BB

TASCC-P-94-01

509408

PREPRINT

tascc

***BREAKUP OF HIGHLY EXCITED ^{35}Cl PROJECTILES ON GOLD
TARGET AT 30A MeV: AN EXCLUSIVE ANALYSIS****

L. Beaulieu, R. Laforest, J. Pouliot¹, R. Roy, C. St-Pierre,
Laboratoire de physique nucléaire, Université Laval, Québec, Canada, G1K 7P4

G.C. Ball, E. Hagberg, D. Horn and R.B. Walker
AECL Research, Chalk River Laboratories, Chalk River, Ontario, Canada, K0J 1J0

¹ Present address: Departement de Radio-Oncologie, Hôtel-Dieu de Québec, 1 rue Collins,
Québec, Canada. G1R 4J1

* Experiment performed at TASCC, AECL Research, Chalk River Laboratories, Chalk
River, Ontario, Canada, K0J 1J0

Submitted to Nucl. Phys. A

CERN LIBRARIES, GENEVA

P00021201

NOTICE

This report is not a formal publication; if it is cited as a reference, the citation should indicate that the report is unpublished. To request copies our E-Mail address is **TASCC@CRL.AECL.CA**.

Physical Sciences
Chalk River Laboratories
Chalk River, ON K0J 1J0 Canada

1994 January

Breakup of highly excited ^{35}Cl projectiles on gold target at 30A MeV: An exclusive analysis*

L. Beaulieu, R. Laforest, J. Pouliot¹, R. Roy and C. St-Pierre
Laboratoire de physique nucléaire, Université Laval, Ste-Foy, Québec, Canada, G1K 7P4

G. C. Ball, E. Hagberg, D. Horn and R. B. Walker
AECL Research, Chalk River Laboratories, Chalk River, Ontario, Canada, KOJ 1J0

Abstract: Projectile excitation and breakup have been studied in the reaction $^{35}\text{Cl} + ^{197}\text{Au}$ at 30A MeV. Differential cross sections and energy distributions were measured. The absolute cross sections of 98 different exit channels made of as many as 7 coincident charged fragments have been determined. Such exclusive measurements allow event-by-event reconstruction of the excited primary nuclei. By selecting specific exit channels, we studied the decay of hot nuclei over a wide range of excitation energy, extending up to 6A MeV. The behaviour of the excited nuclei is consistent with a statistical description. The fragmentation mechanism was also investigated. Although the lowest excited channels are well reproduced by a standard sequential binary decay model, evidence is observed for an evolution with excitation energy of the time scale for particle emission. Model calculations have been performed which show that the lifetime of the excited chlorine projectile should decrease by a factor of 4 when the excitation energy increases from 2.3A MeV to 4.3A MeV.

E

NUCLEAR REACTIONS $^{197}\text{Au}(^{35}\text{Cl},\text{X})$, $E = 30\text{A MeV}$; measured $\sigma(Z,E,\Theta)$; high multiplicity coincidence; event-by-event analysis of $\Sigma Z=17$ channels; deduced excitation energy; source thermalization; breakup mechanisms; time scale; statistical model calculations.

Correspondence to: L. Beaulieu, Département de physique, Université Laval, Ste-Foy(Qué), Canada, G1K 7P4.

¹ Present address: Département de Radio-Oncologie, Hôtel-Dieu de Québec, 1 rue Collins, Québec, Canada, G1R 4J1

* Experiment performed at TASCC, AECL Research, Chalk River Laboratories, Chalk River, Ontario, Canada, KOJ 1J0

1. Introduction

Excitation energy is one of the most relevant quantities in the characterization of hot nuclei formed in intermediate energy heavy-ion collisions [1-3]. Most existing experimental data describe the decay of highly excited nuclei as a function of bombarding energy [4-12], but so far, very few experiments have studied the behaviour of nuclear matter as a function of excitation energy [13-17]. The need to remove the bombarding energy dependence and instead use the excitation energy has often been mentioned [1-3,18]. In that way it would be possible to compare data from various systems on a common basis [18-19].

At a given excitation energy, competition between various decay channels is observed [14,20,21]. Thus, exclusive experiments, which can detect most or all fragments, are needed to identify the different decay channels before one can study the breakup mechanism and/or time scale. Such experiments can be accomplished by a study of peripheral collisions [20-25]. This has numerous advantages [1]: the source is well identified, the degree of thermalization can be determined and the excitation energy evaluated from the decay products.

Excitation energies measured in peripheral interactions generally range from 1A to 6A MeV [14,25]. This range of excitation energy is predicted [26,27] to be a transition region from sequential binary decay to prompt or simultaneous multifragmentation. Indeed, changes in the decay configuration from binary fission at low excitation energy to multibody decay processes around 5A MeV of excitation energy have been observed experimentally [17,18]. At higher excitation energy,

events with a high multiplicity of intermediate mass fragments (IMF) were observed [5-9,28-30].

In the present work, a large number of exit channels from the peripheral collisions of ^{35}Cl on a gold target have been observed. The quasi-projectile(QP) excitation energy was determined, event by event, and its evolution for various exit channels has been characterized. This approach allowed the investigation of hot nuclear matter over a wide range of excitation energy leading to QP decay modes from binary fission to multiple IMF production. The experimental setup and method are described in sect. 2. Coincidence measurements and absolute cross sections are presented in sect. 3. Sect. 4 deals with the evolution of the excitation energy and the degree of thermalization of the source. QP fragmentation mechanisms and lifetime are discussed in sect. 5. Finally, in sect. 6, the results are summarized and conclusions are drawn about the observed trends.

