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NUCLEAR CHEMISTRY PROGRESS REPORT

V.E. Viola, Jr.
Principal Investigator

Department of Chemistry and Cyclotron Laboratory
University of Maryland
College Park, MD 20742

August, 1978

Prepared for

THE U.S. DEPARTMENT OF ENERGY UNDER CONTRACT
No. EY-76-5-05-5172

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I. INTRODUCTION

The past year has been devoted to the initiation of several new experiments at LBL involving complex coincidence studies of heavy-ion reactions and to the completion of our astrophysics measurements at the University of Maryland which relate to problems of Li, Be and B nucleosynthesis. In this report we summarize the current status of these projects and outline the activities of our group during the period August 1, 1977 to August 31, 1978. Since much of this work has only recently been analyzed or is based on preliminary examination of the data, we caution the reader not to quote material directly from this report.

The major research effort of our group has continued to be the study of nucleon-exchange and energy dissipation mechanisms in damped heavy-ion reactions at the LBL SuperHILAC. This work is carried on in collaboration with J.R. Huizenga of Rochester University and K.L. Wolf of Argonne National Laboratory (the RAM group). In addition to our continued study of the nuclear charge, energy and angular distributions of damped reaction products, we have successfully initiated two new types of experiments at the SuperHILAC during the past year. These have included: (1) isotope identification measurements with discrete Z and A resolution for Fe-like fragments and (2) development of a major neutron experiment in which neutron energies, angular distributions and multiplicities are measured. Despite the large amount of time that has been required to perfect these

techniques and the low counting rates inherent in such experiments, a number of important results have emerged already, as described in this report.

Experiments were also performed at the LBL 88-inch Cyclotron involving a collaboration with K.L. Wolf, K. Gelbka of Michigan State University and W.G. Meyer and M.S. Zisman at LBL. These experiments have utilized the fission-fragment angular correlation techniques to determine the linear momentum transfer from projectile to target for heavy-ion reactions in the 8-20 MeV/nucleon region and also to study the projectile-like fragments in coincidence with correlated fission events. This technique permits a high selectivity in the study of projectile-like fragments by defining the linear momentum transfer associated with each event.

Finally, at the University of Maryland we have completed the measurement of yields of ^6He , ^6Li , ^7Li and ^7Be in the astrophysically important $\alpha+\alpha$ reaction between 60 and 160 MeV. Previously, this reaction represented the only major unmeasured system needed to test theories of Li, Be and B nucleosynthesis. These studies are important not only for understanding the origins of Li, Be and B, but also provide insights into the question of the expanding Universe from analysis of the ^7Li results.

The following sections contain brief summaries of the research in which our group has been involved since the last such report. Because of the collaborative nature of the program, some ambiguity exists in defining the scope of our work. Hence, for the purpose of this report we have included in Section II only summaries of experiments or calculations in which our group

at Maryland has been directly involved during the past 13 months. We hope this accurately reflects our research effort. In Section III, we list all publications and published abstracts in which we have been involved. These give a broader view of the overall collaborative programs, integrated over a less well-defined time scale.

II. RESEARCH PROGRAM

A. Heavy-Ion Studies

1. ✓ Investigation of Damped Collisions in the $^{56}\text{Fe} + ^{209}\text{Bi}$ Reaction of 385 and 480 MeV. (H.F. Bruer, B.G. Glagola, V.E. Viola, A. Mignerey, K.L. Wolf, D. Hilscher, D.G. Raich, J. Birkelund, W.U. Schroder and J.R. Huizenga)

In order to understand the systematic evolution of damped heavy-ion reactions as a function of projectile mass, we have studied the $^{56}\text{Fe} + ^{209}\text{Bi}$ system to complement our earlier ^{84}Kr and ^{136}Xe studies on ^{209}Bi . The experiments summarized in this and the following entry are among the first such measurements with an iron beam performed at the SuperHILAC.

Measurements of the fragment charge, energy and angular distributions of the damped reaction products were performed at 385 and 480 MeV. Simultaneous charge and time-of-flight mass identification were also performed at a few angles for one of the 480-MeV runs. The projectile-like fragments were studied with three ΔE -E counter telescopes using surface barrier ΔE detectors of 10-20 Nm thickness and 100 Nm stopping detectors. The Z identification achieved with this system is shown in Fig. A.1-1, where it can be seen that discrete charges up to $Z \sim 34$ can be separated. This figure also gives a schematic view of the spectrum of damped fragments observed in this reaction. For total kinetic energies of $80 < \text{TKE} < 280$ MeV one sees the damped fragment distribution peak near $Z=26$ is skewed toward lower-Z. The fragments at higher Z originate from sequential fission and fusion-fission; at some angles these two components can be distinctly separated in the ΔE -E spectra.

The time-of-flight measurements were performed using ΔE and E elements of one telescope separated by flight path 0 cm. A timing resolution of 80 psec was obtained in tests of the system, producing discrete A resolution for the Fe - like fragments.

In Fig. A.1-2 we show the c.m. angular distributions for all damped fragments (including quasielastic events) and in Fig. A.1-3 the Wilczynski plots for the two energies studied here. In both cases the angular distributions peak just inside the quarter-point angle and the product yields are seen to evolve toward smaller angles as the energy damping (TKE_{loss}) increases. For the 480-MeV bombardment there is a strong indication of orbiting for highly damped events, as exhibited by the rise in cross section as 0° is approached. This behavior of the $d^2\sigma/d\epsilon d\theta$ contours (Fig. A.1-3) is very similar to $^{84}\text{Kr} + ^{154}\text{Sm}$ at similar energies above the barrier¹ $Z_1 Z_2$ is nearly the same in these two cases) and is intermediate between the $^{40}\text{Ar} + ^{232}\text{Th}$ and $^{136}\text{Xe} + ^{209}\text{Bi}$ systems². At the backward angles there is very little evidence for damped events extending far back of the quarter-point, which implies relatively long sticking times for the low l-wave events which are not lost to fusion.

The charge drift and spreading width of the Z- distributions as a function of energy damping in these reactions are shown in Fig. A.1-4. It is noticed that there is a nearly linear decrease in the centroid of the charge distributions as a function of energy-loss. The time-of-flight data show that this Z shift is associated with a corresponding mass shift. The origin of this shift appears to be due to both proton diffusion from the projectile to the target and to charged-particle decay of the

Fe-like fragments. The energy loss curves are compared with similar data from ^{84}Kr and ^{136}Xe reactions³. We note a marked change in the spreading of the Z-distribution widths as a function of energy damping. The results imply a much larger degree of energy damping that is not associated with particle diffusion than is the case with heavier projectiles. Analysis of this effect continues.

1. A. Mignerey and K.L. Wolf, private communication.
2. W.U. Schroder and J.R. Huizenga, Am. Rev. Nucl. Sci. 27, 465 (1977).
3. J.R. Huizenga, J.R. Birkelund, W.U. Schroder, K.L. Wolf and V.E. Viola, Phys. Rev. Lett. 37, 885 (1976).

Fig. A.1-1

Plot of counts versus atomic number for fragments with $80 < \text{TKE} < 280$ MeV from 480 MeV $^{56}\text{Fe} + ^{209}\text{Bi}$ reaction at 27° in the laboratory system.

Fig. A.1-2

Angular distributions for quasilastic and damped events in the reaction of 385-MeV ^{56}Fe (top) and 480-MeV ^{56}Fe (bottom) with ^{209}Bi .

Fig. A.1-3

Contours in $d^2\sigma/dE d\theta$ as a function of total kinetic energy loss (TKE_{loss}) c.m. angle for 385-MeV ^{56}Fe bombardment of ^{209}Bi . Contour lines are labelled according to cross section in mb.

Fig. A.1-4

Left-hand figure: Shift in the centroid of the charge distribution from that of the projectile, ΔZ , as a function of TKE_{loss} for 480 MeV $^{56}\text{Fe} + ^{209}\text{Bi}$; right-hand figure: width of the charge distribution as a function of TKE_{loss} for the same reaction.

