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NUCLEAR CHEMISTRY PROGRESS REPORT

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I. INTRODUCTION

In this report we summarize the research activities of our group during the period August 1, 1978 to July 31, 1979. The major effort of our program has continued to be devoted to 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 K.L. Wolf of Argonne National Laboratory and J.R. Huizenga of Rochester University (the RAM group). Among the most significant accomplishments of the RAM program during the past year has been the measurement of damped fragment spectra with discrete Z and A resolution. These studies have (1) provided detailed information on the A/Z equilibration and nucleon exchange processes in damped heavy-ion collisions, (2) given evidence for structure in the partially damped energy spectra for the Fe + Fe reaction, (3) shown the importance of target-projectile mass asymmetry in governing the evolution of damped reactions, and (4) given tentative evidence for several new isotopes in the Z = 22-26 range.

Experiments were also performed at the LBL 88-inch cyclotron in collaboration with B.B. Back and K.L. Wolf of Argonne National Laboratory and C.K. Gelbke and P. Dyer at Michigan State University. These experiments have utilized the fission-fragment angular correlation technique to determine the linear momentum transfer from projectile to target for ^{16}O reactions in the 8-20 MeV/u region and to study

simultaneously light-ion spectra ($Z = 1-8$) in coincidence with correlated events. These studies have provided a much clearer picture of properties of central and peripheral collisions in heavy-ion reactions, as well as the transition between these two extremes. In addition, at the Maryland cyclotron we have continued to investigate problems of Li, Be and B nucleosynthesis and the relationship of these results to the question of the expanding universe.

The following sections contain brief summaries of the research in which our group has been involved during the last year. Since some of this work is of a preliminary nature, we caution the reader not to quote material directly from this report. Included in this report are both work initiated at Maryland and the major results of our collaborative programs; in general the primary responsibility for each entry is indicated by the lead author and institution.

II. RESEARCH PROGRAM

A. Studies of Damped Collisions Induced by Very Heavy Ions

1. Nucleon Exchange and A/Z Equilibration in Interactions of 8.3 MeV/u ^{56}Fe Ions with ^{56}Fe , ^{165}Ho and ^{209}Bi

(H. Breuer, B. G. Glagola, V. E. Viola, U. of Maryland, K. L. Wolf, A. C. Mignerey, Argonne Nat'l. Lab, and J. R. Birkelund, D. Hilscher, J. R. Huizenga, U. Schröder and W. W. Wilcke, U. of Rochester)

In order to investigate the questions of A/Z equilibration and correlated vs. uncorrelated nucleon exchange, yields of projectile-like fragments have been measured with discrete A and Z resolution as a function of energy loss for both symmetric and asymmetric systems with varying A/Z ratios. The measurements were performed with 465-MeV ^{56}Fe ions from the Lawrence Berkeley Laboratory SuperHILAC accelerator. Self-supporting targets of monoisotopic ^{56}Fe , ^{165}Ho and ^{209}Bi with thicknesses of approximately $500 \mu\text{g}/\text{cm}^2$ were used. The projectile-like fragments were detected with a time-of-flight ΔE -E telescope consisting of $17 \mu\text{m}$ ΔE and $100 \mu\text{m}$ E silicon surface-barrier detectors. Data were taken at selected angles forward of the grazing angles. The separation distance between the ΔE and E detectors was 100cm and timing signals were derived from Sherman-Roddick fast-timing electronics.¹ For elastically scattered ^{56}Fe ions a timing resolution of 100psec and an energy resolution of approximately 3 MeV were obtained, resulting in a mass resolution of $\sim 0.7u$. The ΔE -E signals provided Z resolution of ≤ 0.8 charge units, thus permitting discrete Z and A identification for all Fe-like products.

Since the data represent the yields of residual Fe-like fragments after de-excitation, it is necessary to correct for particle evaporation in order to obtain primary yields. The available excitation energy is assumed to be shared between the two primary products according to their mass ratio. Neutron multiplicity and energy measurements support this assumption for the Ho + Fe system.² Using nucleon binding energies from the compilation of Wapstra and Bos³ and treating the energy spectra of the emitted particles as described in Ref. 2, the measured yields and energies were transformed by an iterative, event-by-event procedure into primary fragment yields and center-of-mass energies. These calculations indicate that neutron evaporation predominates over charged-particle emission for the Ho + Fe and Bi + Fe cases due to the neutron excess and relatively low excitation energies of the primary Fe-like fragments. Hence, the measured charge distributions for these two heavier systems can be considered to be essentially primary yields. However, in the Fe + Fe system greater proton richness and higher excitation energies increase the relative importance of charged-particle emission. These conclusions are corroborated by measurements of charged-particle emission performed simultaneously in these experiments. While particle emission gives measured average masses significantly lower than the average mass of the primary fragments, the effect on the variances of the mass distributions is small. Neutron evaporation leads to measured mass distributions which are narrower than the primary distributions, whereas proton evaporation produces the

opposite effect. Thus the primary variances of the mass distributions for the Fe + Fe reaction fragments are essentially the same as those of the measured distributions.