2. Experimental procedure

The experiment was performed at the Tandem Accelerator Superconducting Cyclotron (TASCC) facility at Chalk River. A 30A MeV ^{35}Cl beam was used to bombard a 2.1 mg/cm^2 thick gold target. The outgoing projectile-like fragments were detected in a forward array made of 40 ΔE -E phoswich detectors mounted in three concentric rings, as shown in Fig. 1. The two outer rings were each made of 16 trapezoidal detectors. The fast scintillator, 0.7 mm thick, was coupled by a heat-

press technique to a 12-cm-long slow scintillator [32]. Energy thresholds for the thin plastic varied from 7.5A MeV for $Z=1$ and 2 to 22.8A MeV for $Z=17$. These two rings provided almost complete coverage of the angular region between 10.5° to 24° for all azimuthal angles. To improve the coverage around the grazing angle of 7.8° , 8 tapered fast/slow plastic scintillators were added as an inner ring. They covered 60.5% of the solid angle between 6° and 10° . Each detector was made of a 1mm fast scintillator glued on a 40cm slow scintillator [33]. The energy thresholds from the 1mm ΔE layer range from 9A MeV for $Z = 1$ and 2 up to 28A MeV for $Z = 17$. The complete 3-ring set-up covered a solid angle of 0.459 sr and provided the granularity needed to study high multiplicity events in peripheral collisions. The beam current was kept below 1 nA to avoid saturation due to high counting rates in the inner detectors.

The phoswich detectors allowed an excellent charge(Z) separation for all charges from $Z = 1$ up to 18 and the protons were resolved from other hydrogen isotopes. The energy calibration of the detectors has been accomplished by means of three different reactions: elastic scattering of ^{35}Cl and ^{12}C on a gold target at 30A MeV and deuterons produced from the knock-out reaction $^2\text{H}(^{12}\text{C},^2\text{H})^{12}\text{C}$ (ground and first excited states) with a 95 MeV ^{12}C beam from the tandem accelerator. The ΔE punch-through energies from $Z = 2$ to 16 were also used as additional values. The energy response was then adjusted as a function of the mass, charge and light output as described in ref. 32. The energy resolution and the precision of the calibration function gave an accuracy

of 10%. Inclusive energy spectra for $Z = 1$ to 17, detected in the second ring, are shown in Fig. 2. The arrows indicate the energy corresponding to the beam velocity. One can see that the quasi-elastic peak and some projectile-like fragments have a distribution centered near the beam velocity. The sharp cut off on the low-energy side is due to the energy threshold of the detectors.

Events were recorded both in singles and coincidence modes. Data with good statistics were obtained for charged-particle multiplicities as high as seven.

3. Experimental results: Exclusive data

In this work, we consider the multiple breakup of the QP. We therefore focus on the events for which the total charge detected is equal to the projectile charge ($\Sigma Z = 17$). Target contributions in the form of low-energy evaporated particles are eliminated by the detector energy threshold.

3.1. Differential cross sections

The differential cross sections of all charged fragments measured in coincidence ($\Sigma Z = 17, M \geq 2$) are shown in Fig. 3. The straight lines come from exponential fits to the angular distributions and were used to determine the detection efficiency (cf. sect. 3.2). The slopes of the distributions become steeper with increasing charge, which is characteristic of peripheral collisions [22,34]. Moreover, an inclusive analysis reveals the same trend with little change of the slope as compared with coincidence analysis. This indicates that the angular distributions are dominated by the QP breakup in the angular range covered by the array.

In coincidence mode, it was also observed that for a given charge, the slope of the angular distribution is the same under different conditions of detected particle multiplicity, pointing out the relative independence of the angular distributions with respect to the breakup channels.

3.2. Detection efficiency

The experimental set-up covers a large solid angle around the beam axis at forward angles, making it an efficient tool for the study of the projectile breakup. Since the particle-particle correlation in the exit channels does not affect the angular distribution, one can determine

empirically the detection efficiency for each charged particle by extrapolating the experimental angular distribution to the angular range not covered by the array [20]. The detection efficiencies range from 39.1% for $Z=1$ to 1.4% for $Z=16$ and peak at 50.8% for $Z=5$. The 6° hole around the beam axis causes the small efficiencies for the heaviest fragments.

3.3. Exit channel cross sections

Dissociation of the projectile into as many as 7 charged fragments was observed. The absolute cross sections of 98 exit channels, shown in Fig. 4a versus the most positive ground-state Q value of their respective isotopic combinations, were deduced from the measured number of events, target thickness, detector solid angles and the integrated beam current. Corrections were made for the acquisition dead time and the detection efficiency for each channel. The latter was obtained by multiplication of the detection efficiencies for individual fragments in a given channel. The use of a unique Q value, in this case $Q_{\max}$, is necessary because the different channels are distinguished only by their atomic-number combinations [20]. Statistical errors on the cross sections are small but the determination of the detection efficiency may introduce a systematic error up to a factor of 2 in the absolute cross sections. However, one may note that these cross sections cover more than five orders of magnitude.

