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Authors

Skulski, W.
Tso, K.
Colonna, N.
et al.

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UNIVERSITY OF CALIFORNIA

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Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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Exploring Multifragmentation with a 4π Detector: Xe-Induced Reactions at E_{beam}=60 MeV/nucleon[#]

W. Skulski,[*] K. Tso, N. Colonna, L. G. Moretto, G. J. Wozniak, D. R. Bowman,
M.Chartier[+], C. K. Gelbke[+], W. C. Hsi[+], M. A. Lisa[+$], W. G. Lynch[+],
G.F.Peaslee[+@], L. Phair[+$], C. Schwarz[+], and M. B. Tsang[+]

ABSTRACT

The reactions ^{129}Xe + ^{27}Al, ^{nat}Cu, ^{89}Y, ^{165}Ho and ^{197}Au at 60 MeV/nucleon were investigated with the combination of a high-resolution forward array of Si-Si-plastic telescopes and a high-efficiency phoswich ball. The projectile-like primary source was reconstructed. Its parallel velocity component is strongly correlated with the observed multiplicity and hence with dissipation. At high multiplicity, large fragments still show a projectile-like and target-like components in their parallel velocity distributions. A further sub-division of highly dissipative events into binary-like and non binary-like subclasses has been performed by applying an additional experimental selection of the orientation of the event in momentum space.

Introduction

The disintegration of highly excited nuclear systems is the subject of much current interest, both experimentally and theoretically (see (1) and references therein). The key quantities determining how the hot nuclear system decays are its size and excitation energy. In experimental studies these quantities are not directly measured. The energy dissipation in the collision can be inferred from the charged particle multiplicity.[2,3)] The size of the hot primary "source" can be accessed by summing all the detected fragments over a suitable range of detection angles.[1)] An important uncertainty still remains: how many hot primary fragments have been produced in the reaction? Theoretical calculations predict that two primary fragments are formed in peripheral collisions, one projectile-like and one target-like, whereas a single equilibrated nuclear system is formed for central events with small impact parameter. Due to fluctuations these two different situations can happen at similar total excitation energy, and thus at similar multiplicity. Therefore, one cannot use particle multiplicity to cleanly separate binary from non-binary reaction events. This is exemplified by a study of the Xe+Bi reaction at 28 MeV/nucleon: a binary reaction mechanism persists even for high particle multiplicity and/or large intermediate mass fragment (IMF) multiplicity.[4)] A clean non-binary reaction mechanism could not be separated at all.

The aim of the present paper is to characterize experimentally reactions of Xe with a range of targets to study to what extent a selection of binary from non-binary events can be achieved at 60 MeV/nucleon bombarding energy.

Experimental procedure

The experiment was performed at the K1200 Cyclotron of the National Superconducting Cyclotron Laboratory at Michigan State University. A 60 MeV/nucleon ^{129}Xe beam bombarded targets of ^{27}Al, ^{nat}Cu, ^{89}Y, ^{165}Ho and ^{197}Au of thickness 2.07, 2.0, 1.0, 2.0 and 1.3

mg/cm^2, respectively. The detection system subtended angles from 2° to 160° with respect to the beam axis and had a geometric acceptance of ~88% of 4π. At forward angles (2° - 16°), fragments (Z = 1 - 54) were detected in a 16-telescope Si(300 μm)-Si(5 mm)-Plastic(7.6 cm) array$^{5)}$ with good energy and position resolution. The geometrical efficiency of the forward array was about 64%. Individual elements were resolved from Z=1 to 54, when counting statistics allowed. Representative detection thresholds in the forward array were 13, 21 and 27 MeV/u for fragments of Z = 8, 20 and 54, respectively. Energy and position calibrations were performed by utilizing analog beams$^{6)}$ of q/A=1/6 [D^4He^+, $^6Li^+$, $^{12}C^{2+}$, $^{18}O^{3+}$] at 22 MeV/nucleon, and two "cocktail" beams$^{6)}$ at 60 MeV/nucleon: [^{30}Si, ^{60}Ni, ^{90}Zr] and [^{43}Ca, ^{86}Rb, ^{129}Xe]. (A "cocktail" beam consists of 3 different ion beams with nearly identical charge to mass ratios.) These low intensity beams were swept directly across each of the array telescopes. These data were used to measure the nonuniformity in the 300 μm ΔE detector thickness and corrections were made off-line. The pulse-height defect was measured and corrected for according to ref. (7). The overall energy calibration was accurate to about 1% and the position calibration to within 1.5 mm.