Fig. A.1-1 presents the experimental results as a function of total kinetic energy loss (E_{loss}). The data points on the left-hand side of the plot represent the shifts of the average mass, $\Delta\bar{A} = \bar{A} - 56$, whereas on the right-hand side the variances of the mass distributions, σ_A^2 , are plotted. Triangles indicate measured data points and circles show values of $\Delta\bar{A}$ and σ_A^2 corrected for neutron emission. The curves represent the corresponding measured values of $\Delta\bar{Z} = \bar{Z} - 26$ and σ_Z^2 , multiplied by A/Z of the composite systems (dashed lines) and $(A/Z)^2$ (solid lines), respectively, for comparison with the mass data. Values for $\bar{Z}$, $\bar{A}$, σ_A^2 and σ_Z^2 were obtained from Gaussian fits to the data.

First, the implications of these data on the charge equilibration mechanism are discussed. For all three systems the data exhibit a drift of $\bar{Z}$ toward smaller atomic numbers as the energy damping increases. For the Fe + Fe system this drift is attributed to charged-particle emission in the de-excitation of the primary fragments. Since for the Ho + Fe and Bi + Fe systems charged particle emission is strongly inhibited, their decrease in $\bar{Z}$ must be attributed to a charge equilibration process in which protons are preferentially transferred from the Fe-like fragments to the heavy partner.

From the measured values of Z and A , corrected for neutron evaporation, for the two heavier systems, it is possible to deduce the dependence of $\bar{A}/\bar{Z}$ on E_{loss} , as shown

in Fig. A.1-2. Also shown as dashed lines are the A/Z ratios of the ^{56}Fe projectile (2.15) and of the composite systems (2.38 for $\text{Ho} + \text{Fe}$ and 2.43 for $\text{Bi} + \text{Fe}$). The data support a nucleon exchange mechanism in which there is an initial increase in the $\bar{A}/\bar{Z}$ value of the primary Fe-like fragments as soon as the Q values permit. Thereafter a monotonic increase in $\bar{A}/\bar{Z}$ is observed which may saturate at energy losses in the range of 100-150 MeV at $\bar{A}/\bar{Z} \approx 2.3$ for both asymmetric systems. These values are close to the equilibrium values defined by potential energy surfaces based on the liquid drip model including shell corrections, which are somewhat smaller than the $\bar{A}/\bar{Z}$ of the combined systems.

The measured variances of the mass and charge distributions are compared on the right hand side of Fig. A.1-1. The relation between the variances σ_N^2 , σ_Z^2 and σ_A^2 of the respective neutron, charge and mass distributions depends on the degree of correlation⁴ between neutron and proton exchange. The correlation coefficient ρ is defined by

$$\sigma_A^2 = \sigma_Z^2 + \sigma_N^2 + 2 \rho \sigma_Z \sigma_N$$

with $-1 \leq \rho \leq 1$. In a classical model⁴ for fully correlated neutron and proton exchange, $\rho = 1$ and $\sigma_A^2 = (A/Z)^2 \sigma_Z^2$; for uncorrelated exchange, $\rho = 0$ and $\sigma_A^2 = (A/Z) \sigma_Z^2$ (where A and Z represent the combined system). Neither assumption of correlated (solid lines) or uncorrelated diffusion (dashed lines) describes the variances of the mass distributions for any of the systems studied in this work. Instead, a behavior intermediate

between uncorrelated and correlated exchange is observed for partially damped events, but with increasing energy loss all three systems evolve toward correlated exchange (consistent with the square of the observed $\bar{A}/\bar{Z}$ ratio). This aspect of the data is demonstrated more explicitly in Fig. A.1-3 where the dependence of σ_A^2/σ_Z^2 on energy loss is plotted. For comparison the upper and lower dashed lines represent the A/Z and $(A/Z)^2$ values of the combined system, respectively.

It is noted in Fig. A.1-3 that the limit of correlated exchange is reached for the Fe + Fe system at about half the energy loss of the two asymmetric systems. Previous studies of the $^{168}\text{Er} + ^{86}\text{Kr}$ system⁵ at energy losses greater than 100 MeV have shown similar agreement with the relation $\sigma_A^2 = (A/Z)^2 \sigma_Z^2$. However, the present data stress the importance of the degree of energy damping in reaching the correlated limit.