Theoretical calculations of the relative cross sections have been done with the statistical code Brandex [35] and compared with the data. Using the experimental excitation-energy distribution for the projectile as input, the code gives the probability of the different channels as a function of the maximum Q value. Fig. 4b shows the results of this calculation for the same 98 experimental channels. The qualitative similarity between the two distributions is striking. It must be noted, however, that the calculated probabilities extend over 8 orders of magnitude, which is 3 orders greater than the experimental data. It seems that the probability of high-multiplicity channels is underestimated by a calculation based on statistical binary fragmentation. This result is consistent with the one found with a lighter projectile, ^{16}O [20].

For further analysis of the QP excitation energy and breakup mechanism, a subset of 32 channels, listed in Table 1, was considered. The channels chosen are those with the highest statistics for each multiplicity.

4. Projectile excitation

4.1. Kinematical reconstruction

Assuming that all the QP fragments are detected, then the QP c.m. velocity is given by:

$$\bar{V}_{qp} = \frac{\sum_n m_n \bar{v}_n}{\sum_n m_n} \quad (1)$$

where m_n are the average masses deduced from a previous experiment [21]. Fig. 5 shows the reconstructed V_{qp} distribution for QP breakup, under the condition $\Sigma Z=17$. The velocity distribution peaks near the beam velocity which is a strong indication that the charged fragments detected come from the QP [20].

We obtained the excitation energies (E_{qp}^*) of the primary nuclei, event by event, by combining the Q value of the channel detected with the relative kinetic energy:

$$E_{qp}^* = \frac{1}{2} \sum_n m_n |\bar{v}_n - \bar{V}_{qp}|^2 - Q_{\max} \quad (2)$$

The sum runs over the number of fragments; v_n is the fragment velocity and V_{qp} is given by Eq.(1). $Q_{\max}$ is the most positive Q value of each channel considered in Eq.(2). The excitation-energy distribution for all $\Sigma Z=17$ channels is shown in Fig. 6a. High excitation energies, up to maximum of 6A MeV, have been reached.

4.2. Evolution of the excitation energy and thermalization

Fig. 6b shows the contribution of the different multiplicities to the total excitation-energy distribution, displaying an increase in excitation energy with the multiplicity. This progression is not simply due to the increase of the Q values. In fact, the average of each distribution plotted as a function of its multiplicity gives a clear picture of the evolution of the excitation energy (Fig. 7) when compared to the Q value of the channel with the highest cross section for each multiplicity. The increase in average excitation energy with the multiplicity of charged particles is larger than the Q -value increase, indicating highly dissipative processes [36].

Fig. 7 exhibits the linear dependence of the average excitation energy and Q value on the multiplicity. Thus, at each multiplicity, the ratio of $\langle E_{qp}^* \rangle$ to Q is approximately a constant. The energy difference between the excitation energy and the Q value is therefore consistent with a level density of the system, $\rho(E^*)$, which increases with excitation energy, as it is characteristic of an equilibrated system. Similar behaviour has been found for more highly excited systems in this mass region [37].

Another approach can be used to investigate the statistical behaviour of the source. The average excitation energy of an exit channel containing a projectile-like fragment (PLF) with $Z \geq 5$ is plotted, in Fig. 8, versus the number of α particles for each of these channels. The

four diagonal trends represent channels with 0,1,2 and 3 hydrogen nuclei. Since we required $\Sigma Z = 17$, the mass of the PLF is a function of the number of α 's. As it can be seen in this graph, a nearly constant value of about 25 MeV of excitation energy is needed for the emission of an additional alpha particle for all exit channels. This independence indicates that the primary QP nuclei were thermally equilibrated.

The value of 25 MeV per emitted alpha particle has also been found recently [39] for a different projectile, ^{24}Mg , and also in α transfer between projectile and target. This value could not be accounted for by a simple addition of the Q values and the two-body spherical Coulomb barriers representing the minimum excitation energy to produce a channel. However, for statistical emission, one would expect a nearly constant value of required average excitation energy.

4.3. Dependence of the cross section on the excitation energy

As has been done for binary decay, Moretto et al. [38] have used the concept of the saddle-point barrier in describing statistical multifragmentation (which could be sequential or simultaneous). They have proposed that the differences of the barriers at the saddle point among the decay configurations for a given multiplicity are small compared to the differences between the average "barriers", B_n , of these configurations. This results in a hierarchy of barriers, $B_2 < B_3 < \dots < B_n$.

Although the values of these barriers for high-order configurations are not known, the experimental excitation energies are much higher

than the ground-state Q values and, for highly excited nuclei, they should also be much higher than the emission barriers. Thus in a qualitative description, the values of B_n can be approximated by the Q values. If a real difference between the barriers exists, this should be reflected by the general evolution of the Q value for the most probable channel. Let us recall that each Q value in Fig.7 is the one corresponding to the channel with the highest cross section for each multiplicity. Fig. 7 seems to provide confirmation of such a hierarchy.

Following Moretto and co-workers [38], the decay probability P_n for each channel should be proportionnal to the level density ρ

$$P_n(E^*) \propto \rho(E^* - B_n) \quad (3)$$

where the excitation energy, $E^* \gg B_n \approx |Q|$. Therefore Eq.(3) gives a relationship for the probability as a function of the level density and depends on the excitation energy and the Q value for any multiplicity n .

