32]. Using density functional theory [31] concludes that clustering is a transitional phenomenon between crystalline and quantum-liquid phases of fermionic systems, which is emphasized by the depth of the confining nuclear potential. This has traces back to the 1960s and 1970s where Morinaga's original idea for the structure of the Hoyle state was that of a linear, crystal like, chain of three α-particles [3], while the microscopic cluster model of Uegaki [26] showed that a delocalised gas-like structure is more appropriate. [32] use the Shell-model extended to the continuum to argue that clustering is intimately related to the proximity of the continuum, and that the phenomenon therefore cannot properly be understood in closed quantum system calculations.

Going one step further up the phenomenology ladder, there is also a vast number of calculations using a 3α structure of ^{12}C without including the microscopic neutron and proton degrees of freedom at all - i.e. macroscopic cluster models. Descouvemont discusses the different possibilities (shallow or deep) for the choice of the effective interaction between the α-particles [33]. The somewhat different approach of Iachello and Bijker came up in the discussions at INPC2013 several times, it uses group theoretical methods to produce a hamiltonian from Casimir operators of suitable symmetry groups of the 3α system [34]. The model predicts several unobserved resonances and also provide electromagnetic transition rates and form factors. The resonances are placed in rotational-vibrational band structures that deviate from those predicted by the microscopic cluster models [27].

3 Open questions

Following the burst of new experimental results, and considerable collection of theoretical works, it seems appropriate to pause, and formulate, which are the most pressing open questions at this moment.

Which resonances exist below, say, the proton threshold?
As discussed above, theory predicts several states some of which are not fully assigned in experiments (e.g. the 2^+ resonances), and some of which lack any experimental support (e.g. 3^+, 3^-, 5^-, 6^+). It may seem surprising that the lowest states in a nucleus like ^{12}C are not fully mapped, the reason is that the missing states are wide and therefore difficult to identify underneath other states in the same energy region in most experimental probes. There is also little consensus among the different theoretical approaches for what should be the answer to this question.

What is the relation between the resonant and non-resonant continuum in different probes?
The structures seen in the β-decays of ^{12}N and ^{12}B are featureless to the extend that one could ask if they are resonances, or, if the non-resonant continuum is populated in these decays. That there could be a significant contribution of non-resonant continuum is indicated by the analysis in [13]. This question can of course be raised for all experimental probes.

Can the pattern of population of resonances in different experimental probes be understood?
Why do the β-decay experiments and scattering experiments not find the same 2^+ resonances? The experimental population of a given resonance can be considered to be determined by a matrix element between an initial state, an operator, and the resonance. Therefore, the pattern of population can be a probe of the structure of the resonance wavefunction. As an example, the reason why the low-lying 2^+ resonance seen in scattering is not seen in β-decay could be that this resonance is highly clustered and therefore has a small overlap via the Gamow-Teller operator with the ground states of ^{12}N and ^{12}B (as e.g. suggested by [27]). However, then it is not clear why the Hoyle state nevertheless is populated in the two β-decays.

Are there collective bands, and how are they related to the intrinsic structure of the resonances?
Assuming all resonances are known, how can we interpret the spectrum in terms of collective motion, be it rotational, vibrational, or some combination as in [34]? Most often in the literature the $J(J+1)$ rule is invoked and from that a moment of inertia extracted, this obviously assumes a purely rotational collective motion. Measurement of electromagnetic transition rates between the resonances would make this assignment more robust.

Which observables can best probe the intrinsic structure of the resonances?
A considerable part of theoretical investigations of clustered nuclei concerns the nature of the clustering as also discussed above, e.g. if crystalline or gaseous analogies are most appropriate. Are there observables sensitive to the specific properties of the of nuclear Bose-Einstein condensed states [29]?

The experimental way forward must be to develop probes with high selectivity to broad, highly clustered states with selectivity for spin-parity. The success of the β-decay, scattering, and HIγS experiments discussed above comes to a large extend from the fact that they fulfill (part of) this criterium. The challenge is to extend these techniques to search for states with higher angular momentum, which seems not possible for the case of the β-decay and HIγS experiments, where the selectivity can not be adjusted to populate other resonances. As will be discussed in more detail in the following section, population by γ-decay of higher lying resonances could be a promising avenue towards discovering broad resonances with higher angular momentum.

Assuming a method for selectively populating a given resonance exists, what probes exist for its structure? In general the only observables seem to be the energy, width, spin-parity and pattern of population in different experimental probes. For ^{12}C resonances, in addition to those, one can also study the decay to the 3α final state. The latter has been suggested to provide sensitivity to e.g. Bose-Einstein correlations [35]. However, the link between decay pattern of resonance structure is far from direct, the effect of the Coulomb barrier must be understood, as e.g. explored in [36, 37]. At a minimum the 3α decay can be used to separate natural parity states (where sequential decay via the 0^+ ground state of ^{8}Be is allowed) from unnatural parity states.