In summary, charge and mass distributions have been measured for the products formed in damped collision processes in three heavy-ion systems of widely differing target-projectile mass asymmetries, and A/Z values. The excellent resolution for Z and A permits the determination of precise values for $\bar{A}$, $\bar{Z}$, σ_Z^2 , and σ_A^2 . The $\bar{Z}$ and $\bar{A}$ results show that charge equilibration develops gradually with increasing energy loss. Hence, for very asymmetric systems, an equilibrium in A/Z is not achieved until the reaction is almost totally damped, requiring comparatively long interaction times.

The relationship between σ_Z^2 and σ_A^2 supports a correlated nucleon diffusion mechanism for interaction times sufficiently long that the limiting $\bar{A}/\bar{Z}$ value has been reached. This is consistent with similar time scales for evolution of the correlations in the nucleon exchange, the equilibration of A/Z , and the energy dissipation. The energy loss time scale leads to an interaction time of $(3-8) \times 10^{-22}$ sec at 100 MeV energy loss for the non-sticking and sticking conditions, at which time the correlations in nucleon exchange and A/Z ratio seem to be close to steady-state values.

REFERENCES

1. I. S. Sherman, R. G. Roddick and A. F. Metz, IEEE Trans. Nucl. Sci. NS-15, no. 3, 500 (1968).
2. D. Hilscher et al., to be published in Physical Review C.
3. A. H. Wapstra and K. Bos, At. Data and Nucl. Data Tables 19, 177 (1977).
4. F. Beck, M. Dworzecka and H. Feldmier, Z. für Phys. A289, 111 (1978).
5. Y. Eyal, et al., Phys. Rev. Lett. 42, 826 (1979).

Fig. A.1-1:

Values of $\Delta\bar{A}$ (left sides) and variances of the mass distributions (right sides) as a function of energy loss for the reactions of ^{56}Fe ions with (a) ^{56}Fe at 8° ; (b) ^{165}Ho at 30° ; and (c) ^{209}Bi at 34° and 38° in the laboratory system. Note the change in scale for σ^2 for the $\text{Fe} + \text{Fe}$ reaction. Arrows indicate the respective Coulomb barriers for touching spheres in the entrance channels. Triangles give measured points with statistical errors; circles represent the data corrected for neutron emission (errors are comparable to measured points). The dashed lines show the values of $\Delta\bar{Z} = 26 - \bar{Z}$ and σ_z^2 multiplied by (A/Z) ; the solid line represents σ_z^2 times $(A/Z)^2$.

Fig. A.1-2:

Ratios of $\bar{A}/\bar{Z}$, corrected for neutron evaporation, as a function of energy loss for the (a) ^{165}Ho and (b) $^{209}\text{Bi} + ^{56}\text{Fe}$ systems. The dashed lines give A/Z of the projectile and of the composite systems.

Fig. A.1-3:

Ratios of σ_A^2/σ_Z^2 as a function of energy loss for the (a) ^{56}Fe , (b) ^{165}Ho , and (c) $^{209}\text{Bi} + ^{56}\text{Fe}$ systems. Data points in (a) (triangles) represent the measured values, in (b) and (c) (circles) values corrected for neutron evaporation. The dashed lines represent A/Z and $(A/Z)^2$ of the composite system.

2. Synthesis of New $Z = 22-26$ Isotopes in the $^{56}\text{Fe} + ^{209}\text{Bi}$ Reaction (H. Breuer, B.G. Glagola and V.E. Viola, Jr., U. of Maryland; K.L. Wolf and A.C. Mignerey, Argonne, Nat'l. Lab; and J. Birkelund, D. Hilscher, J. Huizenga, W. Schröder and W. Wilcke, Rochester U.)

In bombardments of ^{209}Bi with 8.5 MeV/u ^{56}Fe ions we have obtained evidence for the new isotopes ^{52}Sc , ^{53}Sc , ^{54}Sc , ^{54}Ti , ^{55}Ti , ^{56}V , ^{57}V , ^{58}V , ^{58}Cr , ^{59}Cr and ^{61}Mn from study of the damped collision product spectra. Detection of these previously unreported isotopes was achieved with a ΔE -E time-of-flight telescope, as described in the previous section. A Z vs. A contour map for a portion of the data is shown in Fig. A. 2-1. (0.7 u in A and 0.8 Z units). Due to a slight skewness of the Z -identification system, there is some feedthrough from higher Z -values which creates a background in our spectra for neutron excess isotopes. We estimate that this contribution amounts to about 20-40% of the counts for the new isotopes shown in Fig. A. 2-2.

Systematic studies of ^{56}Fe , ^{165}Ho and ^{209}Bi targets demonstrate that the yields of neutron excess isotopes increase with the increasing mass (or neutron excess) of the target. Experiments have recently been performed with a ^{238}U target and it is anticipated that these data will provide unambiguous identification of these isotopes and also establish the existence of several additional species.