It has been found in various experiments [20,40-43] that the cross sections of channels observed in heavy-ion reactions are dependent on the Q values. The results, shown in Fig. 4a, support such a dependence but with larger fluctuations. Pouliot et al. [20,43] have shown for light systems that this dispersion can be attributed to the different isotopic combinations leading to a given channel. From Eq.(3), one expects that the probability, and therefore the cross section, depends more on the excitation energy than on the Q value. The cross sections of all channels in Table 1 are shown in Fig. 9 versus: a) their average excitation energy and b) their maximum Q value. The cross sections are strongly

dependent on the excitation energy, as expected (Eq.3). The Q-value dependence is shown for comparison.

5. Breakup mechanisms

Breakup of highly excited nuclei can be divided into two opposite extremes: succession of binary fissions [44] and simultaneous (prompt) multifragmentation [26,27]. The first mode of disintegration, also called sequential decay, is characteristic of long time processes of the order of 1000 fm/c. The second mode corresponds to a fast mechanism where the nuclei “explode”. Thus the lifetime of hot nuclei is closely related to the nature of the breakup mechanism [2,3]. Observables sensitive to time scale such as event-shape analysis [4,15,45,46] and relative angle distributions [13,25,47] have been used to probe the breakup mechanisms.

From data obtained at different beam energies, evolution of the emission time has been observed [4,13,47]. However, it is not clear how the time scale evolves. These studies were based on the multiplicity of the detected fragments and thus mix many different decay channels corresponding to a wide range of excitation energy. It would be preferable to study the breakup mechanisms and/or time scale as a function of the excitation energy rather than the beam energy [2,3,17].

In the present analysis, the breakup mechanisms and the associated time scale have been studied by a careful selection of specific decay channels of increasing excitation energy. In particular, to eliminate part of the uncertainty in the isotopic composition of the exit channels, we considered only those channels with a PLF and alpha particles (more than 90% of $Z = 2$ are alpha particles).

5.1. Relative angles

The first observable used represents the relative c.m. angles (folding angles) of all pairs of alpha particles in a given channel. It is predicted that for a prompt breakup mechanism, small relative angles will be suppressed by Coulomb repulsion [45]. Furthermore, phase space constraints imply a distribution peaked at lower relative angles than the sequential fragmentation. Still, the difference between the two decay modes is model-dependent.

Results of the simulations using the code SOS [48] were compared with experimental data. Sequential fragmentation events were generated with the experimental excitation-energy distribution (Fig. 6) as input. For each event corresponding to the selected channel, the simultaneous multifragmentation event was obtained by randomly positioning the final sequential fragments in the freeze-out volume, from which they move following Coulomb trajectories. For both mechanisms, the resulting kinematical variables are boosted into the laboratory system and filtered to reproduce experimental conditions of geometry and detector energy thresholds.

The experimental relative angle distributions are shown in Fig. 10 (histogram) for $Al + 2\alpha$, $Na + 3\alpha$, $F + 4\alpha$, $N + 5\alpha$ and $B + 6\alpha$ channels. At low excitation energy, 1.47A MeV, the experimental results are well reproduced by the sequential simulation. It is interesting to note the progression with increasing excitation energies. For $Na + 3\alpha$ and $F + 4\alpha$, the region of small relative angle is well reproduced by both simulations, but the peaks of the experimental distributions shift to lower values. On the other hand, for highly excited channels, such as $B + 6\alpha$, the overall distribution is best reproduced by the prompt simulation.

Although the statistics do not permit determination of a specific breakup mechanism, there is obviously a smooth progression in the observed relative-angle distributions from 1.47A MeV to 4.3A MeV of excitation energy.

5.2. Event-shape analysis

The envelope shape of the velocity distributions constitutes another approach for investigating the breakup mechanism [4,15,45,46]. The velocity distribution for sequential decay will have a more elongated shape corresponding to time-ordered emission while

the isotropic emission of simultaneous breakup leads to a spherical shape.

In the center of mass, the kinetic energy-flow tensor is defined as [49]

$$T_{ij} = \frac{\sum_n P_i^{(n)} P_j^{(n)}}{2m_n} \quad (4)$$

where n represents the number of fragments and i,j the cartesian coordinates. $P^{(n)}$ and m_n are the momentum and the mass of the n -th fragment. One can use ordered eigenvalues of Eq. 4, $t_1 < t_2 < t_3$ and, define the reduced quantities

$$q_i = t_i^2 / \sum_{j=1}^3 t_j^2 \quad (5)$$

The sphericity and coplanarity are respectively defined as $\frac{3}{2}(1-q_3)$ and $\frac{\sqrt{3}}{2}(q_2-q_1)$. The investigation of the event shape in the sphericity-coplanarity plane (S,C) is delimited [45] by (0,0), (3/4, $\sqrt{3}/4$) and (1,0) which correspond to a cigar-like, disk and spherical shape respectively.

The average of the sphericity-coplanarity distribution is shown in Fig. 11, for a)Na + 3 α , b)F + 4 α , c)N + 5 α and d)B + 6 α . Comparison with sequential and prompt simulation is made under the same conditions as in the previous section. The use of the average masses introduces an error of ± 0.002 in the sphericity plane and ± 0.001 in the coplanarity

plane while errors in the angle determination from the position of the detectors are negligible. Finally, the non-detection of neutrons has little effect in the case of the sequential simulation but underestimates the sphericity values in the case of prompt simulation [50].

