Clustering in light nuclei studied with $^6$He beam

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Abstract. Recent development of low-energy $^6$He radioactive beams led to extensive use of such a unusual projectile in studies of neutron-rich light nuclei. $^6$He induced elastic and inelastic scatterings, transfer reactions, quasi-free scattering and sequential decay processes were studied at the radioactive beams facility in Louvain-la-Neuve giving results on both cluster structure of different light nuclei and reactions mechanism involved.

1. Introduction
The $^6$He nucleus is known to have unusual Borromean structure [1] with two loosely bound neutrons orbiting around an $\alpha$-particle core (both two-body subsystems, $^5$He and $^2n$, are unbound). The weak binding of the $^6$He “valent” neutrons implies a large radial extension of their wave function, as experimentally confirmed by measuring its interaction radius. It also causes a large breakup probability leading to an enhancement of the total reaction cross section.

Recent development of low-energy $^6$He radioactive beams resulted in a large number of experiments devoted to studies of the exotic $^6$He cluster structure. Special attention was given to correlation between the valence neutrons and the the influence that they have on reaction processes around Coulomb barrier. Contrary to some early predictions, a dominance of direct reactions over fusion was experimentally established, with the main part of cross-section being related to neutron transfers (see e.g. [2, 3, 4]).

On the other, having in mind the special structure of $^6$He, radioactive $^6$He beam seems also as a good choice for production of exotic states in other light nuclei. For example, it can be expected that adding another particle to a loose $^6$He would be an ideal way to produce a structure resembling a two-centre molecule [5]; the covalent binding of such “nuclear molecule” would be achieved by two loosely bound neutrons of $^6$He.

An important experimental advantage of $^6$He as a projectile is a fact that it has $0^+$ ground state (contrary to $^6$Li, $^7$Li and $^9$Be, stable loosely bound light nuclei of similar structure), which is essential for performing angular correlation analysis for spin assignments in sequential decay reactions (see e.g. [6]). Furthermore, two loosely bound neutrons in $^6$He lead to reactions that usually have a rather positive $Q$-values for population of neutron-rich nuclei; that enables measurements at low beam energies which often give a cleaner observables of structure effects involved.

2. Experimental details
All experiments discussed here were performed at the radioactive beam facility at the UCL, Louvain-la-Neuve, Belgium [7]. It uses two cyclotrons to produce and accelerate $^6$He ions.
The 30 MeV proton beam of the first machine, CYCLONE 30, is used to produce $^6$He by the $^7$Li($^p$,2$p$) reaction in the LiF powder contained in graphite holder. It is then ionised in an on-line electron cyclotron resonance ion source and, after a magnetic separation, injected into the second cyclotron. After acceleration and extraction from the machine, the ions are directed into one of the experimental areas by help of a switching magnet. Typical beam intensities of the $^6$He$^+$ beam (energy range 5.3-18 MeV) were $\approx 5 \times 10^6$ pps, while the $^6$He$^{++}$ beam (30-73 MeV) had intensity of $\approx 3 \times 10^5$ pps. The beam purity was excellent in all experiments; the only impurity seen [8] were the exotic HeH$^+$ ions (easily removed in the off-line analysis).

Targets used in the campaign included $^6$,7LiF, $^6$Li$_2$O, CH$_2$, CD$_2$ etc. “Alpha-particle rich” target nuclei $^6$Li and $^7$Li were used for studied of alpha-particle pick-up by $^6$He and production of molecular states [6, 9, 10]. Several outgoing channels for the $^{12}$C target have also yielded interesting results [11, 12] while data obtained with the pure $^9$Be target are still under analysis [13]. The $^{14}$C target was also used, but due to the fact that it was very fragile, it was put in between two thin CH$_2$ foils which made the obtained results rather unclear [14]. Low energy $^6$He+4He scattering was also measured with a helium gas target [15, 16].