The identification of bands of collective motion by measurement of radiative transitions between the band members is complicated by the fact that the band members are in the continuum. The 0^+, 2^+ and 4^+ states in ^{8}Be illustrate some of the challenges caused by this, as recently discussed in detail [38]. These calculations demonstrate interfering contributions from resonance-resonance, continuum-resonance, resonance-continuum, and continuum-continuum transitions to the observable transition rates.

On the wish list for theory stands the calculation by ab-initio, open quantum system, methods of properties of the same energy region as presently possible for the phenomenological methods [27, 34]. In addition to calculation of the spectrum, it would be desirable to use such ab-initio wavefunctions to directly calculate the observables of the experiments - i.e. not only matrix elements for given transitions, but the actual energy dependent observables for the populated final states, which would include both resonant and non-resonant contributions.

4 New Experimental Methods for broad states

Figure 1 shows the methods aimed at studying the resonances in ^{12}C discussed so far: proton- or α-particle scattering, β-decay of ^{12}N ^{12}B, and photo-dissociation (HIγS). Population via γ-decay from higher lying resonances in ^{12}C is also illustrated. The idea is that the initial state can be chosen such that the spin-parity of the state and the selection rules of γ-decay predominantly populate the state(s) of interest. We identify these γ-transitions by measuring the α-decay of the final states after the γ-decay in complete kinematics such that the final state energy can be determined from the α-particles instead of the intermediate γ-ray.

Our first use of this method focussed on the γ-decay of the 1^+ states at 12.7 MeV and 15.1 MeV populated in the reaction ^{10}B(^{3}He,p)^{12}C [39]. The latter is a member of an isospin triplet together with the ground states of ^{12}N and ^{12}B, and because the M1 operator is related to the Gamow-Teller operator this decay should populate the same states as have been observed in the β-decay experiments, see [39] for a full discussion. In a sense, this case can therefore also be seen as a proof-of-principle of the method.

The next case we have turned to is the 2^+ state at 16.11 MeV in ^{12}C which we populate in the reaction ^{11}B(p,^{12}C*). M1 decays populate 1^+, 2^+ and 3^+ states, while E1 decays populate 1^-, 2^- and 3^- states, and one would therefore expect such states to be populated. The ^{11}B(p,3γ) reaction was last

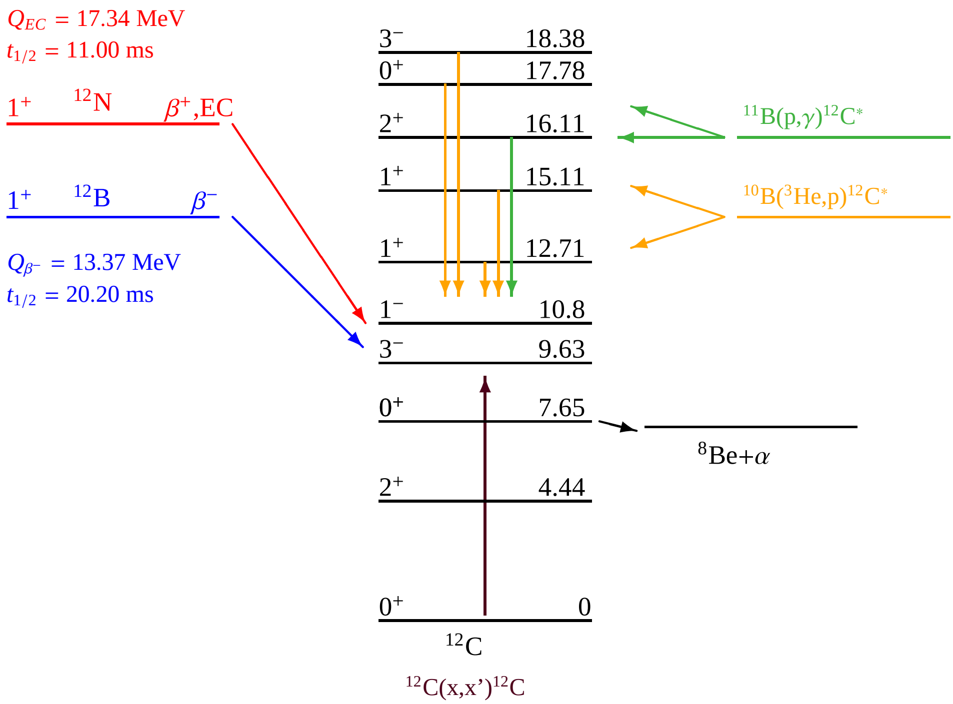

Figure 1. Schematic level scheme of ^{12}C and methods of probing the spectrum.

measured in 1977 [40] with a traditional approach with a single Ge detector. This experiment observed population of the 3^- and 1^+ resonances at 9.63 MeV and 12.7 MeV, but neither the 1^- resonance at 10.8 MeV, nor any of the 2^+ resonances discussed above, were observed.