First, by looking at the simulation, one can note that the distinction between the two mechanisms is improved as the number of fragments increases. The experimental S-C for the channel Na-3 α (Fig.11a) is in good agreement with sequential fragmentation, while at higher excitation energies, the experimental results lie between the predictions from the two simulations. The sequential simulation represents events for which, in each step of the decay, the excited residues have time to thermalize. The time scale is considered as infinitely long. At the opposite extreme, the prompt simulation gives events with instantaneous emission time. Thus, the data in Fig. 11 are consistent with an evolution of the time scale for particle emission with increased excitation energy. Previous results [4] show the same trend but as a function of the bombarding energy from 35A MeV to 85A MeV. Our result suggests, that for light particle emission, the time scale remains between the two extremes for the range of excitation energy studied here.

The lifetimes of excited chlorine nuclei were calculated as a function of the initial excitation energy, using a sequential binary-decay model [51,52]. The lifetime is here defined as the time needed to evaporate the first alpha particle. Fig. 12 presents the lifetime of the chlorine projectile versus its excitation energy. One can see that the emission of the first alpha could be as fast as 90 fm/c at 4.3A MeV of excitation en-

ergy compared to an average value of 1600 fm/c. However, using the mean values, model calculations predict the lifetime to decrease by a factor of 4 as the excitation energy goes from $2.3A$ MeV to $4.3A$ MeV.

That result is consistent with calculations for neutron emission [3], which gives a factor 3, and with experimental values obtained by Louvel et al. [13] at two different beam energies. It supports the present progression found in the relative angle distributions and in the event shape analysis with increasing excitation energy.

6. Summary and conclusions

The breakup of highly excited projectiles has been investigated in the reaction $^{35}\text{Cl} + ^{197}\text{Au}$ at $30A$ MeV. All charged fragments from 98 exit channels were detected in a forward array made of 40 phoswich detectors. The energy thresholds of the detectors combined with the requirement that the total detected charge be equal to the charge of the projectile are strong criteria to select the QP as the source. The angular and velocity distributions observed are typical of particles emitted from the QP in peripheral collisions.

The excitation energies of the primary nuclei have been determined, event by event, to range from $0.7A$ to about $6A$ MeV. Projectile excitation was well described by a statistical approach and its evolution governed by the available phase space. We have also

investigated statistical emission by looking at alpha-particle emission from various channels. Each alpha particle emitted is associated with an average excitation energy of 25 MeV; this value is independent of the exit channel.

For all 98 exit channels, the absolute cross sections were determined and the observed yields versus $Q_{\max}$ agree well with predictions. When the excitation energies are much higher than the barriers, B_n , the absolute cross sections have been found to be strongly dependent on the excitation energy.

The space-time evolution of the reaction was studied as a function of excitation energy. At low excitation energies, the data are in good agreement with the standard binary-decay model. However, the relative-angle distributions and the event-shape analysis indicate an evolution of the kinematical variables with excitation energy. Simulations show that this evolution is consistent with a dependence of the projectile fragmentation time scale upon excitation energy.

Excitation energy is one of the crucial quantities to be measured for a system. In particular, such measurements on the evolution of the decay configuration [17] and determination of the time scale via the correlation function [11,31] are of interest for subsequent experiments.

We are grateful to Dr. B. Djerroud for the simulations of the projectile lifetime and for suggestions and comments on this article. This work has been supported by the Natural Science and Engineering Research Council of Canada.

References

- 1) E. Suraud, B. Tamain and C. Grégoire, *Progr. Nucl. Part. Sci.* 23 (1989) 357.
- 2) W. A. Friedman, *Proc. Int. Symp. Toward a Unified Picture of Nuclear Dynamics*, Nikko, Japan, 1991, edited by Y. Abe, S. M. Lee and F. Sakata, *AIP Conf. Proc.* 250 (1992) 422.
- 3) B. Borderie, *Ann. Phys. Fr.* 17(1992) 349.
- 4) D. A. Cebra, S. Howden, J. Karn, A. Nadasen, C. A. Ogilvie, A. Vander Molen, G. D. Westfall, W. K. Wilson and J. S. Winfield, *Phys. Rev. Lett.* 64 (1990) 2246.
- 5) D. E. Fields, K. Kwiatkowski, D. Bonser, R. W. Viola, V. E. Viola, W. G. Lynch, J. Pochodzalla, M. B. Tsang, C. K. Gelbke, D. J. Fields and S. M. Austin, *Phys. Lett B* 220 (1989) 356.
- 6) R. T. deSouza, L. Phair, D. R. Bowman, N. Carlin, C. K. Gelbke, W. G. Gong, Y. D. Kim, M. A. Lisa, W. G. Lynch, G. F. Peaslee, M. B. Tsang, H. M. Xu, F. Zhu and W. A. Friedman, *Phys. Lett. B* 268 (1991) 6.
- 7) T. C. Sangster, M. Begemann-Blaich, Th. Blaich, H. C. Britt, A. Elmaani, N. N. Ajtanand and M. N. Manboudiri, *Phys. Rev. C* 47 (1993) R2457.
- 8) D. R. Bowman, G. F. Peaslee, N. Colonna, R. J. Charity, M. A. McMahan, D. Delis, H. Han, K. Jing, G. J. Wozniak, L. G. Moretto, W. L. Kehoe, B. Libby, A. C. Mignerey, A. Moroni, S. Angius, I. Iori, A. Pantaleo and G. Guarino, *Nucl. Phys. A* 523 (1991) 386.