![Figure 1. Schematic of a typical experimental setup.](image-url)

In all performed experiments the detector setup consisted of highly segmented silicon strip detector arrays covering a total solid angle higher than several sr (a typical setup is given in Fig. 1). The forward detector array (LEDA) used in every experiment consisted of 8 sectors each containing 16 strips, 300 $\mu$m thick [17]. Different geometrical arrangement of same kind of sectors (six of them) were used at higher angles, closer to target position (LAMP in Fig. 1). In several experiments the CD/PAD telescope [18] was placed at polar angles $10^\circ$-$50^\circ$; the thin $\Delta E$ part of the telescope (“CD”) was segmented into 4 sectors with 16 strips each with a thickness of $\approx 40$ $\mu$m. The remaining energy of the detected particles was collected in PAD, 500 $\mu$m thick and segmented only into 4 sectors.

The time of flight (ToF) method was used to obtain the information on the mass of detected particles with LEDA and LAMP detectors with detector and cyclotron RF-pulses used as start and stop signals. The final mass resolution in the LEDA detector array was good enough to mainly separate $\alpha$-particles from $^6$He nuclei (Fig. 2), whereas in the LAMP detectors the small distance to the target resulted in a poor mass separation. In CD/PAD telescope particle identification was done with a convenient $\Delta E/E$ technique with an excellent separation of alpha-particles and $^6$He nuclei.

3. Elastic and inelastic scatterings

Comparison of the $^6$He and $^6$Li scatterings on the same targets was used to study structure differences of these two nuclei. Measured $^6$He+$^6$,7Li and $^6$He+$^{12}$C elastic scattering data are found [10] to be in fair agreement with the optical model predictions, using the potentials obtained for the $^6$Li scatterings (though better agreement for the $^6$,7Li targets can be obtained e.g. using a larger radius of imaginary part of optical potential). More sophisticated calculation
Figure 2. ToF vs energy for the nuclei detected in the LEDA array during the $^6\text{He}+^6\text{Li}$ measurement at 18 MeV [6, 10].

in the framework of four-body continuum-discretised coupled-channel method gives [19] further better fit and shows that the $^6\text{He}+^{12}\text{C}$ total cross section is enhanced for 15% compared to the $^6\text{Li}+^{12}\text{C}$ one and that half of this enhancement is due to the Borromean structure of $^6\text{He}$.

Inelastic scattering was found to weaker compared to the inelastic scattering of $^6\text{Li}$ on the same targets; the only states clearly observed to be populated by the $^6\text{He}$ inelastic scattering were the $2^+$ state at $E_x= 4.44$ MeV in $^{12}\text{C}$ and the $5/2^-$ state at $E_x= 2.43$ MeV in $^9\text{Be}$.

4. Transfer reactions

Pronounced cluster structure of all target nuclei used is well suited for transfer reaction studies, even at rather low beam energies. Different pick-up reactions (of deuteron, two protons, triton and $\alpha$-particle) have been observed for the first time with the $^6\text{He}$ beam. Two-neutron stripping reaction ($^6\text{He},\alpha$) was also studied on $^6.7\text{Li}$ and $^{12}\text{C}$ (and also on $^{19}\text{F}$ present in both lithium targets). For example, the measured angular distribution [20] of the $^6\text{Li}(^6\text{He},\alpha)^8\text{Li}$ reaction was analysed within the framework of the finite-range DWBA, assuming one-step two-mode transfers (di-neutron from $^6\text{He}$ to $^6\text{Li}$ and deuteron from $^6\text{Li}$ to $^6\text{He}$); the product of spectroscopic amplitudes was found to be: $S_a(^6\text{He}=\alpha+2n)\cdot S_a(^8\text{Li}=^6\text{Li}+2n) = 1.1 \cdot S_a(^6\text{Li}=\alpha+d)\cdot S_a(^8\text{Li}=^6\text{He}+d)$.

Extracted angular distributions for the $^6.7\text{Li}(^6\text{He},^{10}\text{Be})$ reactions could not be completely described with the FRDWBA calculations assuming simple $\alpha$-particle transfers [9] using different potentials found in the literature; however large relative $\alpha$-spectroscopic factor was found for the $^{10}\text{Be}$ doublet at $E_x= 7.5$ MeV indicating that at least one of the states has pronounced $\alpha$-cluster structure.