2. Total Reaction and Fusion-Fission Cross Sections for the $^{56}\text{Fe} + ^{209}\text{Bi}$ System (H.F. Breuer, B.G. Glagola, V.E. Viola, D. Hilscher, J. Birkelund, W.U. Schroder, J.R. Huizenga, K.L. Wolf, D.G. Raich and A. Mignerey)

In conjunction with studies of the damped fragments in the $^{56}\text{Fe} + ^{209}\text{Bi}$ system, elastic scattering and fusion-fission cross sections have been also determined at 385 and 480 MeV. The elastic scattering results are valuable in defining the reaction parameters such as the total reaction cross section, maximum orbital angular momentum and interaction radius. The fusion-fission process is also of major interest, since this is one of the heaviest systems for which a well-defined fusion-fission cross section may exist and hence it gives a critical test of the nuclear interaction potential for heavy-ion reactions.

In Fig. A.2-1 we show the differential cross sections for elastic scattering, σ_{el}/σ_R , for both energies studied in this work. These results have been analyzed using the Fresnel model of Frahn¹ and the resultant values for the total reaction cross section, σ_R ; maximum orbital momentum transfer, l_{max} , and interaction radius, R_{int} , are listed in Table A.2-I. The interaction radii determined in this study are in good agreement with the value $R_{\text{int}} = 13.6$ fm predicted by the systematics of Birkelund, et. al.²

A major point of interest in these studies involves the complete-fusion cross section, σ_{CF} , and its relationship to the nuclear interaction potential and frictional processes in heavy-ion reactions. On the basis of a calculation based upon the standard proximity potential³ and one-body energy dissipation, the complete fusion cross section for the 480-MeV $^{56}\text{Fe} + ^{209}\text{Bi}$ reaction

is predicted to be quite small⁴. However, modifications of the proximity potential which remove the repulsive part of the potential at small radii serve to enhance the value of σ_{CF} .

In the present work we have attempted to derive σ_{CF} in two ways. First, assuming that the total reaction cross section goes into only two channels, damped (plus quasielastic) reactions and complete fusion. Hence, the complete fusion cross section can be determined from

$$\sigma_{CF} = \sigma_R - \sigma(\text{damped}).$$

From Fig. A.1-2 the damped cross section at each energy has been integrated and is listed Table A.2-I. From the difference we obtain $\sigma_{CF} = 640$ mb at 480 MeV and 461 mb at 385 MeV.

A second approach is to measure the actual complete fusion cross section; e.e. fragments with $Z \sim 55$, $A \sim 132$ and $TKE_{CM} \sim 250$ MeV. This process is complicated by the presence of sequential fission products at many angles, especially near the recoil axis of the Bi-like fragments. However, at forward angles there is a clear separation of damped, sequential-fission and fusion-fission fragments that permit the evaluation of σ_{CF} (assuming that all fusion reactions result in fission). For a $1/\sin \theta$ angular distribution, a value of 640 ± 60 mb is obtained for σ_{CF} . This is in excellent agreement with the fusion cross section determined from the difference between the reaction and damped products. Fission-fusion data for 385-MeV are still being analyzed.

These results indicate that σ_{CF} has a measureable cross section at the energies studied in this work. Calculations are in progress to compare the data with theory.

Table A.2-I Parameters for $^{56}\text{Fe} + ^{209}\text{Bi}$ System

E_{lab}	385 MeV	480 MeV
E_{cm}	304 MeV	379 MeV
$E_{\text{cm}}/E_{\text{Co al}}$	1.36	1.70
θ_{cm}	72.6°	49.3°
l_{max}	176	253
R_{int}	13.76 fm	13.95 fm
σ_{R}	1541 ± 68 mb	2530 ± 100 mb
σ (damped)	1080 ± 170 mb	1900 ± 170 mb
σ_{CF} (fission fragments)	-	640 ± 60 mb

1. W.E. Frahn, Phys. Rev. Lett. 26, 568 (1971); Ann. Phys. (N.Y.) 72, 524 (1972).
2. J.R. Birkelund, et. al., Phys. Rev. C13, 133 (1976).
3. J. Blocki, J. Randrup, W.J. Swiatecki and C.F. Tsang, Ann. Phys. (N.Y.) 105, 427 (1977).
4. J.R. Birkelund, J.R. Huizenga, J.N. De and D. Sperber, Phys. Rev. Lett. 40, 1123 (1978).

Fig. A.2-I Ratio of the differential cross section for elastic scattering to Rutherford cross section as a function of c.m. angle for 385-MeV(top) and 480 MeV (bottom) $^{56}\text{Fe} + ^{209}\text{Bi}$.

3. The Reaction $^{56}\text{Fe} + ^{56}\text{Fe}$ at 9.0 MeV/Nucleon

(K.L. Wolf, D.G. Raich, A.C. Mignerey, H.F. Breuer, V.E. Viola, B.G. Glagola, D. Hilscher, J.R. Birkelund, W.U. Schroder and J.R. Huizenga)

Experimental results have been obtained for the bombardment of a thin, self-supporting iron target with 500-MeV ^{56}Fe ions from the LBL SuperHILAC accelerator. Charge, mass and energy distributions of the heavy reaction products were measured with a ΔE -E time-of-flight telescope using solid-state detectors. The fast-timing system was of the Sherman-Roddick design and achieved a mass resolution of about 80 picoseconds. The detector telescope consisted of a 25 mm transmission detector with a thickness of 16 Nm in conjunction with 4cm² heavy-ion stopping counter. Discrete mass and charge identification was made for nearly all heavy reaction products for a flight path of 70cm.

Due to the small quarter-point angle ($\sim 13^\circ$ in the laboratory system) and spatial limitations of the scattering chamber at the SuperHILAC, it was not possible to make measurements inside 11° with a long flight path in these preliminary experiments. In Fig. A. 3-1, we show a plot of total kinetic energy for $Z=27$ fragments obtained with a 25 cm flight path at 16° in the center of mass system (8° lab). Unlike heavier systems at angles well inside the quarter-point angle, the probability for incomplete damping of the projectile energy appears to be much larger for this light, symmetric system. In addition, the charge distributions are skewed to lower- Z values, indicating the emission of charged particles in the equilibration process. A feature of particular interest in Fig. A.3-1 is the existence of anomalous bumps in the energy spectrum at an energy-loss values of about 35MeV

and also perhaps near $\Delta E \approx 65$ MeV (although not statistically significant). The energy spectra for other nearby atomic numbers show analogous behavior. Similar indications of structure in the damped spectra have also been observed by the Orsay group in $^{40}\text{Ca} + ^{40}\text{Ca}$ and $^{63}\text{Cu} + ^{63}\text{Cu}$ reactions². Whether this structure is associated with the mechanism of the collision or an experimental artifact will be investigated in a SuperHILAC run in November. An internal Faraday cup is being constructed for this experiment so that long flight-path measurements can be performed at very small angles to the beam.

1. Sherman and Roddick, Argonne National Laboratory
2. C. Stephan, Orsay, France, private communication, and Orsay preprint IPNO-PHN-77-15 (1977).

Fig.A.3-1 Total kinetic energy loss (c.m.) as a function of differential cross section for $Z=27$ fragments observed at 8° in the laboratory system for 500 MeV Fe + Fe.

4. Neutron Emission in the Strongly Damped Reactions
 $^{56}\text{Fe} + ^{165}\text{Ho}$ and $^{136}\text{Xe} + ^{165}\text{Ho}$ (D. Hilscher, J.R. Birkelund,
A.D. Hoover, W.U. Schroder, W.W. Wilcke, J.R. Huizenga, A.
Mignerey, K.L. Wolf, H.F. Breuer and V.E. Viola).

In order to understand the processes whereby large amounts of kinetic energy of relative motion are transformed into internal degrees of freedom in damped collisions, a program has been initiated at the SuperHILAC to study the neutron spectra associated with these reactions. In the initial stages of damped collisions, projectile kinetic energy is dissipated into intrinsic excitation energy and deformation of the intermediate double-nucleus complex. After breakup of the system, the final fragments de-excite by the emission of light particles and gamma rays. Depending on the time scale of particle emission, different types of energy spectra and angular correlations are expected - thus serving to identify specific features of the energy dissipation process. Of particular interest is the question of whether or not non-statistical mechanisms in the collision stage of damped reactions can be uniquely identified. Even in the case of secondary processes such as the de-excitation of the separating final fragments, a knowledge of light-particle emission properties permits important information about the modes of excitation of the fragments to be derived.

