

Alpha clustering in ^{18}F

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2014 J. Phys.: Conf. Ser. 569 012053

(<http://iopscience.iop.org/1742-6596/569/1/012053>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 131.169.4.70

This content was downloaded on 14/01/2016 at 09:25

Please note that [terms and conditions apply](#).

Alpha clustering in ^{18}F

S Bailey¹, M Freer¹, Tz Kokalova¹, S Cruz^{1,2}, H Floyd¹ and D J Parker¹

¹ University of Birmingham, Birmingham, B15 2TT, UK

E-mail: s.c.bailey@pgr.bham.ac.uk

Abstract. We review some of the key experimental and theoretical studies of α -clustering in ^{18}F . Particular attention is given to the $4p$ - $2h$ nature of such α -clustered states, and the interaction between the holes and clusters is examined in terms of both weak and strong-coupling regimes. The experimental work focuses on α -transfer spectroscopy and α resonant scattering as tools for investigating α -clustering.

1. Introduction

Alpha clustering is a well established concept in the structure of light α -conjugate nuclei [1]. Further to this, it has been shown that neutron-rich nuclei exhibit similar cluster structures with the additional neutrons playing the role of valence particles, contributing to the binding of the clusters in a way that resembles electrons in atomic molecules [2]. This has been investigated in detail recently both from theoretical and experimental perspectives, finding a lot of success in the $\alpha + xn + \alpha$ structures in Be isotopes [3, 4] and the $\alpha + xn + ^{16}\text{O}$ structures in Ne isotopes [5, 6, 7]. There has been comparatively little work done, however, to investigate the persistence of cluster structure in isotopes which deviate from α -conjugate nuclei in ways other than the addition of valence neutrons.

^{18}F is of interest from a clustering perspective because of the predicted $\alpha + ^{14}\text{N}$ structure, and how this compares with the $\alpha + ^{16}\text{O}$ structure observed in ^{20}Ne [7]. It is thought that the cluster structure is amplified in ^{20}Ne by the large shell gap above the p shell, which provides a clear separation between the ^{16}O core and the α -cluster. The $\alpha + ^{14}\text{N}$ structure is therefore expected to manifest itself in $4p$ - $2h$ excitations of ^{18}F [8], displayed in Fig. 1. This produces a shell structure very similar to that of ^{20}Ne , again with a clear shell gap separating the α -cluster from the core, and deviating from ^{20}Ne only by the addition of one proton hole and one neutron hole in the p shell. It is the interplay between these proton and neutron holes and the cluster-core structure that motivates the present work on ^{18}F .

2. Hole-particle coupling

The regime which governs the coupling between the p shell holes and the s - d shell particles in $4p$ - $2h$ states is extremely important for understanding the structure of ^{18}F . This coupling can either be described as weak-coupling or strong-coupling. In the weak-coupling picture, the particle wavefunctions are assumed to be similar to the eigenfunctions of ^{20}Ne , and the

² Present Address: Department of Physics and Astronomy, The University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada



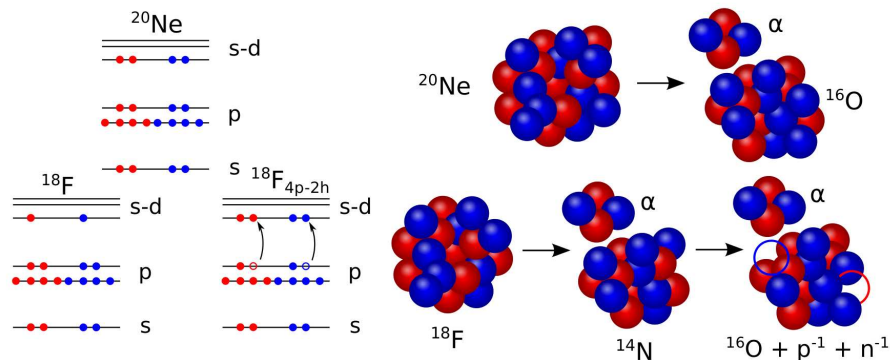


Figure 1. (Colour online) ^{18}F and ^{20}Ne from shell model (left) and cluster model (right) perspectives.

hole wavefunctions like that of the ^{14}N ground state [8, 9, 10]. This is interpreted as weak coupling since the interaction is expected to be well described as a small perturbation on these wavefunctions, leading to a structure very similar in nature to ^{20}Ne with some additional core excitations.