- 9) J. L. Wile, D. E. Fields, K. Kwiatkowski, S. J. Yennello, K. B. Morley, E. Renshaw, V. E. Viola, C. K. Gelbke, W. G. Lynch, N. Carlin, H. M. Xu, W. G. Gong, M. B. Tsang, J. Pochodzalla, R. T. deSouza, D. J. Fields and S. M. Austin, *Phys. Rev. C* 45 (1992) 2300.
- 10) R. T. deSouza, D. Fox, W. A. Friedman, L. Phair, D. R. Bowman, C. K. Gelbke, W. G. Gong, Y. D. Kim, M. A. Lisa, W. G. Lynch, G. F. Peaslee, M. B. Tsang and F. Zhu, *Phys. Lett. B* 300 (1993) 29.
- 11) D. Fox, R. T. deSouza, L. Phair, D. R. Bowman, N. Carlin, C. K. Gelbke, W. G. Gong, Y. D. Kim, M. A. Lisa, W. G. Lynch, G. F. Peaslee, M. B. Tsang and F. Zhu, *Phys. Rev. C* 47 (1993) R421.
- 12) E. Bauge, A. Elmaani, Roy A. Lacey, L. Lauret, N. N. Ajitanand, D. Craig, M. Cronqvist, E. Gualtieri, S. Hannuschke, T. Li, B. Llope, T. Reposeur, A. Vander Molen, G. D. Westfall, J. S. Winfield, J. Yee, S. Yennello, A. Nadasen, R. S. Tickle and E. Norbeck, *Phys. Rev. Lett.* 70 (1993) 3705.
- 13) M. Louvel, G. Bizard, R. Bougault, R. Brou, E. Buta, D. Durand, A. Genoux-Lubain, A. Hajfani, T. Hamdani, J. L. Laville, C. LeBrun, J. F. Lecolley, J. P. Patry, J. Péter, N. Prot, R. Regimbart, J. C. Steckmeyer, B. Tamain, A. Badala, H. Doubre, Y. El-Masri, H. Fugiwara, K. Hagel, F. Hanappe, S. Jeong, G. M. Jin, S. Kato, S. Lee, T. Matsuse, T. Motobayashi, A. Péghaire and F. St-Laurent, contribution to the "XXX Int. Winter Meeting on Nuclear Physics", Bormio (Italy), January 27th-February 1st, 1992 and Laboratoire de Physique Corpusculaire de Caen, Report LPCC 92-01.

- 14) J. Pouliot, G. Auger, P. Bricault, Y. Chan, D. Doré, S. Groult, D. Horn, S. Houde, R. Laforest, E. Plagnol, R. Roy and C. St-Pierre, *Phys. Lett. B* 263 (1991) 18.
- 15) A. Badalà, R. Barbera, A. Palmeri, G. S. Pappalardo, F. Riggi, G. Pollarolo and C. H. Dasso, *Phys. Lett. B* 299 (1993) 11.
- 16) R. Trockel, K. D. Hildenbrand, U. Lynen, W. F. J. Müller, H. J. Rabe, H. Sann, H. Stelzer, W. Trautmann, R. Wada, E. Eckert, P. Kreutz, A. Kühmichel, J. Pochodzalla and D. Pelte, *Phys. Rev. C* 39 (1989) 729.
- 17) G. Bizard, R. Bougault, R. Brou, J. Colin, D. Durand, A. Genoux-Lubain, J. L. Laville, C. Le Brun, J. F. Lecolley, M. Louvel, J. Péter, J. C. Steckmeyer, B. Tamain, A. Badalà, T. Motobayashi, G. Rudolf and L. Stuttgé, *Phys. Lett. B* 302 (1993) 162.
- 18) Y. Blumenfeld, N. Colonna, P. Roussel-Chomaz, D. N. Delis, K. Hanold, J. C. Meng, G. F. Peaslee, Q. C. Sui, G. J. Wozniak, L. G. Moretto, B. Libby, A. C. Mignerey, G. Guarino, N. Santoruvo and I. Iori, *Phys. Rev. Lett.* 66 (1991) 567.
- 19) P. Roussel-Chomaz, N. Colonna, Y. Blumenfeld, B. Libby, G. F. Peaslee, D. N. Delis, K. Hanold, M. A. McMahan, J. C. Meng, Q. C. Sui, G. J. Wozniak, L. G. Moretto, H. Madani, A. A. Marchetti, A. C. Mignerey, G. Guarino, N. Santoruvo, I. Iori and S. Bradley, *Nucl. Phys. A* 551 (1993) 508.
- 20) J. Pouliot, Y. Chan, D. E. DiGregorio, B. A. Harmon, R. Knop, C. Moisan, R. Roy and R. G. Stokstad, *Phys. Rev. C* 43 (1991) 735.
- 21) L. Beaulieu, Université Laval, M. Sc. Thesis, 1992.

