IL NUOVO CIMENTO **39 C** (2016) 394
DOI 10.1393/ncc/i2016-16394-6

Colloquia: IWM-EC 2016

Collision dynamics of alpha-conjugate nuclei

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received 10 January 2017

Summary. — The collision dynamics of alpha-conjugate nuclei is being investigated in reactions induced by 35 MeV/nucleon ^{40}Ca and ^{28}Si projectiles. Data were collected with each of the beams using Ca, Si, C and Ta targets. Particular emphasis is placed on examining the dynamics of collisions leading to projectile-like fragment exit channels. This report presents a brief summary of some of the experimental directions being pursued.

Both theoretical calculations and experimental observations provide strong support for the alpha clustered nature of light alpha-conjugate (even-even $N = Z$) nuclei [1-4]. This is particularly true for loosely bound states with excitation energies near the alpha emission thresholds [5-7]. Cluster effects are often seen in transfer reactions involving light nuclei [8]. The role of clusters in more violent collisions is poorly understood. Studies of alpha-conjugate nuclei might reveal important effects of these correlations on the collision dynamics and in determination of the reaction exit channels. Given that near Fermi energy nuclear collisions can drastically modify the temperatures, densities and cluster properties of nucleonic matter, the possibility that short-lived Bose Condensates might be fleetingly produced in such collisions is an intriguing idea [9].

To pursue the question of the effects of alpha-like correlations and clustering in collisions between alpha-conjugate nuclei we have embarked on a program of experimental studies of such collisions at and below the Fermi energy using the NIMROD-ISiS array at

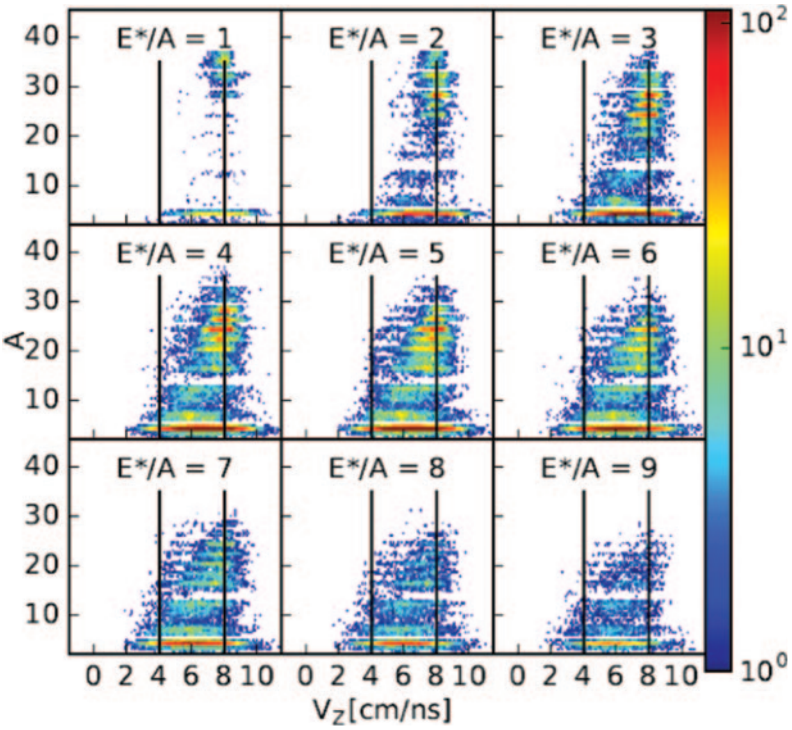

Fig. 1. – Yields of the three heaviest fragments per event as a function of the fragment parallel velocity in different windows of initial apparent excitation energy E^*/A. The projectile velocity is 8.0 cm/ns. The c.m. velocity is 4.0 cm/ns.

TAMU [10]. A dominating alpha clustered nature of the colliding matter could manifest itself in the kinematic properties and yields of the alpha-conjugate products.

1. – Experimental procedures

The experiment was performed at Texas A & M University Cyclotron Institute using beams produced by the K500 superconducting cyclotron. We have studied 35 MeV/u Ca + C, Ca + Ta, Si + C, Si + Si, Si + Ta systems. The reaction products were measured using the 4π array, NIMROD-ISiS (Neutron Ion Multidetector for Reaction Oriented Dynamics with the Indiana Silicon Sphere), which consisted of 14 concentric rings covering from 3.6 to 167 degrees in the laboratory frame [10]. In the forward rings with $\theta \leq 45$ degrees, two special modules were set having two Si detectors (150 and 500 μm) in front of a CsI(Tl) detector (3–10 cm), referred to as super-telescopes. The other modules (called telescopes) in the forward and backward rings had one Si detector (one of 150, 300 or 500 μm) followed by a CsI(Tl) detector. The pulse shape discrimination method was employed to identify the light charged particles with $Z \leq 3$ in the CsI(Tl) detectors. Intermediate mass fragments (IMFs), we identified with the telescopes and super-telescopes using the "ΔE-E" method. In the forward rings an isotopic resolution up to $Z = 12$ and an elemental identification up to $Z = 20$ were achieved. In the backward rings only $Z = 1$–2 particles were identified, because of the detector energy thresholds. In addition, the Neutron Ball surrounding the NIMROD-ISiS charged particle array provided information on average neutron multiplicities for different selected event classes. Further details on the detection system, energy calibrations, and neutron ball efficiency can be found in refs. [11] and [12].