Among other studied transfer reactions, the first time observed ($^6\text{He},^{8}\text{Be}$) reaction [11] is found to be a potentially very useful spectroscopic tool as a rather simple reaction with respect to both experimental method and reaction dynamics. It is observed on $^{12}\text{C}$, $^{16}\text{O}$ and $^{19}\text{F}$ nuclei; the measured angular distributions for the $^{12}\text{C}(^6\text{He},^8\text{Be})^{10}\text{Be}$ (g.s.) and $^{12}\text{C}(^6\text{He},^8\text{Be})^{10}\text{Be}^*(3.37$ MeV) reactions show a clear signature of a direct process. Although the contributions from the $^6\text{Li}(^6\text{He},^8\text{Be})^4\text{H}$ reaction were observed, no clear extraction of the $^4\text{H}$ data was possible (for details see [11]).
5. Sequential decay reactions
The reactions with three or more particles in the exit channel have been studied through the triple coincidences; they were detected with considerable efficiency due to large total solid angle covered by the detector system. The sequential decay reactions $^6\text{He} + ^6\text{Li} \rightarrow ^6\text{He} + \alpha + d$, $^6\text{He} + ^6\text{Li} \rightarrow 2\alpha + t + n$, $^6\text{He} + ^7\text{Li} \rightarrow ^6\text{He} + \alpha + t$ and $^6\text{He} + ^{12}\text{C} \rightarrow ^{10}\text{Be} + 2\alpha$ have been clearly observed and analysed and new results on cluster structure of some states in $^9\text{Be}$, $^{10}\text{Be}$ and $^{14}\text{C}$ have been obtained [6, 12].

For $^9\text{Be}$ it is confirmed [6] that the 5/2$^+$ state at $E_x = 3.05$ MeV decays mainly through the $^8\text{He}(g.s.) + n$ channel, while the 5/2$^-$ state at $E_x = 2.43$ MeV does not. This latter state is shown [6] to be responsible for the “ghost peak” appearing in the $^8\text{Be}$ excitation spectrum at $E_x \approx 0.5$ MeV (at least, for a large fraction of its full intensity).

A very strong population and $\alpha$-decay of the states at $E_x = 7.54$ and 10.15 MeV, have been observed [6] through the $^4\text{He} + ^6\text{Li} \rightarrow ^6\text{He} + \alpha + d$ reaction. The determined branching ratio for the decay of the 2$^+$ state at $E_x = 7.54$ MeV, $\Gamma_{2^+}/\Gamma > (2.0 \pm 0.6) \times 10^{-3}$, indicating that this state belongs to the rotational band based on the intruder $0^+_2$ state at $E_x = 6.18$ MeV. For the state at $E_x = 10.15$ MeV the performed angular correlation studies [6] favour the $J^\pi = 4^+$ assignment.

The $^6\text{He} + ^{12}\text{C} \rightarrow ^{10}\text{Be} + 2\alpha$ reaction was used to obtain information on $\alpha$-cluster states in $^{14}\text{C}$ [10]; those were found to agree with a recently performed systematic study of $^{14}\text{C}$ states [21].

6. Resonant elastic scattering
A gas target was employed [16] with a experimental setup similar to the one in Fig. 1 to probe the 10.15 MeV resonance in $^{10}\text{Be}$ via resonant $^6\text{He} + ^4\text{He}$ elastic scattering. Thick target resonant elastic scattering is a powerful technique to study partial widths and spin/parities of the resonances in a model independent way. The measurements demonstrated [16] that the resonance has a very large $\alpha$-particle component and $J^\pi = 4^+$, in agreement with the results for the $^6\text{Li}(^6\text{He},^6\text{He}o)^2\text{H}$ reaction [6]. Search for another strong resonances in $^6\text{He} + ^4\text{He}$ elastic scattering is being performed.