In Table I we list the heaviest known isotope and the last predicted particle-stable nuclide¹ for each element (neutron drop line) of interest in these measurements. Through studies such as these one hopes to test the nuclear mass surface, especially the neutron-drip line, and also provide essential yield information of use in possible spectroscopic studies of these species.

REFERENCES

1. Nuclear and Atomic Data Tables, 17, 411 (1976).

TABLE I

	<u>Ti</u>	<u>V</u>	<u>Cr</u>	<u>Mn</u>	<u>Fe</u>	<u>Co</u>
Heaviest known isotope	^{53}Ti	^{55}V	^{57}Cr	^{59}Mn	^{62}Fe	^{64}Co
n-drop line' Groote, <u>et al</u>	^{72}Ti	^{73}V	^{80}Cr	^{87}Mn	^{90}Fe	^{93}Co
Seeger & Howard	^{72}Ti	^{75}V	^{78}Cr	^{81}Mn	^{86}Fe	^{89}Co
Liran & Zeldes	^{72}Ti	^{73}V	^{74}Cr	^{75}Mn	^{86}Fe	^{77}Co
Janecke <u>et al</u>	^{72}Ti	^{73}C	^{76}Cr	^{79}Mn	^{82}Fe	^{89}Co

Fig. A.2-1:

Plot of charge versus mass for the Bi + Fe reaction at $60 \leq E_{\text{Loss}} \leq \text{MeV}$. The size of the points corresponds to counts on a quadratic scale. The region of currently known particle-stable nuclei falls between the limits indicated by the intensified solid lines.

3. Investigation of Damped Collisions in the $^{56}\text{Fe} + ^{209}\text{Bi}$ Reaction (H. Breuer, B. G. Glagola and V. E. Viola, U. of Maryland; A. C. Mignerey and K. L. Wolf, Argonne National Laboratory, and J. R. Birkelund, D. Hilscher, J. Huizenga, U. Schröder and W. W. Wilcke, Rochester U.)

The analysis of the reaction of 385 and 480 MeV ^{56}Fe projectiles with a ^{209}Bi target was continued¹. In these experiments charge distributions of projectile-like fragments were measured with discrete Z resolution as functions of angle and total kinetic energy loss (E_{LOSS}). The angle-integrated cross sections for the projectile-like fragments as functions of E_{LOSS} are shown in Fig. A.3-1 for both incident energies. The dashed lines correspond to the actually measured cross sections, the solid lines include the extrapolation to angles near zero degrees not covered in these experiments. Both energy distributions show the well known behavior of a strong peak at low energy losses, followed by a rather flat distribution with a second maximum at high E_{LOSS} . The second maximum lies below the Coulomb barrier of two spherical touching nuclei (indicated as arrows in Fig. A.3-1) in the exit channel. This indicates that the strongly damped events separate on the average from a highly deformed configuration.

The E_{LOSS} scale can be converted into an orbital angular momentum scale assuming a sharp cutoff model where $E_{\text{LOSS}} = 0$ corresponds to ℓ_{max} , as derived from the quarter-point angle¹, from the relation

$$\ell_i(E_{\text{LOSS}}^i) = \{(\ell_{\text{max}} + 1)^2 - \frac{1}{\pi \lambda^2} \int_0^{E_i} \sigma(E_{\text{LOSS}}^i) dE_{\text{LOSS}}^i\}^{1/2} - 1$$

Such an analysis yields nearly linear relations between ℓ and E_{LOSS} which are well represented by

$$\begin{aligned}\ell &= 172 + 0.53 E_{\text{LOSS}} & \text{for } E_{\text{Lab}} &= 385 \text{ MeV} \\ \ell &= 243 + 0.43 E_{\text{LOSS}} & \text{for } E_{\text{Lab}} &= 480 \text{ MeV}\end{aligned}$$

with E_{LOSS} in MeV.

The interaction times corresponding to a given E_{LOSS} can be estimated from the incoming $\ell_i(E_{\text{LOSS}})$ and outgoing angular momentum $\ell_f(E_{\text{LOSS}})$ and the experimental average deflection angle $\bar{\theta}(E_{\text{LOSS}})$. $\bar{\theta}$ can be extracted from the Wilczynsky plot (see Ref. 1). ℓ_i was estimated from the above relations and $\ell_f = \ell_i$ for the nonsticking condition (NS) while for a sticking condition (S) it is assumed that the maximum possible orbital angular momentum is transferred into rotational angular momentum of the reaction partners. With these values the deflection angle due to Coulomb deflection θ_c can be calculated following the procedure described in Refs. 2 and 3. This defines the deflection angle $\Delta\bar{\theta}$ while under the influence of the nuclear forces as

$$\Delta\bar{\theta}(\ell) = \theta_c(\ell) - \bar{\theta}(\ell).$$

Then the interaction time can be estimated from

$$t(\ell_i) = \Delta\bar{\theta}(\ell_i) \cdot \mathcal{I}(\ell_i) / t(\ell_f)$$

with the moment of inertia $\mathcal{I} = \mu R_{\text{SA}}^2$ taken at the strong absorption radius R_{SA} .