The evaporation of neutrons is assumed to be the major de-excitation process. To investigate this de-excitation process, we have begun to measure the emission of neutrons in coincidence with the light damped fragment. The neutron energy spectra, neutron multiplicities for the light and heavy fragments and neutron angular correlations give one information on

how much excitation energy is used to evaporate neutrons and how this energy is divided between the light and heavy fragments. The angular correlations and deviations from an evaporation spectrum give evidence about the probability of pre-compound neutron emission by the dinuclear complex and/or the partially accelerated fragments. This requires, however, long runs in order to obtain the necessary statistical accuracy in the neutron energy spectra because the neutron counting rate is very small. It has also been necessary to construct a special thin-walled ring for the SuperHILAC scattering chamber to minimize scattering and a Faraday cup extension which transports the beam out of the experimental area to reduce the background. Furthermore, the experiments require that the beam be well focussed so that the effects of background neutrons generated by the beam striking the collimator slits are minimal.

In our studies up to this time we have investigated the $^{56}\text{Fe} + ^{165}\text{Ho}$ and $^{136}\text{Xe} + ^{165}\text{Ho}$ reactions at a bombarding energy of 8.5 MeV/nucleon. We have chosen a ^{165}Ho target in order to employ the heaviest target nucleus possible for which sequential fission of the target-like fragment will not interfere with the spectra. The experiments have utilized six Ne213 large volume liquid scintillation, neutron detectors with pulse shape discrimination in coincidence with a ΔE -E telescope for Z-identification of the projectile-like fragment. The neutron detectors are placed at various angles with respect to the projectile-like fragment and the recoil axis of the heavy partner. From this arrangement neutron multiplicities, angular

distributions and time-of-flight energy spectra can be measured.

The results thus far indicate that at the energies characteristic of these experiments - i.e., a few MeV/nucleon above the Coulomb barrier - thermal equilibration is achieved during the reaction time. No positive evidence for an anomalous high energy neutron component in the spectra is observed. However, the analysis of the data is complex and further examination of these results continues. Another important conclusion that can be drawn from the data is that the excitation energy of the system appears to divide according to the mass ratio of the final fragments. Light-ion coincidence spectra (H & He) have also been taken in these experiments, but as yet the data remain unanalyzed.

5. Momentum Transfer in Peripheral Reactions of 20 MeV/Nucleon ^{16}O with ^{238}U . (B.B. Back, A. Mignerey, K.L. Wolf, T.C. Awes, P.Dyer, C.K. Gelbke, H.Breuer, V.E. Viola and W.G. Meyer).

For heavy-ion projectiles well above the interaction barrier one observes a transition in reaction mechanisms in the region 10-20 MeV/nucleon.¹ Reactions below this energy can be characterized in terms of complete fusion, damped and nucleon transfer processes. Well above this energy, phenomena characteristic of high energy nucleon-nucleon collisions become dominant. In order to investigate the gross features of this transition region we have studied the interaction between 315-MeV ^{16}O ions and ^{238}U . The reactions were designed to measure simultaneously the linear momentum transfer to the target - residue and the energy and charge spectrum of projectile - like fragments associated with these transfers.

The experiments involved bombardment of a 200Ng/cm^2 $^{238}\text{UF}_4$ target with 315-MeV ^{16}O ions at the LBL 88-inch Cyclotron. Projectile-like products were identified with a solid-state $\Delta E - \Delta E - E$ telescope (^{27}Ni , 70Ni and 3mm thickness, respectively) at a laboratory angle of 15° . Since in the case of a uranium target nearly the entire reaction cross section results in the fission of the target nucleus, the linear momentum transfer in the reaction can be determined by measuring the angle between coincident binary fission fragments. In order to measure the angular correlation between the fragments, two position-sensitive semiconductor detectors were placed at appropriate angles on opposite sides of the beam angle. Both fission-fission coincidence and fission-

fission-light ion coincidence data were taken. The data were recorded event-by-event on magnetic tape and analyzed off-line. For each event an iterative procedure was used to correct for post-fission neutron evaporation and for pulse-height defect in the fission detectors.

Initial results for these studies are presented in Fig A.5-1. In the top figure (a) is shown the gross fission-fragment angular correlation for all events. One should note that correlation angles corresponding to 180° represent events with zero linear momentum transfer while complete linear momentum transfer events should be peaked near 146° . At the top of Fig. A.5-1(a) is given in the range of correlation angles expected for various fractions of full linear momentum transfer. The quoted angular range is due to the effect of fission fragment mass-asymmetry on the kinematics. This result shows that even at 20 MeV/nucleon a significant portion of the reaction cross section proceeds via nearly complete momentum transfer. Quantitative estimates of the fraction of complete linear momentum events is not possible since in these measurements the detector geometry emphasized incomplete momentum transfer processes and also no out-of-plane measurements were performed. However, it is clear that there is a wide distribution of linear momentum transfers which characterize these reactions.

In Figs. A.5-1(b)-(k) we show the relative yields fission of correlated fission fragment for triple coincidence measurements in which projectile-like fragments were also identified. The yields for $Z > 8$ were small and not statistically meaningful.

In this plot one sees the evolution of the linear momentum transfer associated with increasing charge-loss by the projectile, as well as the spreading of the fission correlation function as more complex processes occur. Hence, the $Z=8$ fragments can be interpreted as involving grazing reactions at the extreme periphery of the nucleus. Fragments with $Z=7,6$, etc. are seen to involve increasingly large transfer of linear momentum, representing an increasingly deeper penetration of the projectile into the matter density of the target. It is also noted that formation of nitrogen and carbon is the preferred path for projectile breakup.

An interesting feature of the $Z=2$ correlation function is the appearance of two components—one corresponding to high linear momentum transfer and the other to low momentum transfer. In the former case we believe this is evidence for transfer of large fragments (e.g. ^{12}C) to the target nucleus, thus yielding large, but incomplete linear momentum transfers. For the $Z=2$ products coincident with nearly axial fission fragments, the most likely origin is in projectile-fragmentation reaction, such as ^{16}O breakup into $^{12}\text{C} + ^4\text{He}$.

In summary, on the basis of this preliminary analysis of the data, one can discern a comprehensive overview reaction with ^{16}O at 20 MeV/nucleon. Further analysis will focus on the energy and mass spectra of the projectile-like fragments.

1. C.K. Gelbke, C.Olmer, M. Buenerd, J. Mahoney, M.C. Mermaz and D.K. Scott, Physics Reports 42, 311 (1978).

Fig. A.5-1 (a) Plot of fission-fission coincidence probability as a function of angle between fragments in the laboratory system. Scale at top refers to fraction of complete linear momentum transfer.

(b)-(h) Same as (a) except coincidence required for Z=2-8 fragments respectively.

B. Light-Ion Studies

1. Mechanisms of Reactions Induced by ^4He Ions above 10 MeV/Nucleon (S.M. Read, W.G. Meyer and V.E. Viola).

Considerable interest is presently focussed on the study of nuclear reaction mechanisms for collisions induced by projectiles with energies in the 10-100 MeV/nucleon region. This transitional behavior has been discussed previously with regard to heavy ions in Sec. II.A.5. Although present accelerators limit the availability of appropriate beams for such studies, ^4He ions represent one complex projectile that can be studied in this energy region. Despite its few-nucleon character, reaction mechanism studies with ^4He ions may provide a valuable guide to the types of phenomena that will be observed with heavy ions of similar E/A values. In addition light-ion studies form an important comparative base from which anomalous behavior indicative of new reaction phenomena may be discerned.