7. Results for $^{10}\text{Be}$
The most important results in the series of experiments reviewed in the present paper are related to unusual states in $^{10}\text{Be}$. A crucial role which $^{10}\text{Be}$ may have in understanding neutron rich nuclei makes all the new experimental information on its states very valuable. With the $^6\text{He}$ beam, the states in $^{10}\text{Be}$ are probed in three ways: by $\alpha$-particle transfer reactions, by sequential decay reactions $^6\text{Li}(^6\text{He},^6\text{He}o)^2\text{H}$ and by resonant elastic scattering $^6\text{He} + \alpha$. In short, the results for $^{10}\text{Be}$ are the following: (i) the 2$^+$ state at $E_x = 7.54$ MeV is found to have a well-pronounced alpha-particle structure; (ii) the state at $E_x = 10.15$ MeV is clearly assigned $J^\pi = 4^+$ and found to have a very large alpha-particle component too.

Other recent results show [22] that the 10.15 states decays into $^6\text{He} + \alpha$ channel (and not into $n + ^9\text{Be}$) and that it also decays into $^6\text{He}(2^+) + \alpha$ channel [23]; it is interesting to note that its energy coincides with the $^5\text{He} + ^5\text{He}$ decay threshold. Furthermore, the observed alpha-decay width of the 7.54 MeV state is in agreement with the one measured via the $^7\text{Li}(^7\text{Li},^6\text{He}o)^4\text{He}$ reaction [24]. Together with the known 0$^+$ “intruder” state at $E_x = 6.18$ MeV, the states at $E_x = 7.54$ and 10.15 MeV form a rotational band with the slope parameter $k = h^2/2I \approx 0.20$ MeV. This should be compared with the ground-state bands of $^8\text{Be}$, $^9\text{Be}$ and $^{10}\text{Be}$ which have slopes of 0.57, 0.53 and 0.56 MeV, respectively (bands are compared in Fig. 3). In other words, the separation of the two $\alpha$-clusters in the $^{10}\text{Be} 0^+_2$ band is greatly enhanced and arises from the presence of the molecular neutrons between two cores.

Many recent cluster model calculations (e.g. [25, 26, 27, 28, 29, 30, 31, 32]) do reproduce all experimentally observed features of the $^{10}\text{Be}$ structure (including molecular states), though they differ in many details. Standard shell model calculations (e.g. [33]), on the other hand,
cannot explain such molecular states even when they contain mixture of highly excited ($\hbar\omega$) components in their wave function, showing that clustering is indeed essential and fundamental in description of light nuclei.

When combined with the other results, especially the recent measurement of the $^{12}$C($^{12}$C,$^{14}$O)$^{10}$Be reaction [34], systematic grouping of all $^{10}$Be states can be obtained as given in Fig. 3. The 4$^+$ member of the ground state band is identified [34] as the 11.8 MeV state; identification of the 6$^+$ members of both 0$^+$ bands would further confirm the proposed interpretation.

Finally, the $^{10}$Be states at $E_x = 7.5 - 12$ MeV might be astrophysically important through the sequence of reactions $^4$He($^2$n,$\gamma$)$^6$He($\alpha$,n)$^9$Be which may compete with the triple-alpha process or other three-particle reactions. This was studied in Ref. [35] and though it was found that such a scenario is very unlikely, it should be noted that for several states (those at $E_x = 10.15$, 10.57 and 11.76 MeV) resonance level parameters used were later experimentally shown to be wrong.

8. Quasi-free reactions
Although quasi-free scattering have been observed in different reactions using stable beams of low energies, observation in the $^6$He+$^6$Li reaction in an experiment with radioactive beams of relatively low intensity may come as a surprise [36]. A strong contribution to the $^6$He-$d$ coincident spectrum was found to correspond to the $^6$He quasi-free scattering off the deuteron in the $^6$Li nucleus and this [36] is the first observation of the quasi-free scattering of fragile radioactive nuclei on clusters in target nuclei.

9. Summary and outlook
Elastic, inelastic and quasi-free scatterings and different transfer and sequential decay reactions were measured with a 18 MeV radioactive $^6$He beam on the $^4$He, $^6$Li, $^7$Li, $^9$Be, $^{12}$C and $^{14}$C targets and results concerning both nuclear structure and reaction mechanism were reported. The $^6$He beam is found to be a good choice for production of exotic structures in light nuclei.