- 22) C. Pruneau, L. Potvin, R. Roy, C. St-Pierre, G. C. Ball, R. Bougault, E. Hagberg, D. Horn, D. Cebra, D. Fox and G. D. Westfall, Nucl. Phys. A500 (1989) 168.
- 23) J. C. Steckmeyer, G. Bizard, R. Brou, P. Eudes, J. L. Laville, J. B. Natowitz, J. P. Patry, B. Tamain, A. Thiphagne, H. Doubre, A. Péghaire, J. Péter, E. Rosato, J. C. Adolff, A. Kamili, G. Rudolf, F. Scheibling, F. Guilbault, C. Le Brun, F. Hanappe, Nucl. Phys. A500 (1989) 372.
- 24) D. Doré, L. Beaulieu, R. Laforest, J. Pouliot, R. Roy, C. St-Pierre, G. Auger, P. Bricault, S. Groult, E. Plagnol and D. Horn, Nucl. Phys. A545 (1992) 363c.
- 25) J. Pouliot, D. Doré, R. Laforest, R. Roy, C. St-Pierre and J. A. Lopez, Phys. Lett. B299 (1993) 210.
- 26) X. Campi, J. Desbois and E. Lipparrini, Phys. Lett. 142(1984) 8.
- 27) J. P. Bondorf, R. Donangelo, I. N. Mishustin and H. Schulz, Nucl. Phys. A443 (1985) 460.
- 28) Y. D. Kim, M. B. Tsang, C. K. Gelbke, W. G. Lynch, N. Carlin, Z. Chen, R. Fox, W. G. Gong, T. Murakami, T. K. Nayak, R. M. Ronningen, H. M. Xu, F. Zhu, W. Bauer, L. G. Sobotka, D. Stracener, D. G. Sarantites, Z. Majka, V. Abenante and H. Griffin, Phys. Rev. Lett 63 (1989) 494.
- 29) D. R. Bowman, G. F. Peaslee, R. T. deSouza, N. Carlin, C. K. Gelbke, W. G. Gong, Y. D. Kim, M. A. Lisa, W. G. Lynch, L. Phair, M. B. Tsang, C. Williams, N. Colonna, K. Hanold, M. A. McMahan, G. J. Wozniak, L. G. Moretto and W. A. Friedman, Phys. Rev. Lett. 67 (1991) 1527.

- 30) D. R. Bowman, C. M. Mader, G. F. Peaslee, W. Bauer, N. Carlin, R. T. deSouza, C. K. Gelbke, W. G. Gong, Y. D. Kim, M. A. Lisa, W. G. Lynch, L. Phair, M. B. Tsang, C. Williams, N. Colonna, K. Hanold, M. A. McMahan, G. J. Wozniak, L. G. Moretto and W. A. Friedman, *Phys. Rev. C* 46 (1992) 1834.
- 31) Y. D. Kim, R. T. deSouza, D. R. Bowman, N. Carlin, C. K. Gelbke, W. G. Gong, W. G. Lynch, L. Phair, M. B. Tsang, F. Zhu and S. Pratt, *Phys. Rev. Lett* 67 (1991) 14.
- 32) C. A. Pruneau, G. C. Ball, P. Dymtrenko, E. Hagberg, D. Horn, M. G. Steer, R. B. Walker, T. Whan, C. Rioux, R. Roy, C. St-Pierre, T. E. Drake and A. Galindo-Uribarri, *Nucl. Inst. Meth.* A297(1990)404.
- 33) J. Pouliot, Y. Chan, A. Dacal, A. Harmon, R. Knop, M. E. Ortiz, E. Plagnol and R. G. Stokstad, *Nucl. Inst. Meth.* A270(1988)69.
- 34) Ch. Egelhaaf, M. Bürgel, H. Fuchs, A. Gamp, H. Homeyer, D. Kovar and W. Rauch, *Nucl. Phys.* A405 (1983) 397.
- 35) R. Knop and R. G. Stokstad, LBL report 26439, 1988.
- 36) D. Guerreau, Enrico Fermi Summer Courses, CXII, Verena(Italy), July 11-21, 1989
- 37) D. Horn, G. C. Ball, D. R. Bowman, A. Galindo-Uribarri, E. Hagberg, R. B. Walker, R. Laforest and J. Pouliot, submitted to *Phys. Lett. B*.
- 38) L. G. Moretto, K. Tso, D. Delis, N. Colonna and G. J. Wozniak, *Prog. Part. Nucl. Phys.* Vol. 30 (1993) 135.
- 39) D. Doré et al., article submitted to *Phys. Lett. B*

- 40) A. G. Artukh, V. V. Avdeichikov, J. Erö, G. F. Gridnev, V. L. Mikheev, V. V. Volkov et J. Wilczynski, Nucl. Phys. A160 (1971) 511.
- 41) V. K. Lukyanov and A. I. Titov, Phys. Lett. 57B (1975) 10
- 42) D. Doré, Université Laval, M. Sc. Thesis, 1990
- 43) J. Pouliot, Y. Chan, A. Dacal, D. E. DiGregorio, B. A. Harmon, R. Knop, M. E. Ortiz, E. Plagnol, R. G. Stokstad, C. Moisan, L. Potvin, C. Rioux and R. Roy, Phys. Lett. B223 (1989) 16.
- 44) J. P. Bondorf, Nucl. Phys. A387 (1982) 25.
- 45) J. A. Lopez and J. Randrup, Nucl. Phys. A491 (1989) 477.
- 46) B. A. Harmon, J. Pouliot, J. A. Lopez, J. Suro, R. Knop, Y. Chan, D. E. DiGregorio and R. G. Stokstad, Phys. Lett. B225 (1990) 234.
- 47) R. Bougault, J. Colin, F. Delaunay, A. Genoux-Lubain, A. Hajfani, C. LeBrun, J. F. Lecolley, M. Louvel and J. C. Steckmeyer, Phys. Lett. B232 (1989) 291.
- 48) J. A. Lopez et J. Randrup, Comp. Phys. Comm 70 (1992) 92.
- 49) M. Gyulassy, K. A. Frankel and H. Stöcker, Phys. Lett. B110 (1982) 185.
- 50) J. P. Bondorf, C. H. Dasso, R. Donangelo and G. Pollarolo, Phys. Lett. B240 (1990) 28.
- 51) J. Richert and P. Wagner, Z. für Phys. A341 (1992) 171 and references therein.
- 52) B. Djerroud, Ph. D. Thesis, Strasbourg University, 1992, Report no. CRN/PN 92-32, 1992.