It is important to note that, for symmetric collisions in this energy range, the increasing thresholds with increasing laboratory angle lead to a condition in which the efficiencies favor detection of projectile-like fragments from mid-peripheral events. Modeling of these collisions using an Antisymmetrized Molecular Dynamics (AMD) code [13] and applying the experimental filter demonstrates that this is primarily an effect of energy thresholds.

In fig. 1 the mass numbers, A, of the three heaviest fragments in each event are plotted against their laboratory-frame parallel velocities for 1 MeV increments in E^*/A. The favored detection of projectile-like species for all windows is clearly seen in this figure. Most of the fragments have velocities above the center of mass velocity, 4.0 cm/ns.

Increasing excitation energy corresponds, at least qualitatively, to decreasing impact parameter and increased collision violence. This is manifested in the figure by the decrease in yields of the heaviest mass products and increasing yields of lighter mass products as excitation increases. At low excitation energies the majority of the heavier products have parallel velocities near the beam velocity of 8.0 cm/ns. The similar mean lab velocities suggest that the lighter fragments are produced by statistical de-excitation of the initial projectile-like fragment. As the excitation energy increases, a clear correlation between parallel velocity and fragment mass. For these excitations, corresponding to the region of mid-peripheral collisions., the parallel velocity decreases as the fragment mass decreases. This behavior is reminiscent of reported hierarchy effects in such collisions [14].

The purpose of the present study was to explore alpha exit channels composed of alpha-particles or alpha-conjugate nuclei. To focus on such channels the event by event

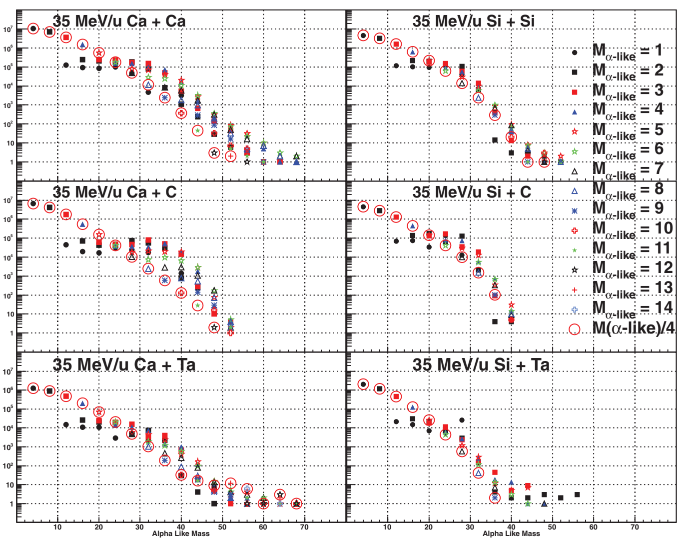

Fig. 2. – Probability distributions of various breakup channels for the different systems studied. The x-axis shows the alpha-like mass and the y-axis shows the probability of the breakup into different channels as depicted by the various symbols. The open circles indicate the probability the total alpha-like mass being contained in alpha-particles.

data were re-sorted as a function of the total detected "alpha-like mass", A_L. *i.e.*, the sum of the masses of the detected products that are alphas or alpha-conjugate nuclei. Figure 2 depicts the resultant event yields for the different alpha-conjugate decay channels as a function of alpha-like mass. Events for which all of the detected alpha-conjugate mass is in alpha-particles are indicated by the large open circles in fig. 2. A total alpha-like mass as large as 85% of the entrance channel mass is seen, but with very low statistics. The shoulders and rapid yield decreases at higher alpha-like masses reflect the detector selectivity for projectile-like fragments from mid-peripheral events. The open circles indicate the probability that all of the alpha-like mass is contained in alpha-particles. We see on all of these plots that there is a significant probability of breakup of a large fraction of the complete system into alpha-like mass. We note that this occurs on all of the studied systems.

