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Search for Molecular States in ^{14}C

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Abstract

It is proposed to study the reaction ^{9}Be(^{9}Be,^{14}C[^{4}He,^{4}He,^{6}He])^{4}He to search for states in ^{14}C with excitation energies larger than 18 MeV and a molecular α+α+α+2n structure. The measurement will be performed at E_{beam} = 56, 63 and 70 MeV, using an array of 4 segmented Si telescopes to observe the charged reaction products.

1 Introduction

Clustering is well known to play an important role in the structure of light nuclei [1, 2]. For example, the properties of the nucleus ^{8}Be (large ground state deformation and α-particle decay width) are extremely well described in the context of an α-α cluster structure. This structure has an important impact upon subsequent neutrons or protons added to the ^{8}Be core, such as ^{9}Be and ^{9}B. In the case of ^{9}Be, the additional neutron can be viewed as providing the energy required to bind the α+α system (the ^{8}Be ground state is unbound to α-decay), much as the valence electron in the covalent binding of the H_2^+-molecule. In addition, in ^{9}Be the two-centre orbit in which the valence neutron resides closely resemble those in the atomic molecules [3]. These observations promote the concept of "covalent molecular binding" on the nuclear scale.

These ideas have been extended to the heavier two-centre α-α systems defined by more than one neutron or proton added to the ^{8}Be core [3, 4]. For example in ^{10}Be and ^{10}B there are series of states at excitation energies (E_x) around 6 MeV, close to the 2α+2n and 2α+d thresholds, which can be associated to rotational bands build on configurations of nucleons in two-centre orbits. An experimental signature of such high spin deformed configurations would be the observation of extensive rotational bands with very large moment of inertia. Indeed, a recent study of ^{12}Be [5] has revealed a spectrum of states in E_x = 10–25 MeV that decay into two ^{6}He nuclei. The correlation between the spin attributed to these states and their energy (see Fig. 1) suggests that the states are linked with a rotational band with moment of inertia consistent with two touching ^{6}He nuclei rather than the more compact structure predicted for the ^{12}Be ground state. However, an unambiguous identification of rotational bands should be provided by a sequence of γ

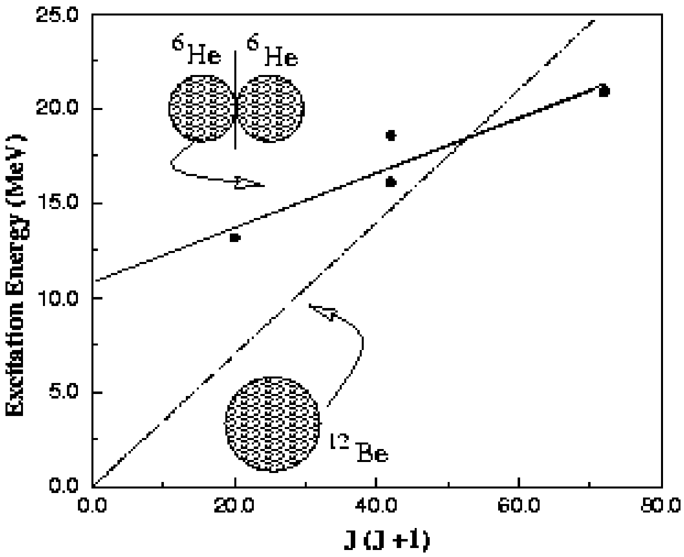

Figure 1: *Energy-spin systematics of the ^{6}He+^{6}He breakup states in ^{12}Be (from [5]).*

transitions, a signature experimentally difficult to measure since the states of interest are located above a light particle emission threshold.

Some further support for the existence of molecular states is provided by the antisymmeterized molecular dynamics (AMD) model (see [6] and references therein). Such calculations predict for example that clustering in ^{10}Be develops in the rotational bands based on the 0_2^+ and 1^- excited levels ($E_x \simeq 6$ MeV) with the valence neutrons in orbits analogous to molecular orbits. These predictions are consistent with the improved AMD calculations presented in Ref. [7].

