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The experimental study of exotic nuclear states using multi-detector arrays

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Abstract. This contribution outlines the work of the CHARISSA collaboration in the investigation of exotic states in nuclei. It outlines the background to the work, the techniques involved and discusses in detail an experiment to study the cluster stucture of ^{12}Be .

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1. Introduction

Break-up reactions provide a powerful tool for the investigation of exotic structures in nuclei. The measurements require a wide angular coverage and accurate determination of the energy and emission angle of the break-up fragments. Therefore large flexible multi-telescope detector arrays are required for this work.

The work to be discussed in this contribution is that of the CHARISSA collaboration. The collaboration has staff, students and technical support from several UK institutions, namely the Universities of Birmingham, Oxford, Staffordshire, Surrey and York and has engineering and computing support from the CLRC Daresbury Laboratory. The CHARRISA group has for many years been using multi-detector arrays to look at exotic states in nuclei, in particular their cluster properties and associated reaction mechanisms. This work has been carried out at several accelerators but mainly using the 14UD facility at ANU Canberra and the Vivitron at Strasbourg for stable beams and GANIL, France for radioactive beams.

The physics programme of the CHARISSA collaboration covers three main areas:

1. Nuclear reaction studies mainly of weakly bound systems and systems where at least one of the participants is strongly deformed.
2. The study of the spectroscopy of exotic nuclei using break-up reactions. This includes such topics as large-scale clustering, resonance phenomena in the ^{12}C + ^{12}C and ^{12}C + ^{16}O systems, multiple alpha particle structures and nuclear molecular analogue states.
3. The development of detector and electronic systems to carry out this programme.

The experimental aspects of the programme are inter-linked with the reaction studies providing the necessary understanding to enable the nuclear structure information to be extracted from the spectroscopy studies.

In this contribution I will concentrate on the second topic, in particular chain states and nuclear molecular analogue states. The detector systems required will be briefly described along with the experimental techniques involved.

To set our work in context I will start with a brief history of the phenomena associated with clustering.

The stability of the alpha cluster has had a strong influence on the structure of light nuclei and a whole range of experimental and theoretical tools have been developed to help understand the role of clustering in these nuclei.

In the 1950s one of the first nuclear states with a cluster structure was put forward by Hoyle [1]. In order to explain helium burning and the formation of ^{12}C in stars he suggested that there must exist an excited state in ^{12}C that had a 3-α-particle structure. This was later shown to be the 0_2^+ state at 7.65 MeV excitation.

The introduction of heavy ion beams in the 1960s saw a large amount of work on the heavy ion resonances in systems such as ^{12}C + ^{12}C [2]. This lead to the introduction of the ideas of nuclear molecules and states formed by the orbiting of two heavy clusters.

One of the first classifications of clustering in light $A = 4n$ alpha conjugate nuclei was put forward by Ikeda [3] in the early 1970s. In this system cluster structures appear at or close to the decay threshold of the particular cluster partition. It is based on the premise that to create internal cluster structures energy equivalent to the binding energy of the constituents is required. On the whole the scheme has been verified by experimental observations. One of the most interesting structures predicted, by the Ikeda scheme, were the linear alpha particle chain states.

The 1980s saw a movement away from this type of phenomenological classification to detailed calculations. Figure 1 shows the result of two such calculations for ^{24}Mg . One based on the block-brink alpha cluster model [4] and the other a Nilsson–Strutinsky potential energy surface calculation [5]. The links between similar structures seen in the two calculations are shown in the figure. One of the structures apparent in these calculations as in the Ikeda classification is the linear-chain state of 6-α particles.

In the 1990s a lot of effort was put into the hunt for this chain state. Wuosmaa *et al* [6] claimed to have found the state in the form of a resonance in the ^{12}C + ^{12}C $\rightarrow$ ^{12}C (0_2^+) + ^{12}C (0_2^+) reaction at approximately the correct excitation energy and with the correct width. However, work reported by Chappell *et al* [7] on the ^{12}C (3^-) + ^{12}C (3^-) exit channel showed that this exit channel also showed a resonance at the same energy. This clearly could not be associated with the ^{12}C chain state. Subsequent work [8] reinforced the conclusion that the resonance observed by Wuosmaa *et al* [6] is not due to the 6-α particle chain state in ^{24}Mg . This does not mean that chain states in general do not exist. The ^{12}C chain is well-known and there are possible candidates for the chain state in ^{16}O .