For the analyses which follow we have chosen to focus on those ^{40}Ca induced events for which $A_L = 40$ and compare the properties of the 19 possible exit channels for the disassembly of the ^{40}Ca nucleus into alpha-particles or alpha-conjugate nuclei. The 19 possible combinations of alpha-conjugate nuclei which satisfy this total alpha-conjugate mass = 40 criterion are schematically indicated in fig. 3. This depiction is similar to that of the Ikeda diagram which is commonly invoked in discussions of the cluster structure of light nuclei [15].

Figure 4 shows invariant velocity plots of the products that originate from events selected to have a total detected alpha-like mass equal to that of the projectile (40). The left side of the frame of each system shows the velocity distributions of the heavier alpha-like fragments and the right side shows the velocity distributions of the alpha-particles associated with those heavier fragments. The vertical lines indicate the location $vz = 0$ which is the frame of the reconstructed decaying system. This distribution shows that the neck-like origin of the alpha-particles is present in the reactions where the complete system is composed of alpha-like nuclei. We note that the majority of the alpha-particles are at velocities less than that of the emitting source in the defined

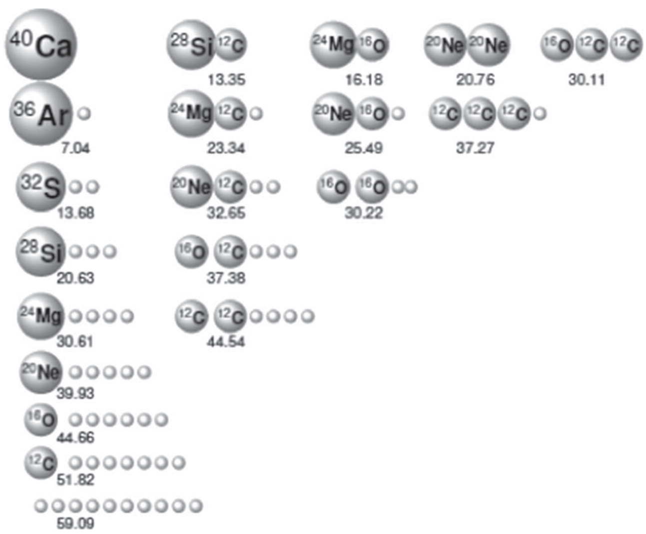

Fig. 3. – Ikeda-like diagram for the possible alpha-conjugate components of ^{40}Ca.

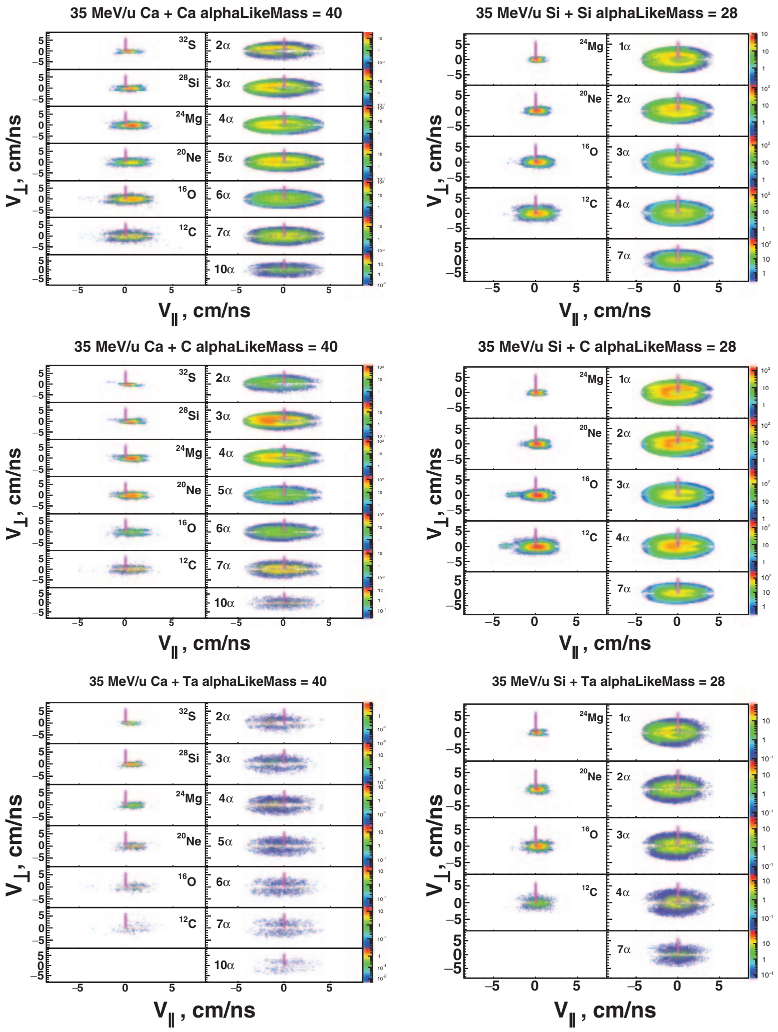

Fig. 4. – Invariant velocity distributions of products resulting from the various decays channels of a decaying source reconstructed in events having a detected alpha-like mass of 40 for the Ca beams and 28 for the Si beams. The vertical lines indicate $vz = 0$, the frame of the reconstructed source.

neck region. It is also shown that the heavy partner is found at a velocity larger than that of the reconstructed source.