The strong-coupling model takes the opposite approach, asserting that the interaction between the holes and particles is too strong for the wavefunctions to be approximated in such a way. Instead more robust techniques are required, leading to more varied and exotic deformations and structures.

One of the earliest experimental investigations of hole-particle states in ^{18}F was performed in 1968 by Middleton *et al.* [8] using the $^{14}\text{N}(^7\text{Li},t)^{18}\text{F}$ α -transfer reaction. It is expected that α -transfer reactions preferentially excite states formed by transferring all four nucleons into the same shell, leading to an amplified cross-section for $4p-2h$ states. In this work it was argued that this allowed the $4p-2h$ excitations to be identified by selecting states which were strongly populated by this reaction but weakly populated by one or two nucleon transfer reactions. However this may be an overly simplistic interpretation since it ignores the effects that the matching conditions have on the cross-section [11]. Additionally the nonzero spins of the nuclei involved in this reaction often lead to ambiguous angular distributions, making experimental J^π assignments very difficult [12].

Middleton *et al.* [8] reported six states to be likely $4p-2h$ candidates at 1.70, 2.52, 3.36, 4.23, 5.30 and 6.55 MeV using this technique. They go on to argue that these states can be well described by the weak-coupling model, coupling the ^{20}Ne ground state band to the $(1p_{1/2})_{1+}^{-2}$ hole configuration. The application of this model led to the following spin-parity assignments for the observed $4p-2h$ states, respectively: $J^\pi = 1^+, 2^+, 3^+, 1^+, 3^+$ and $(4^+, 5^+)$.

This weak-coupling description of the $4p-2h$ states was challenged following an extensive study of the structure of ^{18}F in 1973 by Rolfs *et al.* [13]. In this work the hole-particle states were investigated in detail using the $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}$, $^{17}\text{O}(p,\gamma)^{18}\text{F}$ and $^{16}\text{O}(^3\text{He},p\gamma)^{18}\text{F}$ reactions [13, Part III]. Following these measurements 5 states were identified as being members of a $K^\pi = 1^+$ rotational band of predominantly $4p-2h$ nature, at 1.701, 2.523, 3.358, 5.298 and 6.567 MeV. Spin-parity assignments were made based on measured branching ratios and angular distributions to be respectively $J^\pi = 1^+, 2^+, 3^+, 4^+$ and 5^+ . The reduced α -widths were extracted for the 4^+ and 5^+ members, and in both cases were found to be exceptionally large.

It is clear that these states are the same states as those measured by Middleton *et al.* [8], with the exception that the 4.23 MeV state was found by Rolfs *et al.* to be unlikely to be $4p-2h$ in nature, and was instead assigned to be a $J^\pi = 2^{(-)}$ state of $3p-1h$ structure [13, Part IV]. Additionally the spin-parity assignment for the 5.298 MeV state disagrees with the assignment