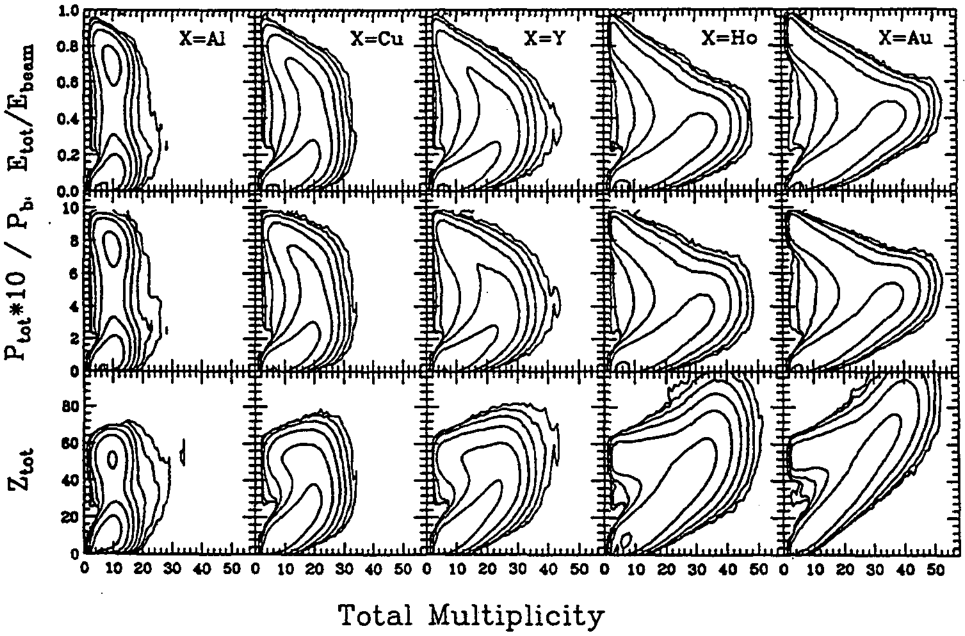

Fig. 1. Logarithmic contour plots of the detected total energy (upper row), total detected parallel momentum (second row) and total detected charge (third row) vs. total charged particle multiplicity, for the 60 MeV/u ^{129}Xe + ^{27}Al, ^{nat}Cu, ^{89}Y, ^{165}Ho and ^{197}Au reactions.

At larger angles (16° - 160°), light charged particles and fragments (Z = 1 - 35) were detected in the MSU Miniball$^{8)}$ consisting of 171 fast plastic (40 μm) - CsI(2 cm) phoswich detectors. The most forward-angle ring and four detectors of the second ring of the Miniball were removed to accommodate the forward-angle Si array. Representative detection thresholds were 2, 3, and 4 MeV/u for Z = 3, 10, and 18 fragments, respectively. For H and He, individual isotopes could be resolved. For heavier elements, only elemental resolution was achieved. The energy calibration was obtained by scaling the previous calibration$^{9)}$ to hydrogen punch-through points in every detector. This procedure was checked for a subset of 8 Miniball detectors that were extensively calibrated by sweeping the q/A=1/6 beams across their face. For this limited subset of detectors, satisfactory agreement with the existing calibration was found.

Results

I. Selection of "completely measured" events

As the excitation energy of the primary reaction products is increased, one expects the number of evaporated neutrons and light charged particles to increase. (Recent measurements[4]) have shown a strong correlation between the measured neutron and charged particle multiplicities.) In our measurements, we utilize the total charged particle multiplicity M, which consists of the measured number of light charged particles (LCPs) and intermediate mass fragments (IMFs). Low M values are characteristic of low-dissipation events, while high M values are associated with more violent collisions. For light targets (Al, Cu) the present experiment does not detect the most peripheral events with good efficiency due to the grazing angle falling below the minimum detection angle of the forward array. In this case a PLF can be detected in the forward array only if it is deflected to $\theta>2^{o}$ due to sequential decay. This introduces a certain bias against large impact parameter events. For heavier targets (Y, Ho, Au), events from a large range of impact parameters can be observed.