The ^{12}C 0_2^+ (7.65 MeV) excited state, well known for its importance in the stellar burning process to bridge the gap from ^{4}He to ^{12}C, has been associated to a cluster made of a chain of three α-particles [8]. This state provides the fondation for building molecular states in a three-centred potential for more neutron rich carbon isotopes [4]. We plan to extend the systematics to include the nucleus ^{14}C. Similar studies have already been undertaken by our collaboration for the nuclei ^{11}C [9], ^{16}C and ^{18}C [10], under analysis, and a proposal has been accepted by the VIVITRON PAC concerning ^{12}C [11]

Following the arguments developed in Ref. [4], such a molecule in ^{14}C should appear close to the ^{12}C*[7.65 MeV]+2n decay threshold, which is located at 20.8 MeV. Similarly the threshold for configurations corresponding to the "unbound chain" ^{10}Be*[6 MeV]+α is at 18.0 MeV. We can then expect resonances in the ^{10}Be*[6 MeV]+α channel just above 18 MeV. A clearer signature for the formation of molecular states in ^{14}C would be the decay into daughter states that themselves show strong clustering. Above E_x=18 MeV, such decay channels would be ^{14}C$\rightarrow^{10}$Be*[$E_x \geq 7.4$ MeV]+^{4}He followed by ^{10}Be* $\rightarrow^6$He+^{4}He, or ^{14}C$\rightarrow^8$Be+^{6}He followed by ^{8}Be$\rightarrow^4$He+^{4}He, Q = -19.4 MeV. The latter, since it gives zero-spin particles in the exit channel, can be used to reconstruct the spin of the populated states using the angular correlation analysis technique presented in Ref. [12]. This would allow us the determination of the excitation energy – spin systematics which might give strong indication of 3α chain states in ^{14}C (see Ref. [5] for a similar result in ^{12}Be). Furthermore, for given states in ^{14}C, the relative comparison between the yields in the decay channels ^{10}Be*[^{6}He,^{4}He]+^{4}He and ^{10}Be$_{g.s.}$+^{4}He may provide an indication of the onset of 3α-chain clustering in ^{14}C and also some signature of strong structural change in either ^{14}C* or ^{10}Be* involving γ-transitions. Finally, the level scheme of ^{14}C is not well known above E_x=18 MeV [13], and these data should give at the very least some new information in this region.

2 Experimental details

We propose to use the reaction ^{9}Be(^{9}Be,^{14}C)^{4}He (Q=+17.3 MeV), to populate states in ^{14}C in excess of the ^{4}He+^{4}He+^{6}He decay threshold, at 19.4 MeV. The choice of this reaction is based on the fact that it benefits of a large positive Q-value and of the well-developed α+n+α cluster structure of the ^{9}Be ground state. Since the population of molecular states may be strongly dependent on the centre of mass energy (this reaction would be studied for the first time), we intend to use 3 different incident beam energies E_{beam} = 56, 63 and 70 MeV. As shown in earlier works [14, 15], such a ^{5}He-transfer reaction can have a cross-section in the range 0.1–1 mb per state. The population of the states in ^{14}C is to be observed via their decay into the proposed cluster components.

It is proposed to detect the decay products from the breakup of ^{14}C in an array of 4 charged particle telescopes composed of 2 elements: a thin (70 μm) Si quadrant detector followed by a 500 μm Si (16) strip detector. Each detector has an active area of 5×5 cm^{2} and they will be arranged around the beam axis in the MEGHA scattering chamber as shown on Fig. 2. The distance between the centre of each detector and the target will be 15 cm, which allows an angular coverage of $\simeq$ 6–25^{o}.

On Fig. 3a the energy – polar angle correlation for the ^{14}C nucleus is presented for the studied excitation energy range (E_x = 18–30 MeV) and for E_{beam} = 70 MeV. We see that the detection arrangement will allow a good angular coverage over all the excitation energy range. The ^{14}C kinetic energy will vary between 30 and 64 MeV, which allows most of the breakup products to pass through the first 70 μm Si detector and to be stopped in the 500 μm Si strip detector (the low ^{14}C kinetic energy part of the correlation will lead to breakup products not enough energetic to be detected). On Fig. 3b is shown the efficiency curve for the coincident detection of the three breakup products of ^{14}C, calculated for the proposed geometry and for E_{beam} = 70 MeV. The efficiency is on average ε = 8% for the channel ^{9}Be(^{9}Be,^{8}Be$_{g.s.}$[^{4}He,^{4}He],^{6}He)^{4}He and 3% for ^{9}Be(^{9}Be,^{10}Be(7.54 MeV)[^{6}He,^{4}He],^{4}He)^{4}He. The results of the calculations show that the efficiency is decreasing rapidly as E_{beam} is decreasing. For the lowest beam energy (56 MeV), we obtain on average ε = 2% and 0.7% for the ^{8}Be and the ^{10}Be breakup channels, respectively. These efficiency values are typical for such reactions. In any case,