Such a procedure results in functions that are well represented by the relation

$$t(\ell) = t_0 \exp(-\ell/\ell_0).$$

For the Fe + Bi reaction the following parameters describe the experimental data:

385 MeV:	NS	$t_o = 1860$	$l_o = 23.0$
	S	$t_o = 625$	$l_o = 35.7$
480 MeV:	NS	$t_o = 2860$	$l_o = 28.8$
	S	$t_o = 962$	$l_o = 42.4$

(t_o in units of 10^{-22} sec).

This corresponds to interaction times at 100 MeV of E_{LOSS} of $3(8) \times 10^{-22}$ sec for $E_{\text{Lab}} = 480$ MeV and $9(21) \times 10^{-22}$ sec for $E_{\text{Lab}} = 385$ MeV for the NS(S) condition.

The details of the most probable charge and the variance as functions of E_{LOSS} are displayed in Fig. A.3-2 for $E_{\text{Lab}} = 385$ and 480 MeV. On the left-hand side is shown the drift $\Delta Z = \bar{Z} - 26$ of the average charge $\bar{Z}$ away from the projectile Z of 26, on the right-hand side the variances σ_Z^2 of the Z distributions as extracted from Gaussian fits to the data.

The analysis showed that $\bar{Z}$ and σ_Z^2 are independent of scattering angle. The drift in Z is in qualitative agreement with the predictions from calculations of potential energy surfaces from a liquid drop model. An example for $l = 0$ is shown in Fig. A.3-3. The steepest slope, and correspondingly the strongest driving force, predicts that the system evolves so that the projectile loses approximately 2 charge units. This trend does not change in calculations for different partial waves and including shell corrections. The observed drift in $\bar{Z}$ (Fig. A.3-2) follows this prediction: $\Delta Z = -2$ at approximately 100 MeV of E_{LOSS} . This agrees with the

observation of a gradual A/Z equilibration process which may saturate above approximately 100 MeV of E_{LOSS} (compare Section II.A.1).

It is interesting to note that ΔZ as a function of E_{LOSS} has the same slope for both energies under investigation. If ΔZ can be taken as a measure of the evolution of the charge equilibration process, this would indicate that A/Z equilibration is more closely related to the energy loss scale than to the time scale. 100 MeV of energy loss corresponds to 3 to 8×10^{-22} sec for 480 MeV and 9 to 21×10^{-22} sec for the 385 MeV data. If in addition σ_Z^2 can be taken as a measure of particles exchanged, then approximately 40% more particles have to be exchanged to produce $\Delta Z = -2$ (Fig. A.3-2). To verify the assumption that ΔZ reflects the A/Z equilibration process, it is necessary to extend the TOF measurements described in Section II.A.1 to different bombarding energies.

The variances σ_Z^2 of the Z distributions as functions for E_{LOSS} are much smaller than expected from other heavy-ion reactions at similar energies per nucleon.⁴ A compilation of σ_Z^2 as expressed by an alpha-parameter for a variety of projectile-target combinations,⁵ including a recent $^{56}\text{Fe} + ^{56}\text{Fe}$ experiment,⁶ shows a very systematic behavior, as can be seen from Fig. A.3-4. The friction coefficient α is defined by the slope of σ_Z^2 versus the logarithm of the fraction of the c.m. energy E_{cm} above the Coulomb barrier V_c dissipated during the interaction⁵:

$$\ln[(E_{\text{cm}} - V_c - E_{\text{LOSS}})/(E_{\text{cm}} - V_c)] = \frac{m}{\mu} \frac{A}{Z} \cdot \alpha \sigma_Z^2$$

Reflecting the surprisingly small σ_2^2 for the Fe + Bi reaction, the corresponding alpha-values are higher than expected. The same observation-though to a smaller degree-was made for the Fe + Ho reaction⁷. It has to be noted, however, that Fe + Bi and, to a smaller extent Fe + Ho, have considerable A/Z asymmetry in the entrance channel in contrast to all other projectile-target combinations which follow the systematics of Fig. A.3-4. The alpha parameter can be interpreted as a measure of energy dissipated in connection with particle exchange (k_{ex}) and without (k_{nex})⁵. Under this condition it seems that the need for charge equilibration in the reactions Fe + Bi and Fe + Ho hinders particle exchange and favors other modes of energy dissipation.