In the present experiment the total detected energy can be smaller than the total available energy minus the Q-value because some charged particles may not be observed due to thresholds and dead regions between the detectors. Also, neutrons are not measured by the present experimental setup. Figure 1 shows contour plots of the total detected charge, kinetic energy and linear momentum versus the total number of detected particles M for five targets. For the lightest target ^{27}Al, the distributions have two peaks. For heavier targets, instead of two peaks one observes two branches (e.g., see the Au target). In both cases, the lower peak (or the lower branch) corresponds to the situation when the heavy projectile-like fragment (PLF) is not detected due either to it being emitted at an angle smaller than 2^{o} or in the dead region between telescopes. When the heavy forward-going PLF is not detected, one sees only the light particles emitted from the target and projectile-like residues. (The slow moving target-like fragment (TLF) is below the detector thresholds.) We thus define "completely measured events" as the ones in which the PLF was *not* missed. Experimentally, they are defined as those with the total detected energy of at least 50% of the beam energy (see the first row in Figure 1). This 50% cutoff serves as a convenient discrimination against incompletely measured events, in which the PLF was not detected due to less than 100% detection efficiency.

II. Primary PLF fragments

When the energy dissipation increases, as reflected by the increasing multiplicity, the excitation of the forward-going primary PLF also increases. At large excitation energies, the primary PLF can decay into several secondary fragments. With our forward array we can detect most of them. During the off-line analysis, we reconstructed the primary PLF "source" defined as the sum of all fragments detected in the forward array ($Z_{fragment}>4$).[1]) When discussing "PLF sources", only "completely" measured events will be considered (see previous section).

One of the conclusions of the previous studies summarized in ref. (1) was that slower PLF sources correspond to increased energy dissipation. One can test this by looking at the total detected charge and/or multiplicity in coincidence with PLF sources moving with different velocities. In Figure 2 the parallel velocity of the reconstructed PLF source is presented versus its charge as a contour plot (upper-right panel). The triangular pattern of the charge-velocity contour plots is similar to those previously reported in the La-induced reactions between 35 and 55 MeV/nucleon.[1]) This pattern was previously interpreted as a result of the incomplete fusion followed by extensive particle evaporation, see (1) for details.

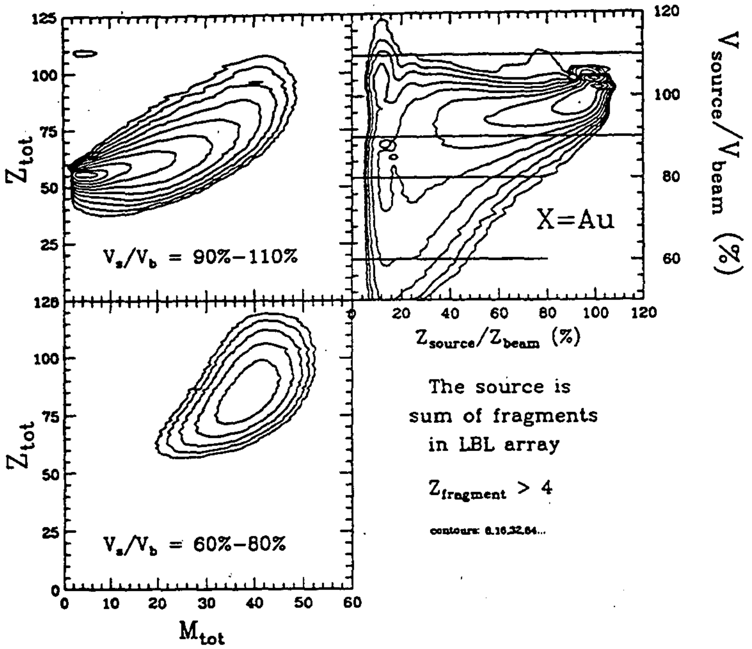

Fig. 2. *Upper right panel:* Contour plot of the mean parallel velocity of the PLF source versus the size of the source (see text). *Left-hand panels:* Distributions of the total detected charge Z_{total} versus multiplicity, gated on two ranges of the PLF source velocity: 90%-110% and 60%-80% of V_{beam}. The distributions are for the 60 MeV/nucleon ^{129}Xe + ^{197}Au reaction. The total detected charge Z_{total} includes Z_{source} as well as all charges of the light charged particles.