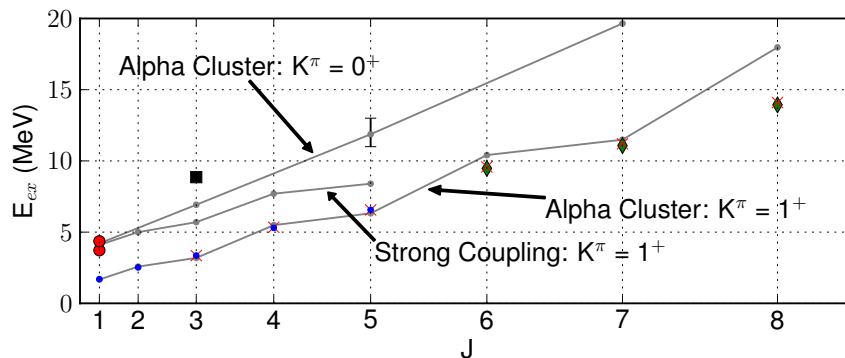


Figure 2. (Colour online) ^{18}F rotational bands, x-axis scaled as $J(J + 1)$. Theoretical calculations displayed as lines (annotated), data displayed as points. Data from Rolfs *et al.* [13, Part III] (blue dots), Cobern *et al.* [12] (green diamonds), Etchegoyen *et al.* [15] (red crosses), Bailey *et al.* [16] (black squares/bars) and the Buck *et al.* mixed states assignment, see text [17] (red circles)

made based on the weak-coupling model by Middleton *et al.* [8]. These considerations led Rolfs *et al.* to reject the weak-coupling model in favour of the strong-coupling model.

A comparison was made between this band and a strong-coupling calculation performed in 1965 by Bassichis *et al.* [14], which predicted a $K^\pi = 1^+$, $4p-2h$ rotational band in ^{18}F . The gradient of the predicted band was found to be in excellent agreement with the measurements and it reproduced the observed zig-zagging in excitation energy, however the predicted band was shifted ≈ 2.5 MeV higher in energy. Rolfs *et al.* [13, Part III] speculated that based on the exceptionally large reduced α -widths observed for the 4^+ and 5^+ members, α -particle clustering may in fact play a prominent role in the structure of this band, and perhaps the explicit inclusion of α -clustering in the microscopic description of the band may reconcile this energy shift.

Based on these results it seems likely that the strong-coupling regime better describes the hole-particle coupling in ^{18}F , since the work by Rolfs *et al.* [13, Part III] is more extensive, allowing the spin-parity assignments to be made based on experimental measurements. Further to this, more α -transfer measurements have been made by Cobern *et al.* [12] and Etchegoyen *et al.* [15], extending the $K^\pi = 1^+$ rotational band observed by Rolfs *et al.* [13, Part III] from $J^\pi = 5^+$ up to 8^+ . This rotational band is displayed in Fig. 2, with the band calculated using the strong-coupling model by Bassichis *et al.* [14] for comparison.

3. Alpha clustering

Based on the work by Rolfs *et al.* [13, Part III] it seems likely that there is a large α -cluster component to the structure of the $K^\pi = 1^+$ rotational band. A semi-microscopic calculation of α -cluster states in ^{18}F was performed in 1979 by Buck *et al.* [17]. In this work all four nucleons from which the α -particle is built up are placed in the $s-d$ shell, enforcing the experimentally determined $4p-2h$ structure discussed previously. This leads to the ^{14}N core wavefunction being given by two p shell holes in the ^{16}O closed shell. Further details regarding this model can be found in Ref. [17].

This model produced two distinct rotational bands, one with $K^\pi = 1^+$ and one with $K^\pi = 0^+$. The states in the $K^\pi = 1^+$ band agreed exceptionally well with the experimentally determined states up to $J^\pi = 5^+$, however above this they began to diverge, with the calculated levels shifted higher in energy compared with the experimentally observed levels. This can be seen in Fig. 2. It was however explained by Buck *et al.* that this may be due to the way the nuclear

potential was modelled, since similar discrepancies have arisen in other calculations involving the same potential [17].

The extremely good agreement between observed and calculated levels in the $K^\pi = 1^+$ band leads us to believe that this is indeed an α -clustered $4p$ - $2h$ rotational band. However if this model is correct, it should also be possible to identify the $K^\pi = 0^+$ rotational band. Buck *et al.* [17] assigned the 1^+ state in this band to two experimentally observed 1^+ states at 3.724 and 4.361 MeV. It is argued that this is due to mixing between this state and a $2p$ shell model state predicted to exist at a similar energy, causing the $4p$ - $2h$ strength to be shared between both states. This hypothesis is confirmed to an extent experimentally by the slightly reduced cross-section for these states in α -transfer measurements [8]. However Buck *et al.* were unable to confidently assign any of the other members of this band.