In the late 1990s the availability of radioactive beams has lead to the possibility of two other possible cluster manifestation:

1. The HALO nuclei which are composed of a core and a neutron or neutrons decoupled from the core. Based on the Ikeda's ideas weakly bound systems such as ^{11}Be ($S_n = 0.5$ MeV) and ^{11}Li ($S_{2n} = 0.3$ MeV) should show cluster structures. This clustering could be amplified by the reduced centrifugal barrier for the weakly bound valence neutrons allowing a greater decoupling of the core and the so-called halo neutrons.

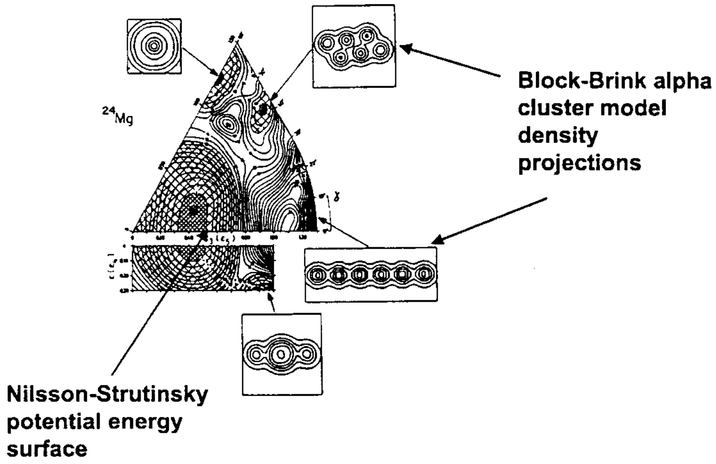

Figure 1. Sample model calculations for ^{24}Mg .

2. Molecular type cluster states composed of α-particles covalently bound by valence neutrons much as the binding of atomic molecules is through the exchange of electrons.

Much effort in the last couple of years has been concentrated on experiments designed to investigate this second phenomena.

2. Molecular analogue states

This concept is probably best illustrated by a comparison of the ^{9}Be nucleus with H_2^+ molecule. ^{8}Be is not stable but the addition of another neutron produces enough binding energy to make the ^{9}Be nucleus stable. However, because ^{8}Be has a dominant structure of two alpha-particle clusters, the potential in which the additional neutron moves must reflect this structure. So the orbits of the neutron are not those expected of the shell model but of a particle moving in a two-centre potential well. This is entirely analogous with the binding of the H_2^+ molecule by an electron orbiting in the two centre potential formed by the two protons. An examination of the low-lying levels of ^{9}Be shows two rotational bands based on the $3/2^-$ ground state and a $1/2^+$ excited state. These bands have moments of inertia consistent with the extended two centre shape and in atomic terms would be due to the π and σ molecular bonds. These ideas form the concept of nuclear molecular analogue states which have provided the foundation for the work of von Oertzen [9–11]. He extended the above idea to systems that included much larger numbers of neutrons or protons e.g. ^{10}Be and ^{11}Be . In ^{10}Be the ground states do not appear to have the requisite deformation to indicate molecular behaviour. However a group of states at around 6 MeV with $J^{\pi} = (0^+$, 1^-, 3^-, $2^+)$ appear to possess a deformation that is consistent with an underlying $\alpha + \alpha$ cluster structure and can be described in terms of combinations of molecular orbits arising from the $1p_{3/2}$ and $1d_{5/2}$ shell model orbits. In ^{11}Be the molecular type structures return to one based on the ground state configuration and one based on a $3/2^-$ configuration

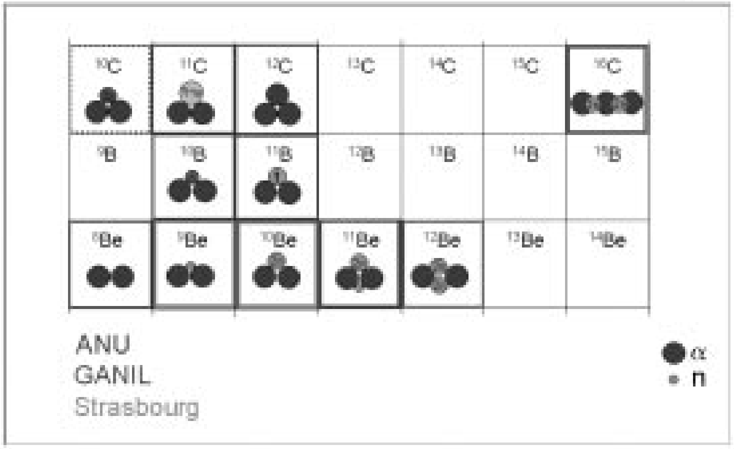

Figure 2. Possible molecular analogue nuclei being studied by the CHARISSA collaboration.