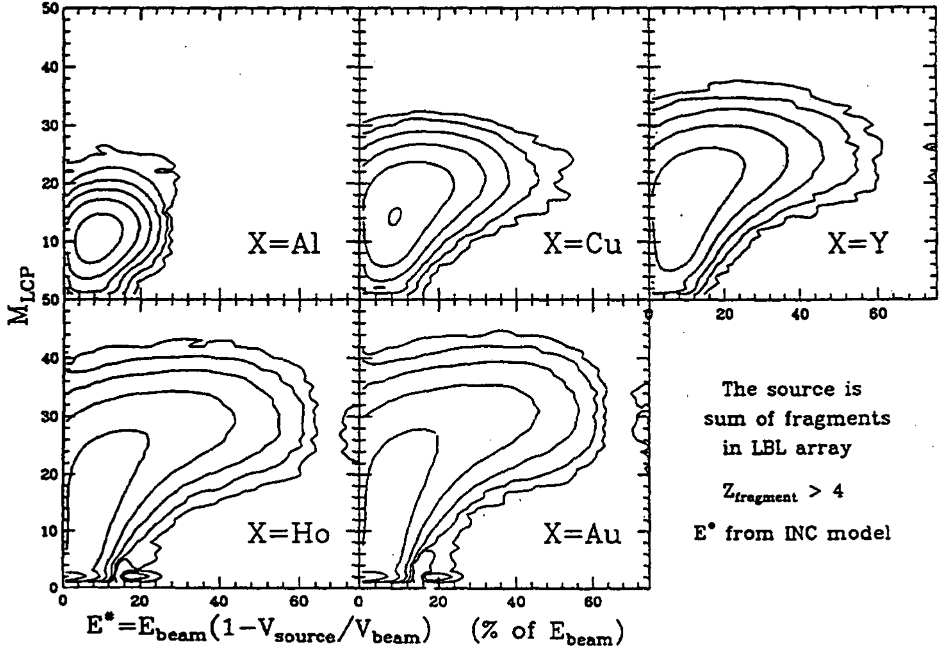

Fig. 3. Logarithmic contour plot of the excitation energy E^* generated in the collision versus LCP multiplicity. E^* was calculated from the PLF source velocity assuming the incomplete-fusion model.

Both total detected charge and total multiplicity are increased on the average, when the gate is set on the slower-moving PLF source (see the left-hand side of Figure 2). The increase is due to the higher degree of dissipation, which corroborates the conclusions of ref. (1). One notes a conspicuous absence of low-multiplicity collisions in the lower left panel of

Figure 2. Only high-dissipation events are selected by gating on the slow PLF source. The multiplicity of these events extends to the highest values observed in the experiment, as revealed by comparing Figures 1 and 2. However, these high-multiplicity events are still relatively peripheral, as indicated by the very existence of a PLF source of substantial size.

In Figure 3 the light-charged particle multiplicity M_{LCP} is plotted versus the excitation energy generated in the collision, as inferred from the PLF source velocity in the framework of the incomplete-fusion model.1) For targets heavier than Al there is a correlation between both variables. It shows that the velocity of the PLF source can indeed be used to infer the energy dissipation. Very little correlation is present for Al target, since in this case only relatively central collisions are observed in the experiment, as discussed previously.

III. Event-by-event selection of non-binary events in high-multiplicity collisions

It has been shown in the previous section that sizeable sources are present at high multiplicity. It shows the existence of very dissipative binary-like collisions. In addition to these, also central collisions are expected to be detected as high-multiplicity events. Can one discriminate between these two types of events? Is it feasible to distinguish experimentally between the "true central" collisions and "highly dissipative binary" background on an event-by-event basis? Clearly, one has to use an additional experimental observable different from the multiplicity itself in order to achieve this goal. We propose an orientation of the event in the momentum space (defined below) as a such additional observable.