4. $^{14}\text{N} + \alpha$ resonant reaction

More recently a study of ^{18}F was performed in 2014 by Bailey *et al.* [16] using the $\alpha + ^{14}\text{N}$ resonant reaction to populate α -clustered states in the compound nucleus ^{18}F . The reduced widths of these states were then extracted by performing an R-Matrix fit simultaneously of these data and data from other sources covering the $d + ^{16}\text{O}$ and $p + ^{17}\text{O}$ channels [18, 19]. Bailey *et al.* [16] proceeded to assign the 3^+ state in the $K^\pi = 0^+$ band to a state at $E_{\text{ex}} = 8.858$ MeV, and also provided tentative evidence for the existence of the broad 5^+ state in the region between 11 and 13 MeV. The 3^+ assignment was made due its unusually large α -reduced width, however the state was predicted at 6.92 MeV, almost 2 MeV lower than observed. These assignments are compared with the calculated $K^\pi = 0^+$ band in Fig. 2.

5. Conclusion

It is clear that α -clustering plays a significant role in the structure of ^{18}F , with perhaps the strongest evidence coming from the excellent agreement between the $K^\pi = 1^+$ rotational band calculated using a semi-microscopic α -cluster model [17] and experimental observations made using α -transfer reactions [13, 12, 15]. However the $K^\pi = 0^+$ rotational band is still not fully understood, and there has yet to be any work done to investigate negative-parity α -clustered rotational bands.

References

- [1] Freer M and Merchant A C 1997 *J. Phys. G: Nucl. Part. Phys.* **23** 261–322
- [2] von Oertzen W, Freer M and Kanada-En'yo Y 2006 *Physics Reports* **432** 43 – 113
- [3] Hiura J and Tamagaki R 1972 *Progress of Theoretical Physics Supplement* **52** 25–88
- [4] Itagaki N and Okabe S 2000 *Phys. Rev. C* **61**(4) 044306
- [5] von Oertzen W 2001 *Eur. Phys. J. A* **11** 403–411 ISSN 1434-6001
- [6] Rogachev G V, Goldberg V Z, Lönnroth T, Trzaska W H, Fayans S A, Källman K M, Kolata J J, Mutterer M, Rozhkov M V and Skorodumov B B 2001 *Phys. Rev. C* **64**(5) 051302
- [7] Richards H T 1984 *Phys. Rev. C* **29**(1) 276–283
- [8] Middleton R, Polsky L M, Holbrow C H and Bethge K 1968 *Phys. Rev. Lett.* **21**(19) 1398–1401
- [9] Arima A, Horiuchi H and Sebe T 1967 *Physics Letters B* **24** 129 – 131 ISSN 0370-2693
- [10] Benson H and Flowers B 1969 *Nuclear Physics A* **126** 332 – 354 ISSN 0375-9474
- [11] Brink D 1972 *Physics Letters B* **40** 37 – 40 ISSN 0370-2693
- [12] Cobern M E and Parker P D 1977 *Phys. Rev. C* **15**(5) 1929–1932
- [13] Rolf C, Berka I, Trautvetter H, Azuma R, Kieser W, Litherland A and Charlesworth A 1973 *Nuclear Physics A* **199** 257 – 350 ISSN 0375-9474
- [14] Bassichis W H, Giraud B and Ripka G 1965 *Phys. Rev. Lett.* **15**(25) 980–982
- [15] Etchegoyen M, Sinclair D, Etchegoyen A and Moreno E 1983 *Nuclear Physics A* **402** 87 – 113 ISSN 0375-9474
- [16] Bailey S, Freer M, Kokalova T, Cruz S, Floyd H and Parker D J 2014 *Phys. Rev. C* **90**(2) 024302
- [17] Buck B, Merchant A and Rowley N 1979 *Nuclear Physics A* **327** 29 – 52 ISSN 0375-9474
- [18] Terwagne G, Genard G, Yedji M and Ross G G 2008 *J Appl. Phys.* **104** 084909
- [19] Seiler R F, Jones C H, Anzick W J, Herring D F and Jones K W 1963 *Nucl. Phys.* **45** 647–656