at about 3.9 MeV. Recently the Kyoto group have looked at this type of nucleus using antisymmeterized molecular dynamics (AMD) calculations [12]. One of the merits of the AMD approach is that it does not rely on model assumptions such as axial symmetry or the prior existence of clusters. Each nucleon is centred on a geometric point and no restriction is placed on the geometry of the system. The output of this type of calculation is a series of density distributions of the total matter, the protons and the neutrons of the intrinsic states. In ^{11}Be for example the density of the protons indicate that the clustering develops more in the 1^-, 2_1^+ states but most markedly in the 0_2^+. Based on the experimental systematics and the AMD calculations it is possible to identify candidates for molecular analogue states in a range of nuclei. Figure 2 indicates some of those at present under investigation by the CHARISSA collaboration.

3. Experimental technique

Break-up reactions and invariant mass spectroscopy (IMS) provide effective experimental tools for the study of exotic cluster states that are particle unstable. With break-up reactions the nucleus under investigation in produced in the required state by some interaction and if it is above the particle decay threshold it will decay or break-up and the products can be measured. Usually the experiments are carried out in inverse kinematics and for many of the measurements the nucleus of interest is the projectile.

By measuring the emission angles and energies of all the break-up products of the nucleus after it decays the invariant mass (or excitation energy) of the parent nucleus can be reconstructed.

This is a technique the CHARISSA collaboration have used with considerable success to study cluster states in stable nuclei. There are a number of advantages of this technique including the ability to determine the spin of states at high excitation. The technique is also well suited for studies with radioactive beams especially those produced by fragmentation. Typically nuclear spectroscopy techniques are limited by beam and detector resolution. In the case of radioactive beams produced by fragmentation the energy and angular resolutions are generally poor and this can be the determining factor in most spectroscopy measurements performed using RNB facilities. However, the IMS technique has the key advantage that the effect of beam resolution cancels to second order enabling high-resolution spectroscopy measurements to be made. In order to carry out these break-up reaction measurements the CHARISSA collaboration has developed a flexible detector system. The main system is installed at the 14UD facility at ANU and subsets of the detector arrays have been used in Vivitron and GANIL. The MEGHA detector array and its associated electronics are fully described in references [13] and [14]

4. Nuclear molecular analogue states in ^{12}Be

The investigation of the ^{6}He + ^{6}He structure of the states in ^{12}Be provides an excellent example of the use of the IMS technique and the remainder of this contribution will be devoted to a discussion of an experiment to investigate this. A secondary beam of ^{12}Be, from the GANIL accelerators, with an energy of 378 MeV, an energy spread of 18 MeV and an intensity of 2×10^4 particles per second was produced by fragmentation. The beam was purified to 95% in ^{12}Be using the LISE spectrometer. The beam was incident on either a 10 mg cm^{-2} ^{12}C or a 20 mg cm^{-2} $(CH_2)_n$ target. The break-up products from the (^{12}Be, ^{6}He ^{6}He) reaction on the protons and ^{12}C targets were detected in an array of ten Si–CsI telescopes based on those used in the MEGHA array [13]. This array was arranged in a symmetric fashion around the beam axis. Particle identification was carried out in the conventional way using the Si detector to provide a ΔE signal and the CsI scintillator to provide an E signal.

From the measurements of the mass, energy and emission angle of the fragments the energy of the undetected recoil was calculated from momentum conservation, and the reaction Q-value obtained. The Q-value spectrum showed a peak around $Q = -10$ MeV corresponding to particles from the ^{12}C(^{12}Be , ^{6}He ^{6}He)^{12}C reaction that had been correctly identified. The events in this peak were used to construct the ^{12}Be excitation energy spectrum. A similar excitation energy spectrum was also constructed for the p(^{12}Be , ^{6}He ^{6}He)p reaction. The results from both reactions were combined to produce the excitation energy spectrum shown in figure 3.

Several peaks due to excited states in ^{12}Be can be seen in figure 3 and the excitation energies obtained are given in table 1.

To help determine the spins of the break-up states it is necessary to parameterize the yield in terms of two angles. The centre of mass angle of the break-up particle θ^* and ψ the emission angle of the break-up products (^{6}He) in the centre of mass frame of the break-up nucleus. The angular correlation in the θ^* vs ψ plane shows ridges characterized by the function $|P_j(\cos[\psi - \alpha\theta^*])|^2$. The phase-shift α is the ratio (l_f/J) (where l_f is the final state grazing angular momentum.) Thus the gradient of the ridges in the angular correlation and an estimate of the final state grazing angular momentum, obtained for example from a coupled channel calculation, allow the spin of the break-up states to be deduced. Symmetry arguments ensure that only even parity states can be excited. The J values deduced in the present work are given in table 1.