REFERENCES

1. Nucl. Chem. Progress Report, Univ. of Maryland, ORO-5172-11 (1978).
2. J. P. Bondorf, J. R. Huizenga, M. I. Sobel, and D. Sperber, Phys. Rev. C11, 1265 (1975).
3. W. U. Schröder, J. R. Birkelund, J. R. Huizenga, K. L. Wolf and V. E. Viola, Phys. Rep. 45, 301 (1978).
4. J. R. Huizenga, J. R. Birkelund, W. U. Schröder, K. L. Wolf and V. E. Viola, Phys. Rev. Lett. 37, 885 (1976).
5. Studies of Heavy Ion Reactions and Transuranic Nuclei, J. R. Huizenga, Univ. of Rochester Report #COO-3496069 (1978).
6. A. C. Mignerey, private communication.
7. A. D. Hoover, private communication.

Fig. A.3-1:

Cross section for projectile-like fragments as a function of total kinetic energy loss for the reaction $^{209}\text{Bi} + ^{56}\text{Fe}$ at (a) 385 MeV and (b) 480 MeV lab. energy. The arrows indicate the Coulomb energy of two spherical touching nuclei in the exit channel.

Fig. A.3-2:

The drift in the centroids of the charge distributions $\Delta Z = \bar{Z} - 26$ away from the projectile charge (left hand sides) and the variances σ_Z^2 of the charge distributions (right hand sides) for the reaction $^{209}\text{Bi} + ^{56}\text{Fe}$ as functions of energy loss at (a) $E_{\text{Lab}} = 385$ MeV and (b) 480 MeV.

Fig. A.3-3:

Potential energy surface for the reaction $^{209}\text{Bi} + ^{56}\text{Fe}$ calculated from the liquid drop model for $l = 0$ and without shell corrections. The mass (A) and atomic number (Z) scale refers to the projectile-like fragment. The lines of constant potential are normalized to $V = 0$ for the entrance channel (indicated by cross) and given in MeV.

Fig. A.3.4:

Alpha-parameter (see text) versus bombarding energy per nucleon above the Coulomb barrier (from Ref. 5). Included are the new data from the reactions $^{209}\text{Bi} + ^{56}\text{Fe}$, $^{165}\text{Ho} + ^{56}\text{Fe}$ and $^{56}\text{Fe} + ^{56}\text{Fe}$.

4. Structure in the Energy Spectra of Damped Products from the $^{56}\text{Fe} + ^{56}\text{Fe}$ Reaction (A.C. Mignerey and K.L. Wolf, Argonne Nat'l. Lab; H. Breuer, B.G. Glagola and V.E. Viola, U. of Maryland; and W. Wilcke, U. Schröder, J.R. Huizenga, D. Hilscher and J. Birkelund, Rochester U.)

The recent discovery of structure in the energy spectra of specific final fragments formed in damped collisions between symmetric target-projectile pairs has stimulated considerable speculation concerning their origin.¹⁻² Two explanations have been proposed to account for this observation: (1) an entrance channel effect - involving the excitation of giant resonance modes,³ and (2) an exit channel effect - resulting from statistical decay processes for the primary damped collision fragments.

We have studied this structure for specific fragments formed in the $^{56}\text{Fe} + ^{56}\text{Fe}$ reaction at 8.5 MeV/u at the LBL SuperHILAC. In Fig. A. 4-1 we show the partially damped energy spectrum for ^{57}Co in which the existence of structure is apparent. Similar spectra are obtained for nuclei near ^{56}Fe , but as the Z and A values of the fragments become increasingly different than ^{56}Fe , the structure gradually disappears. Similar results have been obtained at ORSAY² with the $^{40}\text{Ca} + ^{40}\text{Ca}$ and $^{63}\text{Cu} + ^{63}\text{Cu}$ reactions. The spectrum of Fig. A. 4-1 was obtained at 8° to the beam; recent measurements have been performed at the grazing angle of 14° to examine the angle dependence of this phenomenon. In addition, the $^{51}\text{V} + ^{56}\text{Fe}$ reaction has been studied to examine if target-projectile asymmetry is a significant parameter in the strength of this structure.

In order to explain the origin of structure in the energy spectra of damped collisions, we have examined the role of statistical evaporation processes following the production of the primary fragments, assuming their formation in nucleon-exchange processes. Calculations have been performed for the $^{40}\text{Ca} + ^{40}\text{Ca}$ system⁴ which have included: (1) the yield distribution of the primary fragments as a function of fragment excitation energy; (2) partition of the excitation energy according to the mass ratio of the fragments, but with a Gaussian distribution about the most probable value, and (3) light particle emission whenever it is energetically possible, which is described by using the decay probabilities of Ref. 5, tabulated separation energies, appropriate Coulomb barriers and the assumption of a Maxwellian distribution for the light-ion energy spectrum.