In earlier studies¹ linear momentum transfer in the $^4\text{He} + ^{233}\text{U}$ reaction has been studied between 12-35 MeV/nucleon. The macroscopic features of the entire reaction are illustrated by the data presented in Fig. B.1-1. In the figure the energy spectra of light ions (H and He) from bombardment of ^{232}Th with 35-MeV/nucleon alpha particle are shown².

the properties of the residual heavy nucleus in these reactions are demonstrated by the fission-fragment angular correlation results for 35-MeV/nucleon ^4He incident upon ^{233}U . In this lower plot correlation angles near 180° imply low-momentum transfer; peripheral reactions and the arrow designates complete linear momentum transfer from the projectile to the target. From the

angular correlation it is clear that a rather broad distribution of linear momentum transfer characterizes the residual heavy nuclei. Analysis of these data indicates that for this reaction about 50% of the reaction cross section results in complete fusion (defined here as complete linear momentum transfer); 40% goes into high momentum transfer but incomplete fusion events, and 10% can be classified as peripheral reactions. This behavior is reflected in the light-ion spectra by rather flat energy distributions at forward angles - where peripheral, damped and evaporation processes all contribute - to spectra characteristic of highly damped and evaporation mechanisms which are observed at the more backward angles.

It is of interest to extend the concept of complete fusion reactions to ^4He -ion-induced reactions at energies well-above the interaction barrier. For the $^4\text{He} + {}^{208}\text{Pb}$ reaction optical model potentials have been derived from elastic scattering measurements at 35 MeV/nucleon³, including backward-angle measurements which limit the set of ambiguous potentials. All reasonable potentials indicate that complete absorption of the projectile should occur for greater than 90 Percent of the reaction cross section. In order to understand our much lower result, we have compared the complete-fusion cross sections (σ_{CF}) of Ref.1 with the predictions of the proximity potential⁴ (no energy dissipation included). This comparison is shown in Fig. B.1-2. For the rather shallow proximity potential, it is found that a much lower fusion cross section is predicted at 140MeV bombarding energy. By adjusting the radius of the alpha particle to the electron scattering value of 2.08fm, a rather good fit to σ_{CF} at 140MeV can be obtained.

However, the slope of σ_{CF} versus $1/E$ is much steeper than indicated by the data.

A more realistic approach is to consider the effects of one-body energy dissipation, which will serve to increase the fusion cross section by damping radial motion into internal excitation. The solid curve in Fig. B.1-2 shows such a prediction for the model of Sperber and Huizenga⁵, which fits a large body of heavy-ion data quite well. In this case the values for σ_{CF} greatly exceed the experimental results, but on the other hand, are in good agreement with expectations based on the experimentally-derived optical model potentials. We consider this difference between our experimental results and the potential model predictions to be evidence for the increasing importance of two-body energy dissipation at bombarding energies above 10MeV/nucleon. Hence, as the probability for nucleon-nucleon scattering increases with respect to nucleon-potential scattering, light (pre-equilibrium) particles are emitted in the interaction which exhibit a broadly damped energy spectrum and yield residual heavy nuclei with large, but incomplete, linear momentum transfer.

In order to account for these results in the proximity potential approximation, it appears essential to include both one- and two-body energy dissipation in the friction term.

1. W.G. Meyer, University of Maryland, thesis (1975).
2. C.C. Chang, J.Wu and H.Holmgren to be published.
3. D.A. Goldberg, S.M. Smith, H.G. Pugh, P.G. Roos and N.S. Wall; Phys. Rev. C7, 1938 (1973).
4. J. Blocki, J. Randrup, W.J. Swiatecki and C.F. Tsang, LBL-Report - 5014.
5. J.R. Birkelund, J.R. Huizenga, D. Sperber and J.N. De, Phys. Rev. Lett. 40, 1123 (1978).

Fig. B.1-1 - Left-hand: Angular correlation for fission fragments from 140-MeV ^4He bombardment of ^{233}U and ^{209}Bi . Arrows indicate complete momentum transfer; 90° , zero momentum transfer; Right-hand: Energy spectra for α particles from 140-MeV ^4He + ^{232}Th . Descending curves represent increasing angle of observation.

Fig. B.1-2 -

Plot of σ_{LF} versus $1/E_{cm}$ for $^4\text{He} + ^{233}\text{U}$ reaction. Solid curve is linear extrapolation of low-energy data; dashed curve represents proximity potential, and dotted curve is for proximity potential plus one-body energy dissipation.

2. Intranuclear Cascade/Fermi Breakup Calculations for Nucleon-, ^2H - and ^4He - Induced Reactions. (B.G. Glagola, A. Gokmen, G.J. Mathews, R.A. Moyle and V.E. Viola).

We have continued development of a code which introduces deuteron and alpha-particle clusters into the intranuclear cascade code, both as incident projectiles and as components of the target nucleus. Calculations have been performed on the 140-MeV $^4\text{He} + ^{27}\text{Al}$ system and for 150- and 300- MeV protons on ^{27}Al and ^{181}Ta . The latter systems were chosen for the purposes of comparison with previous cascade code calculations.¹ Total inelastic cross sections and cascade particle multiplicities are given for the 140 MeV ^4He bombardment of ^{27}Al with zero, one, two and three alpha-particle clusters in Table B.2-I. It is observed that as the number of clusters increases the inelastic cross section remains approximately constant, whereas the particle multiplicities decrease. This latter effect is also reflected in an increased average excitation energy of the residual heavy nuclei, indicating the effectiveness of clusters in damping the initial energy of the projectile. A mass distribution for a cascade-plus-evaporation calculation for 140 MeV $^4\text{He} + ^{27}\text{Al}$ is shown in Fig. B.2-1 for the case of zero and three α clusters in the 27 nucleus. The presence of clusters does not affect the final mass spectrum significantly. The bump in the mass distribution at $A \approx 16$ has recently been verified experimentally.²

For proton-induced reactions the introduction of clusters in the target nucleus tends to enhance the inelastic cross section, but as in the case of ^4He reactions, also produces a decrease in the average number of emitted cascade particles and corresponding

increase in the excitation energy of the residual nuclei. The energy spectrum of emitted protons is found to be severely attenuated at low energies by the addition of clusters, although the high-energy portion is not affected and is even enhanced at backward angles. This is shown in Fig. B.2-2 where the present calculation is compared with that of Bertini¹. The sensitivity of the calculations is greatest for 150-MeV $p + {}^{27}\text{Al}$ and least for 300-MeV $p + {}^{181}\text{Ta}$.

The model appears to be most useful for ${}^2\text{H}$ - and ${}^4\text{He}$ -induced reactions and for light target nuclei. To this end the evaporation part of the standard two-stop calculation is being replaced by a Fermi breakup model which permits multibody breakup of the residuals from the cascade stage of the reaction. Levels for all nuclei up to ${}^{20}\text{Ne}$ have been included in this code at present.

Although the inclusion of clusters in the cascade model represents a more realistic physical picture for the description of intermediate-energy nuclear reactions, it requires additional parameterization in the sense that it requires spectroscopic factors for the existence of clusters in the target nucleus. This information can hopefully be provided by quasi-free scattering-experiments or appropriate nuclear shell-model calculations.

Further improvements to the model still need to be considered; for example, corrections for multiple scattering of the clusters and inclusion of Coulomb deflection of the clusters and nucleons. Of practical concern is the failure to reproduce charged particle spectra adequately and the fact that model improvements-such as the addition of refraction and clusters-seem to decrease the ability of the model to fit experimental data. A partial solution to this problem may reside in our choice of the Fermi energy for clusters,

which would appear to be too low in the present version of the code.

Nonetheless, the cluster model provides a substantially broader application of the cascade model. It permits a more realistic approach to cluster structures for light target nuclei and the important generalization of the model to deuteron- and alpha- particle induced reactions.

1. V.S. Barashenkov, H. Bertini, K. Chen, G. Friedlander, G.D. Harp, A.S. Iljinov, J. Miller and V. Toneev, Nucl. Phys. A187, 531 (1972).
2. W. Hornyak and M. Glascock, private communication.

Table B.2-I

Total inelastic cross section and cascade particle multiplicities for the reaction of 140-MeV ^4He ions with ^{27}Al .

<u>Clusters</u>	<u>σ_{inel}</u>	$\bar{\nu}_p$	$\bar{\nu}_n$	$\bar{\nu}_d$	$\bar{\nu}_\alpha$
0 α	716	0.256	0.312	0	0.518
1 α	693	0.204	0.239	0	0.481
2 α	681	0.174	0.298	0	0.415
3 α	689	0.198	0.265	0	0.394

Fig. B.2-1 -

Mass distribution for cascade plus evaporation calculation for 140-MeV $^4\text{He} + ^{27}\text{Al}$.