We note, however, that the alpha-like heavier fragments and the alpha-particles themselves do not exhibit such behavior in the reactions with the Ta target for both the Ca and Si beams. The fragments and alpha-particles are more or less symmetric around the velocity of the reconstructed source.

With the possibility of reaction induced Bose condensates in mind, we are pursuing a "matter analysis" of the various exit channels. For this purpose we isolate events for which all of the observed products are bosons, or are fermions, etc. This type of classification is exhibited in fig. 5 where the yields of different types of events are compared.

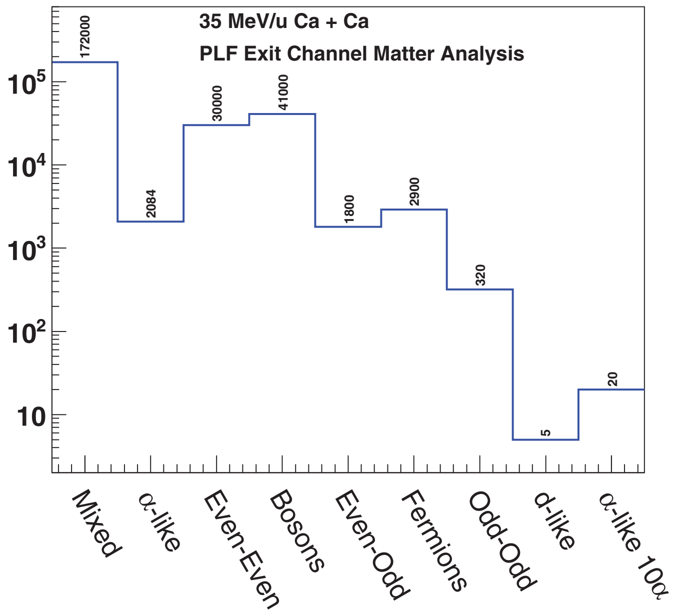

Fig. 5. – Yields of observed $A = 40$ events selected by matter type as indicated in the figure.

Our goal is to compare these various types of events to see if signatures of different nuclear matter compositions exist. We are limited, of course, by the limitation to exit channel characterizations as some statistical de-excitation can modify the original composition.

Among the additional topics to be explored is the possibility that light alpha-conjugate nuclei have high excitation energy, high spin toroidal states. In general nuclei have

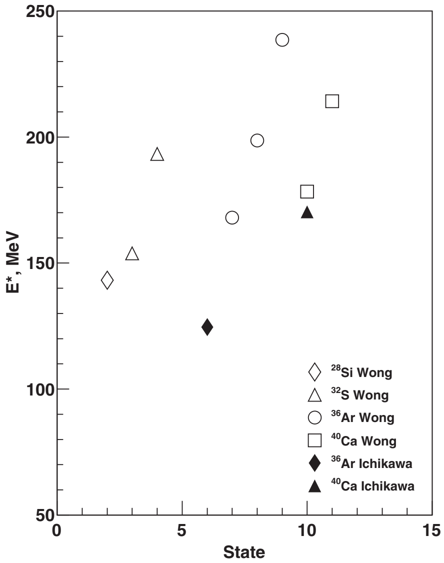

Fig. 6. – Predicted excitation energies for stabilized toroidal states in light alpha-conjugate nuclei.

compact near spherical topologies. Nuclei with high excitation energies, high angular momenta or very high atomic numbers have been predicted to assume bubble or toroidal configurations [16-18]. A great deal of theoretical effort has been devoted to the investigation of such shapes, and to delineating the conditions under which they might occur. Both macroscopic and microscopic models have been employed [16-23]. The most recent work by Ichikawa *et al.* [19, 20] and by Wong and Stasczak [21-23] has led to specific predictions of highly excited, shell stabilized, high angular momentum toroidal states in light nuclei. Both models employ constrained cranked Hartree-Fock techniques but they differ in starting conditions, interactions utilized and wave function descriptions. Figure 6 indicates the excitation energies predicted for such states. While this experiment cannot determine the angular momenta of these states, the observed mass and excitation energy systematics of these states might provide evidence for the states predicted.

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This work was supported by the United States Department of Energy under Grant # DE-FG03- 93ER40773 and by The Robert A. Welch Foundation under Grant # A0330.

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