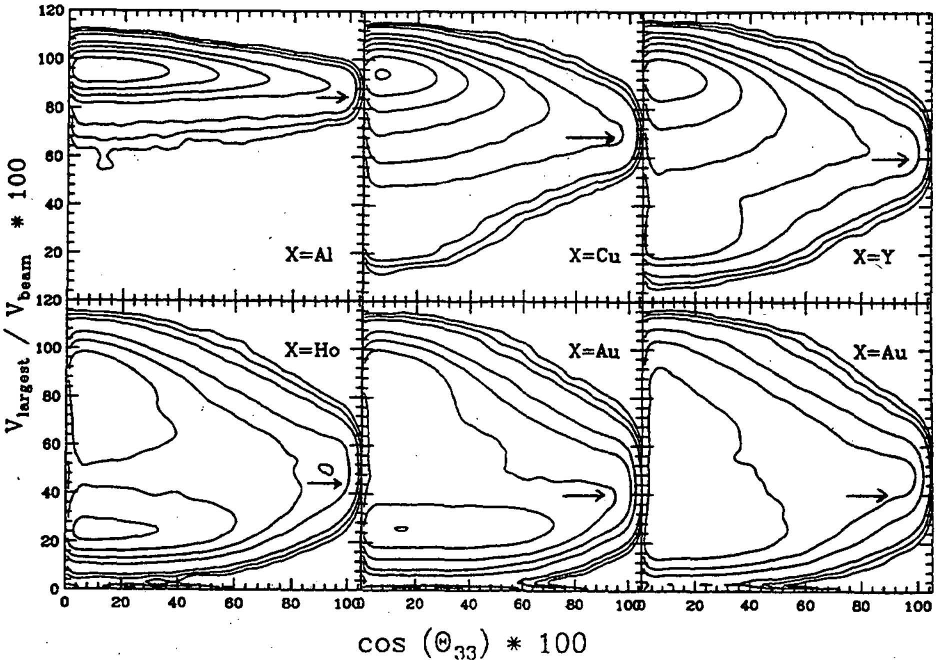

Fig. 4. Logarithmic contour plots of the parallel velocity of the largest fragment vs. the orientation of the momentum tensor. Only "complete" high multiplicity events were included in the analysis. In the lower-rightmost panel, the largest detected fragment was dropped from analysis of the ^{129}Xe + ^{197}Au reaction to augment the effect of incomplete detection efficiency of the experimental setup. In each case, the compound nucleus velocity is marked by a horizontal arrow.

The orientation of an event in momentum space is defined by means of the sphericity tensor11) constructed for each event according to:

$$T = \sum P_k{}^T P_k / 2 M_k, \qquad k = 1 \text{ to } M_{IMF}$$

The momentum tensor was determined using IMFs with $Z>2$, in order to minimize the effect of double-hits in the forward detectors. At least three IMFs were required to calculate the tensor. The tensor T is a real symmetric matrix and corresponds to an ellipsoid in momentum space.[11)] Its eigenvectors are perpendicular to each other and oriented along the principal axes of the ellipsoid. For every event the tensor T was diagonalized to find its eigenvectors and their directions in space. The "orientation of the event" is defined as $\cos(\Theta_{33})$, where Θ_{33} is the angle between the shortest eigenvector and the beam axis.

In Fig. 4 the parallel velocity of the largest detected fragment is plotted as a function of $\cos(\Theta_{33})$. Only "completely measured" high-multiplicity events were selected to construct this Figure, to concentrate on the most dissipative events in each case. High multiplicity cuts were introduced at M= 10, 20, 25, 35 and 35 for Al, Cu, Y, Ho and Au, respectively; cf. Fig.1. If the momentum ellipsoid is oriented parallel to the beam, then Θ_{33} = 90 degrees, $\cos(\Theta_{33})=0$, which corresponds to the left side of Figure 4. The case of perpendicular orientation is to the right.