Fig. B.2-2

Spectrum of protons emitted at 30° and 80° from 150 MeV protons + ^{27}Al .

3. Measurement of $^4\text{He} + ^4\text{He}$ Elastic Scattering at 158.2 MeV
(A. Nadasen, P.G. Roos, B.G. Glagola, G.J. Mathews and V. E. Viola).

In order to extend the energy-dependence systematics of $^4\text{He} + ^4\text{He}$ elastic scattering measurements, we have studied this system at an energy of 158.2 ± 0.5 MeV at the Maryland Cyclotron. The target consisted of a 12-cm-diameter gas cell filled with high purity helium gas to a pressure of about 1 atmosphere. The detection system consisted of a double-collimator slit system with angular resolution of 0.8° (FWHM) and a ΔE -E detector telescope (1-mm Si-surface barrier ΔE and 4-mm Si(li) E rotated at 60°). Measurements of the $^4\text{He} + ^4\text{He}$ differential cross sections were made over the laboratory angular range 5° to 47° , corresponding to 10° to 94° in the c.m. system. To check the system, the beam energy was lowered to 118.6 MeV and agreement to within 5% was obtained with the data of Darriulat, et. al.¹.

The resultant measurements are presented in Fig.1, along with data^{1,2} at three lower energies. These data show systematic trends with energy such as the increasing slope and movement of the minimum to smaller angles with increasing energy. In addition the data at 158.2 MeV show a less pronounced minimum near 77° when compared with the 140-MeV data².

Initial analysis of the data was made with a complex 6-parameter Woods-Saxon potential (potential 1). The resultant parameters are shown in Table B.3-1. The fit is unsatisfactory and the resultant parameters are similar to those obtained by Frisbee² with the same form of the potential. In particular, for the real potential an almost exponential potential results.

In order to improve the fit, a second attractive potential of Woods-Saxon form was added to provide more flexibility in the shape of the real potential (potential 2). This provides a significantly improved fit, as indicated by the much lower value of $\chi^2/N = 1.5$ in Table B.3-I. This more flexible approach allows the potential to break into two regions; (1) a Gaussian which applies to the low partial waves, and (2) an exponential tail which accounts for the higher partial waves. Analysis of the volume integrals with this new measurement lead to a linear energy dependence with coefficient $-1.3 \pm 0.3 \text{ MeV-fm}^3/\text{MeV}$ for the real potential and $+1.2 \pm 0.2 \text{ MeV-fm}^3/\text{MeV}$ for the imaginary potentials.

1. P. Darriulat, G. Igo, H. Pugh and H.D. Holmgren, Phys. Rev 137, B315 (1965).
2. P. Frisbee, Ph.D Thesis, University of Maryland, 1972 (unpublished).

TABLE B.3-I

Optical model parameters for one fits to the data shown in Fig. B.3-1 and described in the text.

V	r_o	a_o	W_v	r_w	a_w	V'	r'_o	a'_o	χ^2/N
Pot 1-273.2	0.151	1.059	12.86	2.86	2.169	0.362			18.0
Pot 2-53.75	1.629	0.613	9.623	2.094	0.465	43.97	0.545	0.142	1.5

Figure B.3-1 Differential cross sections for ${}^4\text{He} + {}^4\text{He}$ elastic scattering at 100, 120, 140 and 158.2 MeV.

C. Astrophysics

1. Production of A=6 and 7 Isotopes in the $\alpha + \alpha$ Reaction
(B.G. Glagola, G.J. Mathews, H.F. Breuer, V.E. Viola, P.G. Roos, A. Nadašen and Sam M. Austin).

In order to provide essential cross section data for evaluating models of light-element nucleosynthesis, we have measured the yields of ${}^6\text{He}$, ${}^6\text{Li}$, ${}^7\text{Li}$ and ${}^7\text{Be}$ in the $\alpha + \alpha$ reaction from 61.5 to 158.2 MeV. These measurements represent the first systematic determination of the $\alpha(\alpha, {}^6\text{Li})$ and $\alpha(\alpha, {}^6\text{He})$ cross sections over a wide range of energy and also complete definition of the total excitation functions for A=6 and 7 in the $\alpha + \alpha$ reaction.

The present measurements were carried out at the Maryland Cyclotron using beams of 61.5-, 80.8-, 118.9-, 139.2- and 158.2-MeV ${}^4\text{He}$ ions to bombard a gas target cell. Both the heavy-ion reaction products and the light-ion products were identified with appropriate solid state counter telescopes. The light-ion telescope was used to cross-check the heavy-ion data-e.g. $\alpha(\alpha, {}^7\text{Li})_p$ versus $\alpha(\alpha, p){}^7\text{Li}$ - and agreed to within ten percent in all cases.

The cross sections for ${}^7\text{Li}$ and ${}^7\text{Be}$, shown in Fig. C.1-1(a) are found to be identical within the limits of error for all energies measured in the present study and agree well with previous measurements¹. It is observed that beyond 60 MeV there is an exponential decrease in the A=7 cross section with increasing ${}^4\text{He}$ energy, which, when extrapolated to higher energies, is in good agreement with the measurements of Yiou and Raisbeck² who reported cross sections of 0.04mb and 0.03mb for ${}^7\text{Be}$ at 400 and 1000 MeV, respectively. Hence, the present data lead to the conclusion that beyond 200 MeV, the $\alpha + \alpha$ reaction is a negligible source of ${}^7\text{Li}$.

In Fig. C.1-1(b) the results for A=6 production via the (α, d) , (α, pn) and $(\alpha, 2p)$ reactions are presented along with detailed balance calculations for the ${}^6\text{Li}$ two-body final state based upon the measurements of Refs. 3 and 4 (the data of Ref. 4 were normalized to those of Ref. 3 in the calculation). The data for formation of ${}^6\text{Li}$ via the two-body (α, d) reaction are similar to the A=7 result beyond the peak near threshold; i.e. the cross sections decrease exponentially with increasing ${}^4\text{He}$ energy, although the slope is less steep than for A=7. The (α, pn) reaction reaches a maximum value of 22 mb at 61.5 MeV and decreases only slowly with energy thereafter. Consequently, for energies above about 80 MeV, the total ${}^6\text{Li}$ cross section becomes the dominant heavy reaction product in the $\alpha + \alpha$ reaction. In Fig. C.1-2 we have plotted the ratio of the total cross section for A=7 production to that for A=6, as a function of alpha-particle bombarding energy to illustrate this behavior.

The new experimental data are significantly different than previous estimates ^{5,6} for the A=6 and 7 cross sections, particularly for A=6 as is illustrated in Fig. C.1-1(c). From examination of C.1-2 it is apparent that for any mechanism which invokes reactions induced by energetic particles ($E > 50$ MeV), the $\alpha + \alpha$ reaction cannot have any significant role in synthesizing sufficient ${}^7\text{Li}$ to yield the solar system abundance ratio ${}^7\text{Li}/{}^6\text{Li} = 12.5$. Since the cross-section ratios for the $p + \text{CNO}$ and $\alpha + \text{CNO}$ reactions imply values of ${}^7\text{Li}/{}^6\text{Li} \approx 2$ at energies well above threshold, the present data preclude the possibility of reproducing the experimental ${}^7\text{Li}/{}^6\text{Li}$ ratio with single-

component models which invoke galactic-cosmic-ray or stellar-flare particle spectra. In addition, more rigorous constraints on the amount of ^6Li and ^7Li that can be synthesized by such mechanisms are now imposed on the model calculations.

Under any circumstances, there is no question of the need for a low-energy mechanism for ^7Li production in nature. Since ^7Li is also predicted to be formed in the big bang, it has been argued that this may be the additional source of ^7Li . Using this assumption, it has been possible to derive limits on basic big bang parameters such as the universal baryon density (See II. C.4). Whether the big bang - or mechanisms such as supernovae shock waves, novae, neutron stars, or helium shell flashes - constitute this additional source remains open to debate, but certainly the present results are consistent with a picture in which ^2H , ^3He , ^4He and ^7Li are primarily of big bang origin and ^6Li , ^9Be , ^{10}B , ^{11}B and small amount (~10%) of ^7Li are produced via galactic cosmic ray mechanisms.