A rotational band based on the $0^+_2$ state at $E_x = 6.18$ MeV is identified in $^{10}$Be and its very large moment of inertia indicates that its states have strongly deformed molecular structure (definitely one of the highest axis ratios of all known nuclei). A next step would be identification

Figure 3. Rotational bands in $^8$Be (green, full circles), $^9$Be (blue, open circles) and $^{10}$Be (red, open squares).
of analog states in $^{10}$B and $^{10}$C, which e.g. might be accomplished with another radioactive beam, $^7$Be. Experimental efforts in that direction are already under way in Louvain-la-Neuve.

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References

[1] Zhukov MV, Danilin BV, Fedorov DV, Bang JM, Thompson IJ and Vaagen JS 1993 Phys. Rep. 231 151
[2] Di Pietro A et al 2004 Phys. Rev. C 69 044613
[3] Raabe R et al 2004 Nature 431 823
[4] Keeley N, Raabe R, Alamanos N and Sida JL 2007 Prog. Part. Nucl. Phys. 59 579
[5] von Oertzen W, Freer M and Kanada-En'yo Y 2006 Phys. Rep. 432 43
[6] Milin M et al 2005 Nucl. Phys. A 753 263
[7] Darquennes D et al 1990 Phys. Rev. C 42 R804
[8] Miljanić Đ et al 2000 Nucl. Instrum. Methods Phys. Res. A 447 544
[9] Milin M et al 1999 Europhys. Lett. 48 616
[10] Milin M et al 2004 Nucl. Phys. A 746 183c
[11] Milin M et al 2004 Phys. Rev. C 70 044603
[12] Milin M et al 2004 Nucl. Phys. A 730 285
[13] Raabe R et al. 2002 proposal for an experiment at CRC LLN
[14] Milin M et al 2007 Eur. Phys. J., accepted for publication
[15] Freer M et al 2006 Phys. Rev. Lett. 96 042501
[16] Davinson T et al 2000 Nucl. Instrum. Methods Phys. Res. A 454 350
[17] Ostrowski AN et al. 2002 Nucl. Instrum. Methods Phys. Res. A 480 448
[18] Matsumoto T et al. 2004 Phys. Rev. C 70 061601
[19] Milin M et al. 2006 Phys. Atom. Nucl. 69 1360
[20] von Oertzen W et al. 2004 Eur. Phys. J. A 21 193
[21] Soić N et al. 1996 Europhys. Lett. 34 7
[22] Miljanić Đ et al. 2001 Fizika (Zagreb) B 10 235
[23] Liendo JA, Curtis N, Caussyn DD, Fletcher NR and Kurtukian Nieto T 2002 Phys. Rev. C 65 034317
[24] Kanada-En'yo Y, Hor炊chi H and Dote A 1999 Phys. Rev. C 60 064304
[25] Itagaki N and Okabe S 2000 Phys. Rev. C 61 044306
[26] Ogawa Y, Arai K, Suzuki Y and Varga K 2000 Nucl. Phys. A 673 122
[27] Fujimura J, Baye D, Desouvremont P, Suzuki Y and Varga K 1999 Phys. Rev. C 59 817
[28] Ito M, Kato K and Ikeda K 2004 Phys. Lett. B 588 43
[29] Al-Khalili JS and Araï K 2006 Phys. Rev. C 74 034312
[30] Pei JC and Xu FR 2007 Phys. Lett. B 650 224
[31] Warburton EK and Brown BA 1992 Phys. Rev. C 46 923
[32] Bohlen HG, Dorsch T, Kokalova Tz, von Oertzen W, Schulz Ch and Wheldon C 2007 Phys. Rev. C 75 054604
[33] Bartlett A, Görres J, Mathews GJ, Otsuki K, Wiesher M, Frekers D, Mengoni A and Tostevin J 2006 Phys. Rev. C 74 015802
[34] Miljanić Đ et al. 2006 Europhys. Lett. 76 801