In Fig. A. 4-2 a fit to the ^{41}Ca energy spectrum for the $^{40}\text{Ca} + ^{40}\text{Ca}$ reaction is shown. It is observed that this model can satisfactorily describe the data. Hence, it would not appear necessary to involve the giant resonance explanation in order to account for structure in the energy spectra of damped heavy-ion reactions, since particle decay must be a major de-excitation channel. Similar calculations for the $^{56}\text{Fe} + ^{56}\text{Fe}$ system are in progress.

1. K.L. Wolf et al., BAPS 23, 46 (1978); A.C. Mignerey et al., BAPS 24, 629 (1979).
2. N. Frascaria et al., Phys. Rev. Lett. 39, 918 (1977); N. Frascaria et al., ORSAY Report IPNO-PHN-79-17 (1979).
3. R.A. Broglia, C.H. Dasso and A. Winther, Phys. Lett. 61B, 113 (1976); Phys. Rev. Lett. 41, 25 (1978).
4. D. Hilscher et al., to be published in Physical Review.
5. D. Bodansky, Ann. Rev. Nucl. Sci. 12, 79 (1962).

Fig. A.4-2:

The heavy line is the calculated laboratory energy spectrum of ^{41}Ca using maximum recoil broadening. The remaining curves represent the individual contributions to the production of ^{41}Ca from various primary fragments. The curve labeled ^{41}Ca corresponds to the yield of primary fragment ^{41}Ca that has survived particle decay. The other curves are labeled by the particles emitted from the primary fragments to produce the final fragment ^{41}Ca .

Fig. A.4-1:

Spectrum of ^{57}Co fragments observed at 8° (lab) from the reaction $^{56}\text{Fe} + ^{56}\text{Fe}$ at 465 MeV.

5. Neutron Emission in Damped Collisions

(D. Hilscher, J. Birkelund, U. Schröder, W. Wilcke and J.R. Huizenga, Rochester U.; K.L. Wolf and A.C. Mignerey, Argonne Nat'l. Lab.; and H. Breuer and V.E. Viola, U. of Maryland).

Neutron and α -particle emission have been measured for the damped collision and fusion-fission products resulting from the bombardment of ^{165}Ho with 8.5 MeV/u ^{56}Fe ions. These experiments were performed at the LBL SuperHILAC and involved the measurement of neutrons and light-ions coincident with Fe-like damped collision products. The damped collision products were Z-identified with a ΔE -E semiconductor detector counter telescope; neutrons were measured with six liquid scintillator (NE 213) detectors, and light-ions (H and He) were detected with a ΔE -E counter telescope which employed 500 μm ΔE and 3mm E detectors. The six neutron detectors were placed at angles corresponding to the flight paths of both the light fragment and the coincident heavy recoil fragment, as well as appropriate angles for obtaining both in-plane and out-of-plane angular distributions. A specially constructed thin-walled scattering chamber ring was used to minimize neutron attenuation and scattering. The beam was magnetically focussed to obtain the target spot-size and the Faraday cup, located about 6 meters downstream from the chamber, was heavily shielded to minimize extraneous sources of neutrons. The properties of the measured fragments are given in Table A.5-I.

From examination of the resultant c.m. neutron kinetic energy spectra at several angles, in Fig. A. 5-1, it is concluded that both light and heavy reaction partners exhibit equal nuclear temperatures. This result is consistent with complete equilibration of excitation energy during the lifetime of the relatively short-lived dinuclear complex formed in the interaction. The important implication of this result is that the excitation energy in damped reactions can be apportioned between the light (L) and heavy (H) fragments according to the relationship

$$\frac{E_L^*}{E_H^*} = \frac{a_L T_L^2}{a_H T_H^2}$$

If a universal value of the level density parameter $a = A/8 \text{ MeV}^{-1}$ is assumed, then

$$\frac{E_L^*}{E_H^*} = \frac{A_L}{A_H}$$

This assumption has been generally employed in the analysis of damped collision data.

From examination of the high energy tail of these spectra we estimate the contribution from pre-equilibrium neutron emission to be less than 5% of the total. This result argues against the existence of exotic mechanisms for the emission of neutrons in damped reactions, such as Fermi jets, at least at these relatively low energies. These results are consistent with other similar measurements.¹⁻³

Both the total neutron multiplicity (M) and the ratio of the heavy-to-light fragment multiplicities (M_H/M_L) are shown in Fig. A. 5-2. These results, when compared with shell-dependent potential energy surface calculations, suggest that the fragment N/Z ratio rapidly approaches a value corresponding to the minimum in the potential energy of the composite system. By converting the energy-loss parameter to a time scale, it can be estimated that N/Z equilibrium is reached in $5-10 \times 10^{-21}$ sec, corresponding to an energy loss of about 100 MeV. This conclusion is in good agreement with the studies of damped product spectra from this system reported in II. A.1.