1. C.H. King, H.H. Rossner, S.M. Austin, -W.S. Chien, G.J. Mathews, V.E. Viola, Jr. and R.G. Clark, *Phys. Rev. Lett.* 35, 988 (1975).
2. F. Yiou and G.M. Raisbeck, *Proc. 15th Int. Cosmic Ray Conf.* (Ploudiv, Bulgaria) OG.133 (1977).
3. c.R. Mclenahan and R.E. Segel, *Phys. Rev.* C11, 370 (1975).
4. J.M.F. Jeronymo, G.S. Mani, F. Picard and A. Sadeghi, *Nucl. Phys.* 38, 11 (1962); G.S. Mani, R.M. Freeman, F. Picard, D. Redon and A. Sadeghi, *Proc. Phys. Soc.* 85, 281 (1965).
5. M. Meneguzzi, J. Audouze and H. Reeves, *Astron. and Astrophys.* 15, 337 (1971).
6. H. Mitler, *Astrophys. and Space Sci.* 17, 186 (1972).

Figure C.1-1 - Excitation functions for A=6 and 7 production in the $\alpha + \alpha$ reaction:

- (a) ${}^7\text{Be}$ and ${}^7\text{Li}$ (sum of ground state and first excited state); data below 50 MeV solid line are from King, *et. al.* ; above 50 MeV, this work (dashed line).
- (b) ${}^6\text{Li}$ ground state. Solid line based on detailed balance for $(\alpha, d) {}^6\text{Li}$ from Refs. 3 and 4. Dashed lines represent this work: $x - (\alpha, 2p) {}^6\text{He}$ reaction; $\Delta - (\alpha, pn) {}^6\text{Li}$ reaction; $- (\alpha, d)$ reaction, and $- \text{total } {}^6\text{Li}$ cross section.
- (c) Comparison of the total A=6 cross sections from this work with estimates of Refs. 5 (---) and 6 (---).

Figure C.1-2 - Ratio of the total A=7 cross section to that for A=6 as a function of alpha particle laboratory energy.

2. Nucleosynthesis of Li, Be and B: Contributions from the $p + {}^{16}\text{O}$ Reaction at 50, 90 MeV. (R.A. Moyle, B.G. Glagola, G.J. Mathews and W.E. Viola)

Cross sections for the production of $A=6, 7, 9, 10$ and 11 isobars in the reaction of 50-, 55-, 65-, 75- and 90- MeV protons with ${}^{16}\text{O}$ have been measured. Product masses were identified by time-of-flight techniques, using either a channel-plate fast-timing device or rf fast timing. The timing resolution was about 250 psec for the channel-plate system and flight paths of 25 cm were used. For rf timing the resolution was about 1 nsec and a flight path of 65 cm was used. In addition, particle-identification was performed at 90-MeV. Mass, kinetic energy and angular distributions were determined for the products. The cross section results for these products are listed in Table C.2-I.

The present measurements of the cross sections for LiBeB production in the $p + {}^{16}\text{O}$ system complete the set of $p + \text{CNO}$ excitation functions necessary for interpretation of LiBeB nucleosynthesis. These new data, along with those for the $\alpha + \alpha$ reaction described in the previous section, have been added to existing data and used to test stellar-flare and galactic - cosmic - ray models for the origin of LiBeB. The calculated results for the ratios ${}^7\text{Li}/{}^6\text{Li}$, ${}^{11}\text{B}/{}^{10}\text{B}$, ${}^6\text{Li}/\text{Be}$ and $\text{B}/{}^6\text{Li}$ are presented in Table C.2-II. The present analysis does not substantially alter previous conclusions presented in Refs. 1-3, primarily because the excitation function for $p + {}^{16}\text{O}$ does not differ substantially from those for Li, Be and B produced in the $p + {}^{14}\text{N}$ and $p + {}^{12}\text{C}$ reactions, except for threshold effects.

All of the model calculations underproduce ${}^7\text{Li}$ by an order of magnitude. This necessitates an additional astrophysical source of ${}^7\text{Li}$, a likely candidate appears to be cosmological production in the big-bang.

The remaining ratios-- ${}^{11}\text{B}/{}^{10}\text{B}$, ${}^6\text{Li}/\text{Be}$ and $\text{B}/{}^6\text{Li}$ -- can all be approximately reproduced by either a galactic-cosmic-ray mechanism or a flare spectrum with $\gamma \approx 2$. Furthermore, the absolute abundances can be adequately described by the GCR model. Hence, the need for more elaborate mechanisms for synthesis of those nuclides does not seem imperative. Nonetheless, several problems remain. The GCR model predicts a ${}^{11}\text{B}/{}^{10}\text{B}$ ratio that is a factor of two low; this discrepancy appears to be significant in view of the present completeness of the data for the boron isotopes. One possible explanation is that there is a low-energy component in the GCR flux that enhances the ${}^{11}\text{B}/{}^{10}\text{B}$ ratio because of the differences in the threshold for these reaction products. This explanation could yield satisfactory results for ${}^{11}\text{B}/{}^{10}\text{B}$ and ${}^6\text{Li}/\text{Be}$, and would be consistent with $\text{B}/{}^6\text{Li}$ for a low boron abundance.

1. H. Reeves, W.A. Fowler, and F. Hoyle, *Nature* 226, 727 (1970).
2. M. Meneguzzi, J. Audouze, and H. Reeves, *Astron. Astrophys.* 15, 337 (1971).
3. H.E. Mitler, *Astrophys. Space Sci.* 17, 186 (1972).

Table C.2-I

Cross sections for production of LiBeB isobars from bombardments of oxygen with 50-90 MeV protons.

Energy (MeV)	A=6	Cross Section (mb)			
		7	9	10	11
50	17.6±3.1	26.9±3.6	3.6±0.9	19.7±2.8	73.4±8.9
55	23.0±3.1	42.7±4.8	7.9±1.3	33.8±4.5	86.9±10.6
65	28.5±3.3	54.8±6.3	10.0±1.4	34.3±4.7	72.0±10.0
75	-	35.0±4.2	7.2±1.2	31.8±3.8	60.4±8.9
90	17.9±3.6	$\left. \begin{array}{l} 19.9 \pm 4.0 \\ 9.7(^7\text{Li}) \\ 10.2(^7\text{Be}) \end{array} \right\}$	-	18.8±3.8	45.6±9.1
				1.8(^{10}Be)	
				9.5(^{10}B)	
				7.4(^{10}C)	

Table C.2-II

LiBeB production ratios for various particle spectra compared with experimental values.

$\phi(E)$	$^7\text{Li}/^6\text{Li}$	$^{11}\text{B}/^{10}\text{B}$	$^6\text{Li}/\text{Be}$	$\text{B}/^6\text{Li}$
Experiment	12.5	4.1	4.5	2-95
$(E+E_0)^{-2.6}$	1.3	2.0	6.8	2.3
$R^{-M(R)}$	1.4	2.2	8.0	2.1
E^{-1}	1.2	2.4	8.0	2.1
E^{-2}	2.2	3.8	13	1.8
E^{-3}	3.3	6.1	17	2.5
E^{-4}	4.3	8.4	19	4.4
$k(E+E_0)^{-2.6}$	2.6	4.1	11	2.4
$+k'E^{-3}$				

3. Light Element Nucleosynthesis and Estimates of the Universal Baryon Density. (G.J. Mathews and V.E. Viola)

The present mean universal baryon density, ρ_b , is of particular interest because it is this quantity together with the Hubble constant, H_0 , which determines the spatial curvature of the universe; i.e., whether it is open or closed. The available indicators of ρ_b (and in particular the only datum which seems to preclude the possibility of a closed universe), comes from the present deuterium abundance. This conclusion is derived from the assumption that big-bang nucleosynthesis must produce enough D to at least match the abundance of this nuclide in the interstellar medium²⁻⁴. We propose an alternative method to evaluate the range of permissible values of ρ_b . By utilizing the abundance ratio of ^7Li to D, we show here that the difficulty associated with the astration process can be essentially cancelled from the problem. Further, this method is more sensitive to ρ_b than the method which uses the D abundance alone.