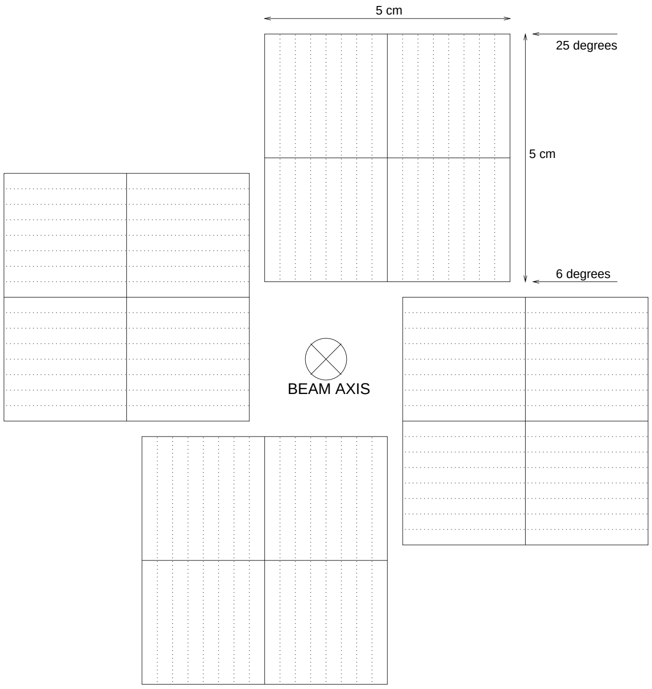

Figure 2: *Geometrical arrangement of the detectors. Solid lines represent the first 70 μm Si quadrant detectors and the dotted lines represent the following 500 μm Si (16) strip detectors.*

the simulation shows that the recoil is never detected since it is emitted out of the angular acceptance of the detectors.

The ^{4}He and ^{6}He nuclei will be identified by their characteristic energy loss profiles in the Si elements of each telescope. Using the technique of invariant mass spectroscopy the reaction Q-value and the excitation energy of ^{14}C will be reconstructed using the energy, angle and mass information provided through the detection of the charged particles. To estimate the expected experimental resolution on the ^{14}C excitation energy, we have performed Monte Carlo simulations which take into account the resolution of the proposed detection setup. The result is shown on Fig. 4 for the two ^{14}C breakup channels of interest, i.e. via the intermediate nuclei ^{10}Be and ^{8}Be. For convenience, the first calculation has been made for an excitation energy in ^{14}C equal to 24 MeV and the second for 25 MeV. We see that we obtain a resolution of the order of 150 keV (500 coincident events were recorded). The results of these calculations are shown for E_{beam} = 70 MeV, but the same resolution is obtained for E_{beam} = 56 and 63 MeV. Owing the selectivity of the two studied breakup channels, this should be enough to resolve the states in ^{14}C.

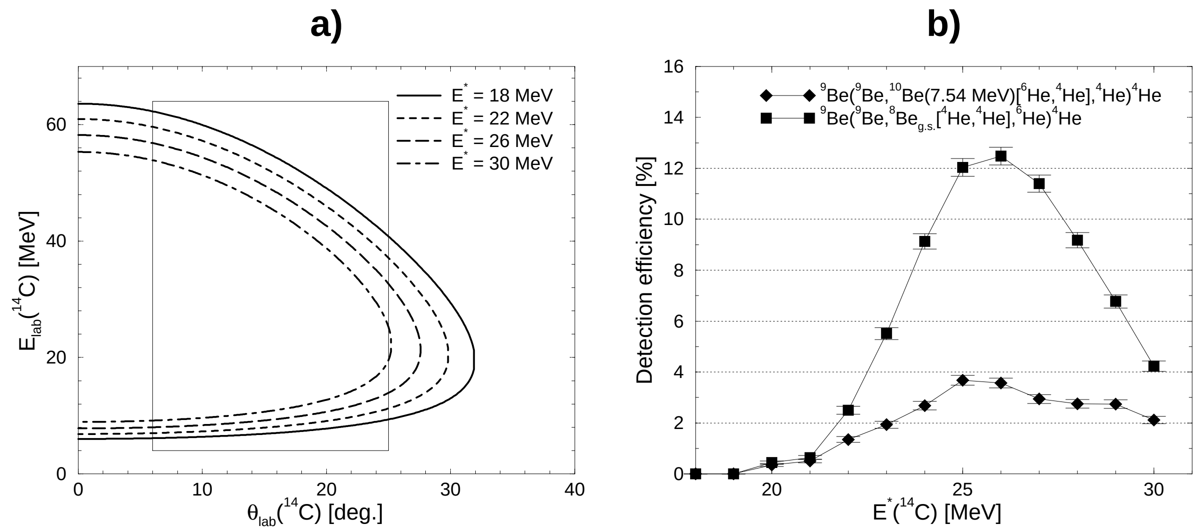

Figure 3: *a) Kinematic correlation between the kinetic energy and polar angle of the nucleus ^{14}C. The rectangle shows the angular acceptance of the detectors. b) Calculated detection efficiency of the 3 breakup products of ^{14}C (^4He, ^4He, ^6He) for the two channels (via ^{10}Be and ^8Be), as function of the excitation energy of ^{14}C. The calculations are made for E_{beam} = 70 MeV.*

