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Publication Date
1986-02-01
Presented at the Workshop for Nuclear Dynamics IV, Copper Mountain, CO, February 23-28, 1986

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February 1986

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3-Body Final States in Peripheral Heavy-ion Collisions: 
Nuclear Clustering Structure and Projectile Excitation 
Revisited†.

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† Presented at the Workshop for Nuclear Dynamics IV, Copper Mountain, Colorado, February 1986. Work supported under DOE contracts DE-AC03-76SF00098 and DE-AM03-76SF00326.
Even though peripheral heavy-ion collisions are less violent than their central counterparts, the large energy exchange between the reactants often leaves the primary products in excited particle-unstable states whose subsequent decay leads to 3 or more nuclei emerging in the final exit channel. These post-reaction, predominantly sequential de-excitation processes can sometimes provide interesting structural information about the parent nuclei. In fact, provided these processes are well understood, one can employ them as probes for studying initial properties of the fragments.

The present talk will discuss results of two experiments that deal with (i) non-statistical, rare decay modes of the projectile, and (ii) internal excitation energy of the projectile- and target-like fragments in peripheral collisions. The physics addressed in each is different, but the experimental and data-analysis techniques are so similar that it is relevant to join them together. Both experiments accept events of the form: Projectile + Target → 1 + 2 + X, where 1 and 2 are two nuclei detected in coincidence and X = x₁ + ... + xₙ are the undetected particles. The first experiment deals with a case where n=1 and one has a positively identified 3-nuclei final-state (in fact, three ¹²C's), while the second one deals with a less unambiguous situation and additional assumptions are required.

1. Clustering structure of ²⁴Mg revisited: Non-statistical ¹²C decay of ²⁴Mg following nuclear inelastic scattering.

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† Presented at the Workshop for Nuclear Dynamics IV, Copper Mountain, Colorado, February 1986. Work supported under DOE contracts DE-AC03-76SF00098 and DE-AM03-76SF00326.
There is evidence from electromagnetic studies (electro- fission and radiative capture) that some states in $^{24}\text{Mg}$ have significant $^{12}\text{C}$ decay-widths. Unambiguous support of this from nuclear scattering experiments has not been established, however. It is the purpose of this experiment to pursue this problem further with exact 3-body final-state measurements.

In order to identify 3-body final states unambiguously, a simultaneous high-resolution measurement of the fragment momenta is necessary. The expected small cross section for this process also dictates a good detection efficiency. To achieve this, large solid angle (5msr each) position-sensitive $\Delta E-E$ Si telescopes and reverse kinematics were used. In this geometry, decay products from the projectile are emitted within a narrow breakup cone and can be detected with high efficiency. The measurement was performed at the LBL 88-Inch Cyclotron by bombarding a 0.5mg/cm$^2$ $^{12}\text{C}$ target with a 15 MeV/nucleon $^{24}\text{Mg}$ beam. The telescopes were positioned symmetrically at $\Theta = \pm 10^\circ$ w.r.t. the beam covering an opening-angle range of 15° - 25°. Fig.1(a) shows a 2-dimensional energy-correlation spectrum of the two $^{12}\text{C}$ nuclei. Besides a continuous background, well-defined loci corresponding to 3-body final states are evident.

3-body kinematics were employed to generate the energy ($E_3$) of the undetected effective third particle. The spectrum of the total kinetic energy, $E_{\text{tot}} = E_1 + E_2 + E_3$, is shown in Fig. 1(b). One can clearly see a peak corresponding to the emergence of three $^{12}\text{C}$ nuclei in their respective ground states ($Q_{\text{ggg}} = -13.93$ MeV). The two other peaks at lower $E_{\text{tot}}$ energies correspond, respectively, to one or two of the three $^{12}\text{C}$ nuclei being in their first excited state (4.44 MeV). Events in the ground-state peak at $Q_{\text{ggg}}$ may be interpreted as resulting from the sequential breakup of the $^{24}\text{Mg}$ projectile following inelastic scattering: $^{12}\text{C}($$^{24}\text{Mg}$, $^{24}\text{Mg}^* \rightarrow 12\text{C}_{g.s.}^{12}\text{C}_{g.s.})^{12}\text{C}_{g.s.}$. Information about the excited states in $^{24}\text{Mg}$ which decay into $^{12}\text{C} + ^{12}\text{C}$ can be obtained from the relative-energy spectrum of the two detected $^{12}\text{C}$'s. The excitation-energy spectrum of $^{24}\text{Mg}$, $E_{\text{exc}} = E_{\text{rel}} + 13.93$ MeV, is shown in Fig.2(a). Well-defined peaks at $E_{\text{exc}} = 21.9$ MeV, 23.6 MeV and 24.8 MeV can be observed. The energy width of these peaks is about 0.5-1.0 MeV. The spin of these peaks are obtained by fitting a Legendre polynomial to the in-plane angular correlation in the rest frame of the $^{24}\text{Mg}$ (Fig.2(b)). The first peak at 21.9 MeV has a spin of 2, in agreement with the $2^+$ resonance at the same excitation energy observed$^1$ in the radiative capture reaction $^{12}\text{C}(^{12}\text{C},\gamma)_{10}^{24}\text{Mg}_{g.s.}$. The other two peaks were not seen in the radiative-capture processes. Preliminary analysis
indicates both of them have $J^\pi = 0^+$. The structures seen in Fig. 2(a) cannot be explained on purely statistical grounds since the fluctuation width for $^{24}\text{Mg}$ in this excitation-energy range, $\sim 100$ keV, is much smaller than that observed in our experiment.