FIGURE CAPTIONS

Fig. 1. Experimental set-up. 40 fast/slow phoswich detectors were mounted in three concentric rings, from 6° to 24° around the beam axis.

Fig. 2. Inclusive energy spectra for $Z = 1$ to 17. The arrows indicate the corresponding energy of the beam velocity. The sharp cuts in the low-energy part of the spectra are due to the energy threshold of the detectors.

Fig. 3. Differential cross sections for projectile breakup fragments. The lines represent exponential fits and have been used to determine the detection efficiency. Correspondence between the symbols and the particle charges is indicated at the right of the figure. The factors applied for better separation of the lines are also shown. Errors are in most cases smaller than the symbols.

Fig. 4. a) Experimental cross sections of 98 exit channels as a function of the most positive ground-state Q value corresponding to all possible isotopic combinations for each channel. b) Theoretical calculations for the same channels, based on a statistical decay model.

Fig. 5. Reconstructed velocity for projectile breakup in units of c . The arrow indicates the beam velocity.

Fig. 6. a) Excitation energy distribution obtained from eq. 2 for all the 98 projectile exit channels. b) Contribution of the different multiplicities to the total excitation energy distribution. The yields of these spectra are in arbitrary units to permit a better distinction between them.

Fig. 7. Evolution of the average excitation energy (left-hand ordinate) as a function of the charged particle multiplicity (circles). Black squares represent the ground-state Q value (right-hand ordinate) for the channel with the highest cross section at each multiplicity.

Fig. 8. Evolution of the average excitation energy as a function of the alpha particle multiplicity in each channel. Channels from Table 1 with only one heavy residue are shown. See text for details.

Fig 9. Dependence of the absolute cross section on: a) the excitation energy and b) the Q value for the 32 channels listed in Table 1.

Fig 10. Comparison of the relative angles between all pairs of alpha particles for five different channels of increasing (a to e) average excitation energy. The histograms represent the experimental data. The full and the dash curves correspond respectively to sequential and simultaneous multifragmentation calculations.

Fig 11. Analysis in the sphericity-coplanarity plane of the event shape. The channels are a)Na-3 α , b)F-4 α , c)N-5 α and d)B-6 α . Centroids for the experimental data are given by circle, the rectangle is for the sequential simulation and the diamond symbol for prompt simulation. The average excitation energy for each channel is indicated. Error bars, shown when larger than the symbol, correspond to the statistical errors of the mean.

Fig 12. Calculated lifetime of the excited chlorine nuclei as a function of the QP excitation energy. The lifetime is defined as the time needed for the emission of the first alpha particle. The full curves indicate the maximum and the minimum lifetime while the dash curve

represents the mean lifetime. Calculations are based on a sequential binary decay model from ref. 51.

TABLE HEADING

TABLE 1: Subset of 32 exit channels with their maximum Q values and calculated cross sections.

TABLE

Channels	Q (MeV)	σ (mb)
S H	-6.37	4413
P He	-7.00	1265
Si Li	-21.21	12.3
P H H	-17.25	385
Si He H	-14.29	613
Al He He	-16.67	101
Si H H H	-26.79	70.5
Al He H H	-27.81	80.5
Mg He He H	-24.94	72.4
Na Li He H	-44.11	5.33
Na He He He	-26.76	12.9
Ne Li He He	-41.71	1.74
O C He H	-37.01	1.50
N C He He	-33.97	1.09
Mg He H H H	-38.29	19.6
Na He He H H	-39.09	19.4
Ne He He He H	-35.55	13.6
F Li He He H	-54.58	1.57
F He He He He	-37.23	2.28
O Be He He H	-49.03	1.83
O Li He He He	-46.46	1.06
N B He He H	-49.93	1.08
N Be He He He	-50.5	0.86
C C He He H	-44.18	1.37
C B He He He	-51.47	0.97
Ne He He H H H	-49.72	6.55
F He He He H H	-50.82	4.92
O He He He He H	-45.22	6.29
N He He He He He	-41.24	2.82
N He He He He H H	-61.17	3.22
C He He He He He H	-51.45	2.60
B He He He He He He	-52.53	0.54

Table 1

Fig. 1. L. Beaulieu et al.

Fig. 2. L. Beaulieu et al.

Fig 3. L. Beaulieu et al.

Fig 4. L. Beaulieu et al.

Fig. 5. L. Beaulieu et al.

Fig. 6. L. Beaulieu et al.

Fig. 7. L. Beaulieu et al.

Fig. 8. L. Beaulieu et al.

Fig. 9. L. Beaulieu et al.

Fig. 10. L. Beaulieu et al.

Fig. 11. L. Beaulieu et al.

Fig. 12. L. Beaulieu et al.