II. THE METHOD

The method we propose is quite straightforward. To begin with, the present mass fraction of D and ^7Li , (x_D^P and $x_{7\text{Li}}^P$) in the interstellar medium can be written as the sum of galactic (x^G) and big-bang (x^{BB}) contributions:

$$x_D^P = F_D x_D^{BB} + x_D^G \quad (1)$$

$$x_{7\text{Li}}^P = F_{7\text{Li}} x_{7\text{Li}}^{BB} + x_{7\text{Li}}^G \quad (2)$$

The quantities F_L ($L = D, {}^7\text{Li}$) refer to the fraction of the primordial material of each species which has survived astration. Although these quantities depend on the details of galactic evolution and are not known, it is expected that they are very similar⁵.

The sensitivity of the ratio $X_{7\text{Li}}^{\text{BB}}/X_D^{\text{BB}}$ to ρ_b can be seen in figure C.3-1 where we plot the results obtained from the big-bang nucleosynthesis code of Wagoner (1973)². In the region of interest (near $10^{-31} < \rho_b < 10^{-30}$) the ratio varies as $\rho_b^{3.6}$. This is to be compared with the X_D value alone which varies as ρ_b^{-2} in the same region. The reason that $X_{7\text{Li}}^{\text{BB}}/X_D^{\text{BB}}$ is more sensitive to ρ_b than X_D alone is that $X_{7\text{Li}}^{\text{BB}}$ increases while X_D^{BB} decreases with increasing ρ_b . This behavior is a natural consequence of the nuclear reaction rates.

In table C.3-I the range of inferred values are given for ρ_b and Ω (the ratio of the present density to that required to close the universe). These results are very close to the results obtained in Ref. 1 using X_D alone, which showed that $\rho_b = 4(3) \times 10^{-31} \text{ g/cm}^3$ for $\xi = 1$, $G_D = 0$, and $F_D = 0.5$, yet the present results are less model dependent since the parameter F_D has been eliminated.

Hence, by considering the ratio $X_{7\text{Li}}/X_D$, one can place more stringent limits on the mean universal baryon density. This new technique is significant because, unlike previous approaches which relied on X_D alone, this method is virtually independent of the

degree to which the elements have been processed through stars. Furthermore, this method has been shown to more sensitively indicate the value of ρ_b . The results obtained from the analysis applied here indicate an open universe with a best guess of ρ_b , and finally has the added advantage of potential ability to set both upper and lower limits to ρ_b . The results obtained from the analysis applied here indicate an open universe with a best guess of $\rho_b = 7.1(1.0) \times 10^{-31} \text{ g/cm}^3$, $\Omega = .15(1)$ and limits 4.0×10^{-31} $\rho_b < 7.1 \times 10^{-31}$, $.09 < \Omega < .30$. if 90% of the D or ${}^7\text{Li}$ is of galactic origin, or the big-bang expansion rate during nucleosynthesis differs from the standard big-bang free trajectory.

1. R.J. Gott, J.E. Gunn, D.N. Schramm, and Tinsley, B.M. 1974, Ap. J., 194, 543.
2. R.V. Wagoner, Ap. J. Suppl., No. 162, 18, 247 (1969); Ap. J., 179, 343 (1973).
3. D.N. Schramm, and R.V. Wagoner, Ann. Rev. of Nucl. Sci., 27, 37 (1977).
4. Sam M. Austin, and C.H. King, Nature, 269, 782 (1977).
5. H. Reeves, 1974 Ann. Rev. Astron. and Ap. 12, 437.

Table C.3-I

	$x_{7\text{Li}}^{\text{BB}}/x_{\text{D}}^{\text{BB}}$	$\rho_b \text{ (gm/cm}^3\text{)}$	Ω ($H_0 = 50$)
Best Guess ($\xi = 1$, $G_D = 0.0$, $G_{7\text{Li}} = 0.15$)	2.1×10^{-4}	$7.1(1.0) \times 10^{-31}$	.15(2)
$G_D = .90$, $G_{7\text{Li}} = 0$	2.5×10^{-3}	1.4×10^{-30}	.30
$G_{7\text{Li}} = .90$, $G_D = 0$	2.5×10^{-5}	4.0×10^{-31}	.09
$\xi = 0.5$	2.1×10^{-4}	5.5×10^{-31}	.12
$\xi = 2$	2.1×10^{-4}	1.0×10^{-30}	.21

Figure C.3-1 - The ratio of ${}^7\text{Li}$ to D mass fractions as a function of the present baryon density for a present background temperature of 2.8°K . The curve labeled $\xi = 1.0$ corresponds to the standard big bang². The curves labeled $\xi = 0.5, 2.0$ correspond to a scaling of the free expansion trajectory consistent with the range of the observed ${}^4\text{He}$ abundance.

4. Synthesis of Superheavy Elements in the r-Process
(V.E. Viola and G.J. Mathews; based on an invited talk at the International Symposium on Superheavy Elements, Lubbock, TX, March, 1978).

Static r-process calculations have been performed for three sets of nuclidic masses¹ according to the formalism outlined by Seeger². The conclusions derived from these results are reviewed with respect to the possibility of synthesizing superheavy elements in nature.

The abundances before decay-back of the r-process which best fit the $A = 195$ peak for each mass table are shown in Figs. C.4-1 and C.4-2. Also shown for comparison are the abundances calculated with the Myers and Swiatecki liquid-drop formula. Although previous work seemed to indicate that the r-process could form the minimum mass number necessary to reach the island of superheavy nuclei, the newer atomic mass compilations provide a much more pessimistic conclusion.

The primary reason for the difficulties in reaching the superheavy nuclei is the increased magnitude of surface asymmetry term in the newer mass formulae. A second reason for the decrease in the maximum mass number is that the new mass tables predict slightly less neutron-excess r-process paths near the fission cutoff. This effect is most significant for the empirical masses, and is consistent with predictions based on the energy-density mass formula of Brueckner et. al.³. A consequence of these less neutron-excess r-process paths is that even if fission barriers were not reduced to the extent implied by the newer mass formulas, one would still

encounter difficulty in obtaining mass numbers of $A \geq 290$ needed to form the superheavy nuclei.

Hence, it seems that in view of recent nuclear mass compilations and fission barrier estimates, the probability of producing superheavy nuclei in the r-process is quite low. Furthermore, the SF lifetimes for $N > 184$ species encountered in the decay-back chain are probably quite short. Nonetheless, the situation is not totally bleak. One hopeful alternative would be the production of smaller abundances of superheavy elements during freeze out in the dynamic r-process. Odd-Z products, might then successfully decay back to the island of stability. The primary advantage gained in such an environment would be the capture of neutrons in a lower temperature, non-equilibrium environment where (γ, n) reactions would be less competitive. Hence, a slightly more neutron-excess path might be followed, leading to the superheavy region. Since this would lead to only small abundances of the lighter elements, the existence of such a process would not be noticed in the standard r-process abundance curves, except as a smoothing effect. Another possibility-fundamentally more intriguing - is that there may exist nuclear and/or astrophysical phenomena that are yet to be discovered which would permit the formation of the superheavies. Thus, despite a theoretical picture that does not look too hopeful at present, it should not discourage the experimentalists. The positive identification of the superheavy elements would lead to insights into nuclear structure and astrophysics which would have truly exciting possibilities.

1. G.J. Mathews and V.E. Viola, Jr. *Nature* 261, 382 (1976).
2. P.A. Seeger, W.A. Fowler and D.D. Clayton, *Astrophys. J. Suppl. Ser.* 11, 121 (1965); P.A. Seeger, W.A. Fowler and D.D. Clayton, *Nucleosynthesis* (Gordon and Breach), 241 (1968).
3. K.A. Brueckner, *et. al.*, *Phys. Rev.C1*, 2123 (1973).

Figure C.4-1 - r-process abundances before decay-back predicted for the best fit to the $A=195$ abundance peak for the mass formulas of Seeger and Howard (S-H) and of Myers (1974). Also shown is that portion of the abundance curve above $A=270$ for the mass formula of Myers and Swiatecki (1966).