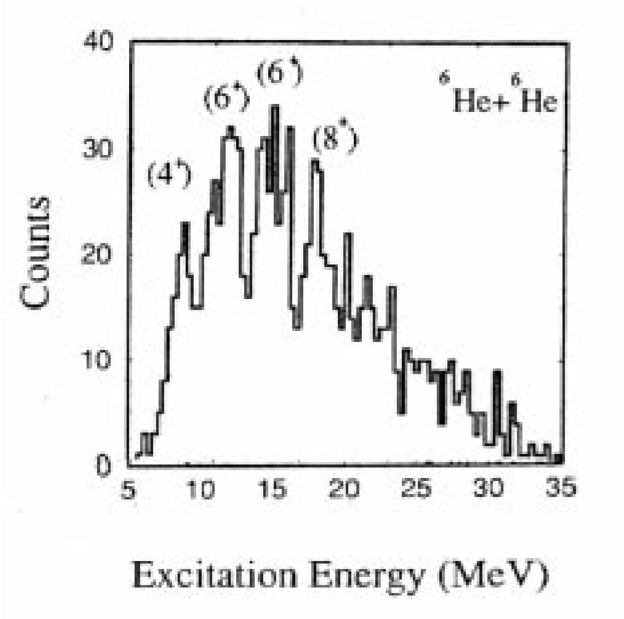

Figure 3. The combined ^{12}Be excitation energy spectrum for ^{6}He + ^{6}He decays from the proton and carbon targets.

Table 1. Excitation energies and deduced spins for the $^{12}\mathrm{Be} \rightarrow {}^6\mathrm{He} + {}^6\mathrm{He}$ break-up. The quantities in brackets indicate tentative values.

E_x (MeV)	13.2	14.9	16.1	$\underbrace{17.8\ 18.6\ 19.3}$	20.9	22.8	(24.0)	(25.1)
J	4		6	6	8			

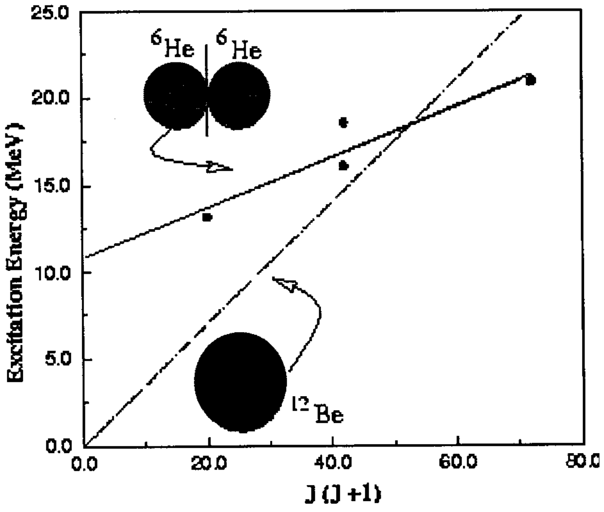

Figure 4. Energy vs spin systematics.

Figure 4 shows the energy-spin systematics for the break-up states. The line is a linear fit to the four points and the gradient gives a value of $(\hbar^2/2\mathcal{I}) = 0.15 \pm 0.04$ MeV and an intercept of 410.8 ± 1.8 MeV. This can be compared with calculations for a spherical ^{12}Be and two touching ^{6}He nuclei which give values of 360 and 165 keV respectively. The first 2^+ state of ^{12}Be is at 2.1 Mev and if this is a rotational state this would imply a $(\hbar^2/2\mathcal{I}) = 360$ keV. This suggests that the ground state of ^{12}Be has only a small deformation in agreement with the AMD calculation as [12,15]. Whereas the gradient obtained from the present data is consistent with a deformed ^{6}He $+$ ^{6}He molecule. The ideas of Ikeda [3] would indicate that such cluster structures should be expected to appear close to the break-up threshold of 10 MeV, in agreement with the observed intercept.

These measurements provide evidence for a deformed ^{6}He $+$ ^{6}He cluster structure in ^{12}Be which may be linked to a α-4n-α molecule. Confirmation of these speculations requires further measurement including the measurements of the partial widths of possible decay channels.

The full details of these measurements have recently been published [16].

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