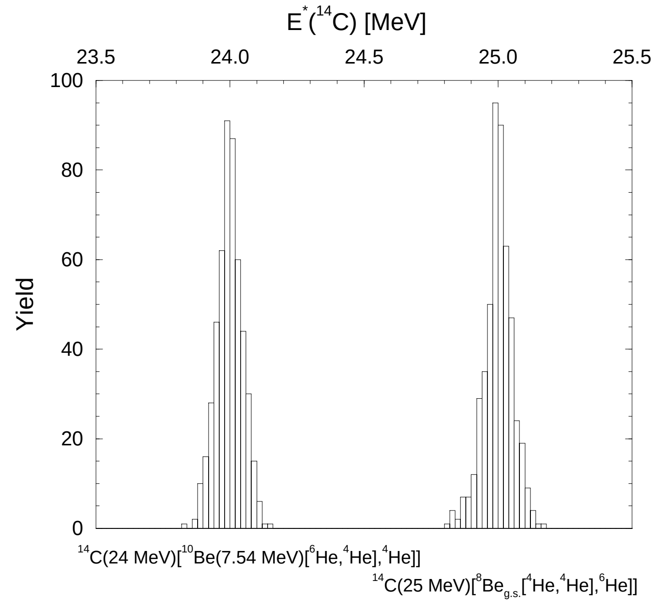

Figure 4: *Simulated excitation energy spectra of ^{14}C reconstructed via the two breakup channels, i.e. the intermediate nuclei ^{10}Be and ^8Be. For convenience, the first calculation has been made for an excitation energy in ^{14}C equal to 24 MeV and the second for 25 MeV. The calculations are made for E_{beam} = 70 MeV.*

3 Beam time request

To tune the ion source, the accelerator and the beam lines to focus the 70 and 63 MeV $^{9}Be^{4+}$ beams (14 and 12.6 MV on the terminal, respectively) on the target, it is estimated that **2 shifts** are required. We should not need much time to tune the 56 MeV $^{9}Be^{3+}$ beam (14 MV on the terminal) on the target since it has the same magnetic rigidity than the 70 MeV $^{9}Be^{4+}$ beam. In addition, we estimate the time to debug the electronics ($\simeq$ 270 channels), instrumented by the MEGHA data acquisition system, to **2 shifts**. To calibrate the detectors in energy and position, we will use the ^{9}Be beam scattered from ^{197}Au and ^{12}C targets, at two different incident energies (56 and 70 MeV) to give a range of energies of the scattered ^{9}Be which covers the expected energies of the breakup particles (^{6}He and ^{4}He). We would need **2 shifts** for these calibrations. At some stage during the experiment, an additionnal **1 shift** would be required to take data using a carbon target in order to quantify the contribution from the carbon buildup on the ^{9}Be metal target during its use.

We estimate a minimum of around 2000 counts per state in ^{14}C in order to extract angular correlation information with suitable background substraction, information needed to perform a spin assignement. To be conservative, we assume a cross section of 0.1 mb to avoid any risk of the measurement being compromised by a below expected cross section. Hence, using the breakup channel and incident beam energy associated with the lowest detection efficiency (0.7%) and assuming a reasonnable $^{9}Be^{4+}$ beam intensity of 4 nA on the target (such intensity has been achieved during the last Charissa experiments at ANU), we would obtain about 2500 coincident events per day. We thus require **3 shifts** of beam time per energy explored.

In conclusion, we request a total of **16 shifts** of beam time for the experiment, including all calibrations:

Measurement	Beam	Energy (MeV)	Target	Shifts
Beam tuning	^{9}Be	56, 60, 70	–	2
Debugging	^{9}Be	70	^{197}Au	2
Calibrations	^{9}Be	56, 70	^{197}Au, ^{12}C	2
^{12}C buildup	^{9}Be	70	^{12}C	1
^{9}Be(^{9}Be,^{14}C)^{4}He	^{9}Be	56, 60, 70	^{9}Be	9
TOTAL				**16**

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