In conclusion, we have provided evidence for the existence of states (or groups of states) in $^{24}\text{Mg}$ that have significant widths decaying into two $^{12}\text{C}$ nuclei following nuclear excitation. It seems that these specific states with large $^{12}\text{C}$ widths must have well-developed clustering structure. They are not related to the molecular states observed in the $^{12}\text{C} + ^{12}\text{C}$ entrance channel, however, since their spins are quite low. It is more likely that they are states with large shape deformations. It would be interesting to investigate the possible doorway role of these states to giant resonances. One should point out that the structures appear to be concentrated in energy and that no significant structures are observed above 26 MeV excitation.

2. Division of excitation energy in peripheral heavy-ion reactions

The partition of excitation energy for peripheral processes could be quite different from the familiar mass-ratio sharing picture observed in highly-damped collisions. Taking advantage of the relatively low particle multiplicity in a peripheral collision, we have attempted to study this problem with similar methods described in section 1, namely, to reconstruct the excitation spectrum of the projectile by detecting the projectile-like fragment (PLF) and the corresponding emitted light particle (LP). With further assumption, one could also estimate the target excitation and hence the energy-partition pattern. In order to cover the widest possible excitation region of the projectile, large area ($20\text{cm} \times 20\text{cm}$) position-sensitive and charged-particle-sensitive phoswich detectors were developed. The phoswich array is composed of 8 segments ($20\text{cm} \times 2.5\text{cm}$), each having position sensitivity along the long dimension. The trigger detector, a compact geometry $\Delta E-E$ Si telescope, was positioned at the center of the array. Due to the large geometrical coverage, the array can also be operated in a "veto" mode providing additional information about the population strength of the proton- and $\alpha$-bound states.

The reaction $^{197}\text{Au}(^{20}\text{Ne},\text{PLF-LP})X$ has been studied at 11 MeV/nucleon. The detection array was positioned at $\Theta_{\text{lab}} = 28^\circ$ slightly forward of the classical grazing angle. The $\alpha$ channel is the predominant charged-particle decay mode for all fragments.
except $^{21}\text{Na}$, where proton decay prevails. Decays into more than one charged light particle are about two orders of magnitude smaller and are not included in our analysis. Sample spectra of the phoswich slices are shown in Fig. 3 for $\alpha$'s in coincidence with $^{16}\text{O}$ (corresponding to a $^{20}\text{Ne}^*$ primary fragment). It can be seen that we have almost 100% efficiency in catching the sequential-breakup cones. The internal excitation energy spectra for charge-particle decaying states in the primary fragments ($E_x(PF) = E_{rel} - Q_2$, where $Q_2$ is the separation energy of the light particle) are shown in Fig. 4. The hatched areas represent the population strength to states below the first charged particle emission threshold. Generally speaking, the reconstructed average internal excitation energies of the primary projectile fragments are quite low, centered typically below the particle thresholds. The initial population strength that goes to neutron decaying states will be missed in the present analysis. From threshold and energetic considerations, except possibly for $^{17}\text{O}$ and $^{21,22}\text{Ne}$, such contributions are estimated to be a small fraction.

Under the assumption that both the PLF and the LP are detected in their respective ground states, the quantity $Q_{ggg} - Q_3$ can be identified with the excitation energy in the primary target fragment ($\equiv E_x(TLF)$). Here $Q_3$ is the total-kinetic energy loss, calculated by 3-body kinematics. We find that the shapes of the TLF excitation spectra do not change significantly with the projectile excitation. The most probable values of the $E_x(TLF)$ spectra are extracted and shown in Fig. 5. In order to understand the trend of the data, we have calculated the most-probable total excitation energy, $E_x(\text{total}) = Q_{gg} - Q_{opt}$, according to the Siemens's prescription for $Q_{opt}$. The most probable-fragment excitation energies are then obtained by assuming the excitation partition ratio is determined by the gross number of nucleons acquired by each fragment,

$$E_x(\text{PLF}) = [m/N] \times E_x(\text{total}) \text{ and } E_x(\text{TLF}) = [n/N] \times E_x(\text{total})$$

where $N \equiv m + n$, and $m(n)$ is the number of nucleons transferred from the target(projectile) to the projectile(target). The calculation for $E_x(\text{TLF})$ agrees well with the data.

In summary, with the excitation energy reconstruction method, we have observed relatively cold primary projectile fragments in peripheral collisions, in particular for the stripping-like processes. Most of the excitation energy is associated with the primary target-like product in this case. This appears to remain true at subsequent higher bombarding energy measurements (20-30 MeV/nucleon). Probably due to the short reaction
time scale, the excitation energy appears to be produced by particle transfer without further redistribution. We have compared the most-probable values of the excitation energy with a simple scheme based on $Q_{\text{opt}}$ formula of Siemens. One interesting observation is that the most probable TLF excitation energy, for $^{17,18}$O, is better described by the gross (and not the net) number of nucleons acquired by each fragment.

References:

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Fig. 1 (a) Energy correlation spectrum of the two detected $^{12}$C nuclei. (b) The total kinetic energy spectrum calculated by 3-body kinematics.

Fig. 2 (a) Structures observed in the excitation energy spectrum of $^{24}$Mg. (b) Legendre Polynomial fit of the angular correlation for the structure at 21.9 MeV.
Fig. 3 $\alpha$ spectra in $\beta$-fold coincidence with $^{16}\text{O}$ (x-axis is the $\alpha$-energy and the y-axis is the $\alpha$-position along the long dimension of the phoswich slice). The intense rings are related to the sequential breakup cones of the $^{20}\text{Ne}$ fragments.

Fig. 4 Excitation energy spectra of the primary projectile-like fragments. These spectra were obtained by assuming 3-body kinematics.

Fig. 5 The most-probable excitation energies in $E_x\text{(TLF)}$ for various stripping and pickup channels deduced from the data. See text for the details of the calculated points.
This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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