Figure 2 shows preliminary results from the new approach based on detection of the α-decay of the final states. The direct α-decay of the 16.11 MeV state is evidenced from the intense peak at the high energy end of the spectrum. In one out of 10^5 events a γ-ray is emitted to lower lying unbound states, which is seen as events with less energy than the direct α-decay events. Population in this way of the known 3^-, and 1^+ states is evident, which confirms the results from 1977 [40]. However, now population of the 1^- state is also observed with an intensity even higher than the previously known transitions. Clearly, the reason this was missed by [40], is that states with considerable natural width (for the 1^- state $\Gamma \simeq 300$ keV), are hard to identify in spectra measured with a Ge detector.

Apart from the known states we also see evidence for broad natural parity states indicated by the circles along the diagonal in the upper part of Figure 2. Due to the selection rules of γ-decay the most likely assignment for these states is 2^+.

We plan to also try this method using the same reaction at slightly higher energy to populate the 17.88 MeV 0^+ resonance, and the 18.35 MeV 3^- resonance. The γ-decay of these state was previously studied in the traditional approach in [41], again only the relatively narrow 3^- and 1^+ resonances were identified. With our approach we hope in this way to be sensitive for broad 2^+, 2^-, 3^+, 3^-, 4^+ and 4^- states. This approach potentially could not only identify some of the missing resonances, but also

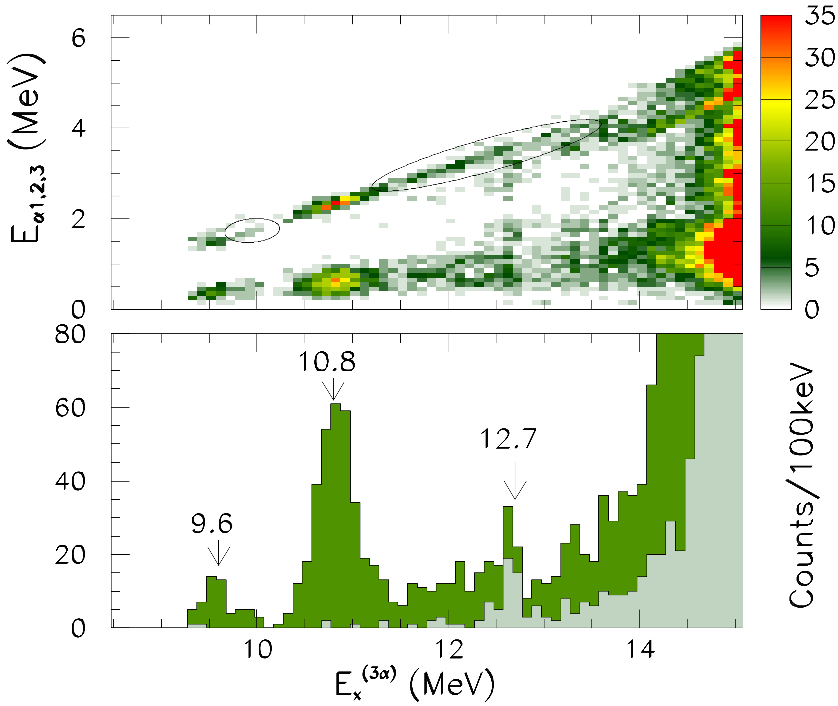

Figure 2. The lower plot shows the sum energy of three α-particles detected in coincidence from the ^{11}B(p,3α) reaction measured for the 2^+ resonance at 16.11 MeV in ^{12}C. In the upper plot is shown the distribution of the individual energies for each 3α event. The diagonal signifies sequential 3α decay via the ground state of ^{8}Be, which can only occur for natural parity states. Population of 3^- (9.63 MeV), 1^- (10.8 MeV) and 1^+ (12.7 MeV) states as well as broad natural parity states marked by circles can be seen.

give further information from the strength of the linking electromagnetic transitions and the pattern of their α-decay.

This method for identifying and studying broad resonances can of course also be used for other nuclei, e.g. for ^{8}Be and ^{16}O using various reactions to populate higher lying resonances with properly chosen properties. By using this method it may eventually be possible to also identify radiative transitions between members of potential collective bands where broad resonances may be involved. By varying the beam energy it could also be possible to study the resonant and non-resonant contributions to a given triansition.

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