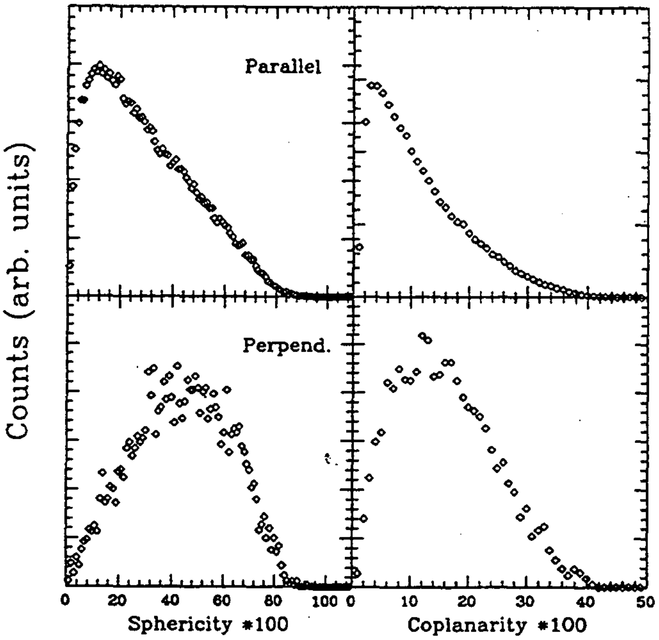

Fig. 5. Projected sphericity-coplanarity spectra for the parallel (upper row) and perpendicular (lower row) orientation of the momentum tensor, for the 60 MeV/u ^{129}Xe+^{197}Au reaction.

The parallel velocity of the largest detected fragment is used in Fig. 4 as an indicator of the binary character of the collision. As shown in the Figure, the largest fragment is likely to carry memory about the primary PLF for parallel event orientation (left side of the contour plots). For Au and Ho targets this is shown by the double-humped velocity distributions, when the $\cos(\Theta_{33})$ is close to zero. This conclusion is not sensitive to the efficiency of the forward array, as shown by the last box of the Figure, where the largest fragment was dropped from the analysis (also from the momentum tensor calculation). The *second* largest fragment in the event shows the same qualitative behaviour as the largest one. It shows, that for the most dissipative collisions the primary PLF breaks into a few fragments of substantial size, each one moving with a parallel velocity close to that of the projectile. The primarily binary character of the collision can be revealed by detecting any of these fragments.

As shown in Fig. 4, for highly dissipative high-M collisions one can distinguish binary from non-binary events by additionally selecting the orientation of the event in momentum space. Those events whose momentum ellipsoid is oriented parallel to the beam show binary PLF-TLF characteristics, namely the velocity spectra of the largest fragments show PLF and TLF components. For those events whose momentum ellipsoid is perpendicular to the beam, the largest detected fragment moves with a velocity similar to the CN velocity and the velocity distribution is no longer bimodal. It is important to note that the momentum ellipsoid is still non-spherical even for perpendicular event orientation. This is shown in more detail in the case of Au target in Figure 5 where the projected sphericity and coplanarity distributions are compared directly for parallel and perpendicular orientations of the momentum tensor. A transition from a very elongated shape (rod-like, longest:shortest axis ratio of 5:1) to a more spherical shape with the ratio 3.6:1 is observed in this case. The change of shape can presumably be interpreted as a transition to more equilibrated compound-like system, produced in more central collision events.

Summary and conclusions

We have established that in 60 MeV/nucleon ^{129}Xe + ^{27}Al, ^{nat}Cu, ^{89}Y, ^{165}Ho and ^{197}Au reactions the parallel velocity of the reconstructed PLF source is useful to select events with a varying degree of dissipation. More dissipative events are selected on the average in coincidence with slow sources, than the ones observed in coincidence with fast moving sources.

For the high-multiplicity events, large fragments still show target-like and projectile-like components in their parallel velocity distributions. A further sub-division of highly dissipative events into binary-like and non binary-like can be performed event-by-event by applying an additional experimental selection on the orientation of the event in momentum space. This selection is in addition to and independent of selections already performed according to multiplicity and total detected energy and/or momentum. It serves to distinguish binary from the "true-central" non-binary events in the class of high-multiplicity events (i.e., the most dissipative events) detected in the experiment.

Footnotes and References

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*On leave of absence from Heavy Ion Laboratory, Warsaw University, Poland
+NSCL, Michigan State University, East Lansing, MI 48824.
$Present address: Lawrence Berkeley Laboratory, Berkeley, CA 94720
@Present address: Hope College, Chemistry Dept., Holland, MI 49423

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UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720