Figure C.4-2 - r-process abundances before decay back predicted for the best fit to the A=195 abundance peak for the masses of Viola, Swant and Graber. Also shown is the portion of the abundance curve above A=270 for the mass formula of Myers and Swiatecki (1966).

III. PERSONNEL

FACULTY

V.E. Viola, Jr., Professor of Chemistry

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H.F. Breuer
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GRADUATE STUDENTS

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S. Eagleson
B. White

IV. PUBLICATIONS AND ACTIVITIES

A. Papers in Referred Journals and Conference Proceedings

A.C. Mignerey, D. G. Raich, R.L. Boudrie, K.L. Wolf, V.E. Viola, J.R. Birkelund, W.U. Schroder and J.R. Huizenga, "The Dependence of Nuclear Orbiting and Charge Exchange on Bombarding Energy in the $^{144}\text{Sm} + ^{84}\text{Kr}$ Reaction", Proc. Topical Cont. on Heavy-Ion collisions US-TIS-CONF-770602, Dept. of Commerce, 497 (1977)

D.G. Raich, A.C. Mignerey, K.L. Wolf, R.L. Boudrie, C.T. Roche, W.U. Schroder, J.R. Birkelund and V.E. Viola, Jr. "Possible Static Deformation Effects in ^{84}Kr and ^{86}Kr -Induced Reactions on targets of ^{144}Sm and ^{154}Sm , *ibid.*, 498 (1977).

W.U. Schroder, J.R. Huizenga, J.R. Birkelund, K.L. Wolf and V.E. Viola, "Dissipation, Mass Exchange and the Microscopic Time Scale of Heavy-Ion Collisions", *Phys. Lett.* 71B, 283 (1977).

W.U. Schroder, J.R. Birkelund, J.R. Huizenga, K.L. Wolf and V.E. Viola, Jr., "Mechanisms of Very Heavy-Ion Collision: The $^{209}\text{Bi} + ^{136}\text{Xe}$ Reaction at $E_{\text{lab}}=1130$ MeV", *Physics Reports*, to be published (1978).

V.E. Viola, Jr. and W.G. Meyer, "Search for Shock Wave Effects in Reactions of 35-MeV/Nuclear ^4He Ions with Heavy Target Nuclei" University of Maryland Report ORO-5172-2; unpublished (we didn't find anything), 1978.

V.E. Viola, Jr. and G.J. Mathews, "Synthesis of Super-heavy Elements in the r-Process", Proc. Int. Syn. on Super-heavy Elements, Lubbock, TX, March, 1978).

G.J. Mathews and V.E. Viola, Jr., "On the Light Element Abundances, Galactic Evolution and a More Sensitive Indicator of the Universal Baryon Density", LBL Report-LBL-7709, submitted to the *Astrophysical Journal*, (1978).

R. A. Moyle, B.G. Glagola, G.J. Mathews and V.E. Viola, Jr., "Nucleosynthesis of Li, Be and B: Contributions from the $p + ^{16}\text{O}$ Reaction at 50-90 MeV", U. of Maryland Report ORO-5172-0007, submitted to *Physical Review*, (1978).

A. Nadasen, P.G. Roos, B.G. Glagola, G.J. Mathews and V.E. Viola, Jr., "Study of Elastic Scattering in the $\alpha + \alpha$ Reaction at 158.2 MeV", submitted to *Phys. Rev. Comments*, (1978).

B.G. Glagola, G.J. Mathews, H.F. Breuer, V.E. Viola, Jr., P.G. Roos, A. Nadasen and Sam M. Austin, "A=6 and 7 Production in the $\alpha + \alpha$ Reaction", U. of Maryland Report ORO-5172-0008, submitted to *Phys. Rev. Lett.*, (1978).

B. Published Abstracts

1. R.A. Moyle, B.G. Glagola, G.J. Mathews and V.E. Viola, "Inclusion of α and d Clusters in Intranuclear Cascade Calculations", ACS National Meeting, Chicago, Il, paper no. 46 (1977).
2. A. Mignerey, D. Raich, K. Wolf, R. Boudrie, C. Roche, J. Birkelund, W. Schroder, J. Huizenga and V.E. Viola, "The Dependence of Nuclear Orbiting and Charge Distributions on Bombarding Energy in the $^{144}\text{Sm} + ^{84}\text{Kr}$ Reaction", *ibid.*, paper no.80.
3. R.A. Moyle, B.G. Glagola, G. Mathews and V.E. Viola, "Nucleosynthesis of Li, Be and B: Production Cross Sections from Reactions of 50-90 MeV Protons with ^{14}N and ^{16}O ", BAPS 22, 998 (1977).
4. A. Mignerey, D. Raich, K. Wolf, R. Boudrie, J. Birkelund, W. Schroder, J. Huizenga and V.E. Viola, "The Dependence on Bombarding Energy in the $^{144}\text{Sm} + ^{84}\text{Kr}$ Reaction", BAPS 22, 1020 (1977).
5. W. Wilcke, A. Hoover, J. Birkelund, W. Schroder, J. Huizenga, A. Mignerey, K. Wolf, D. Raich and V.E. Viola, "Bombarding Energy Dependence of the Strongly Damped Reaction $^{209}\text{Bi} + ^{136}\text{Xe}$ ", BAPS 22, 1020 (1977).
6. J. R. Huizenga, W.U. Schroder, W.W. Wilcke, J.R. Birkelund, K.L. Wolf and V.E. Viola, "Entrance-Channel Dependence of Energy Dissipation and Nucleon Exchange in Heavy-Ion Reactions", BAPS 23, 46 (1978).
7. K.L. Wolf, D.G. Raich, A.C. Mignerey, D. Hilcher, J.R. Birkelund, W. Wilcke, J.R. Huizenga, W.U. Schroder, V.E. Viola, H.F. Breuer and B.G. Glagola, "The Reaction $^{56}\text{Fe} + ^{56}\text{Fe}$ at 9.0 MeV/nucleon", BAPS 23, 46 (1978).
8. G.J. Mathews and V.E. Viola, "On the Abundance of Light Elements and the Question of an Open or Closed Universe", BAPS 23, 67 (1978).
9. P.G. Roos, B.G. Glagola, G.J. Mathews, A. Nadasen and V.E. Viola, "Elastic Scattering of ^4He Ions from ^4He ", BAPS 23, 97 (1978).
10. W.G. Meyer, V.E. Viola and R.G. Clark, "Reaction Mechanism Studies with ^4He Ions and Heavy Target Nuclei", BAPS 23, 502 (1978).
11. D. Hilscher, J.R. Birkelund, W.U. Schroder, W. Wilcke, J.R. Huizenga, A. Mignerey, K.L. Wolf, H. Breuer and V.E. Viola, "Neutron Emission in the Strongly Damped Reaction $^{56}\text{Fe} + ^{165}\text{Ho}$ ", BAPS 23, 523 (1978).

12. H.F. Breuer, B.G. Glagola, V.E. Viola, K.L. Wolf, A. Mignerey, D.G. Raich, D. Hilscher, J.R. Birkelund, W.U. Schroder and J.R. Huizenga, "Study of the $^{56}\text{Fe} + ^{209}\text{Bi}$ Reaction at 490 MeV", BAPS, 523 (1978).
13. V.E. Viola, B.G. Glagola, G.J. Mathews, P.G. Roos, A. Nadasen and Sam M. Austin, "Cross Sections for A=6 and A=7 Isotopes in the $\alpha + \alpha$ Reaction", BAPS 23, 633 (1978).

G PROFESSIONAL ACTIVITIES

Chairman, SuperHilac Users Association, 1977

Co-organizer, 1978 Joint SuperHilac-Bevalac Users Meeting,
Jan. 26-28, 1978

NUSAC subcommittee on Facilities, 1978

ACS Division of Nuclear Science and Technology, Membership
Committee, 1977

University Senate Committee on Honors and Prizes, 1977-78

Chemistry Department Faculty Advisory Committee, 1977-79

Chemistry Department Admissions Committee, 1977-78

Chairman, Division of Nuclear and Atmospheric Chemistry,
Department of Chemistry, 1977-78

Search Committee For Chairman of Chemical Engineering
Department, 1978.

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