Table 1: Mean neutron multiplicities and neutron energies

θ_T	$\langle E^* \rangle^a)$ [MeV]	$\langle M_L \rangle^b)$ $\pm 10\%$	$\langle E_L \rangle^c)$ [MeV]	$\langle M_H \rangle^b)$ $\pm 10\%$	$\langle E_H \rangle^c)$ [MeV]	$\langle M_{TOT} \rangle$ $\pm 10\%$	$\langle E_R \rangle^d)$ [MeV] $\pm 15\%$	Reaction ^{e)}
16°	113	1.93	3.1	5.77	3.1	7.69	27.5	SDC
20°	100	2.02	3.0	5.59	3.1	7.65	15.2	SDC
25°	83	1.56	2.4	4.01	2.5	5.57	20.7	SDC
$\langle 16, 20, 25 \rangle$	224	5.7	3.6	5.7	3.6	11.4	88	FF

a) $\langle E^* \rangle = \langle \text{TKE loss} \rangle + \langle Q_{gg} \rangle$ weighted mean with $\text{TKE loss} > 36$ MeV.

b) Weighted-mean neutron multiplicity with $\text{TKE loss} > 36$ MeV.

c) Weighted-mean first moment of c.m. neutron energy spectrum.

d) Residual excitation energy that is not carried away by neutron emission.

e) SDC : $20 \leq Z_L \leq 30$.

FF : $35 \leq Z_L \leq 55$.

REFERENCES

1. F. Plasil et al., Phys. Lett. 40, 1164 (1978).
2. Y. Eyal et al., Phys. Rev. Lett. 41, 625 (1978).
3. J. Péter, Z. Phys. A203, 413 (1977).

Fig. A.5-1:

Neutron energy spectra in the rest frames of the light (open circles) and the heavy (filled squares) fragments for all neutron detector angles. The spectra were averaged over Z between 20 and 30, TKE-losses larger than 36 MeV.

Fig. A.5-2:

(a) Neutron multiplicities M_L (open circles), M_H (filled squares) and (b) the ratio M_H/M_L (filled circles) are plotted versus TKE-loss for $20 \leq Z \leq 30$. The open and filled triangles represent exaporation calculations for M_L , M_H and M_H/M_L assuming an N/Z value corresponding to the valley of beta-stability and a value equilibrated towards N/Z of the composite system, respectively. The solid and dashed lines in (a) and (b) are drawn through the calculated points to guide the eye.

B. ~~Reactions Induced by Complex Projectiles above 10 MeV/u~~

1. Linear Momentum Transfer in the $^{16}\text{O} + ^{238}\text{U}$ Reaction

(V.E. Viola and H. Breuer, U. of Maryland; B. Back, K.L. Wolf and A.C. Mignerey, Argonne Nat'l. Lab.; and C.K. Gelbke, T.C. Awes and P. Dyer, Michigan State U.).

Determination of the fraction of projectile linear momentum transferred to the target in nuclear collisions provides important information on the global features of the target-projectile interaction. In a sense, measurement of the linear momentum distribution of the target-like products represents a description of the frictional characteristics of the interaction, ranging from near zero for grazing collisions to infinite friction for complete fusion of the colliding species. Furthermore, complete linear momentum transfer is a necessary minimum condition for definition of the complete fusion (CF) process.

In an effort to understand the global features of light heavy-ion reactions as a function of bombarding energy, we have investigated the $^{16}\text{O} + ^{238}\text{U}$ reaction at 8.5- and 20-MeV/u. These data complement earlier measurements ^{1,2} at 6.9 and 10.4 MeV/u, thus spanning the energy region between the Coulomb barrier and the Fermi energy. Linear momentum transfer distributions were measured via the fission-fragment angular correlation technique, using two 8 x 50 mm position-sensitive, ion-implemented semiconductor detectors placed at $\pm 80^\circ$ on either side of the beam axis. From the separation angle between coincident fission fragments, the linear momentum

transfer can be deduced. Special care was taken in these measurements to insure the absolute angular accuracy of the results; precautions included careful definition of the beam spot on target, determination of relative detector angles and rotation of the target angle through angles of 45° , 135° , 225° and 315° to normalize out any target-centering inaccuracies. Data for the angular correlation function for $^{16}\text{O} + ^{238}\text{U}$ are shown in Figure B. 1-1.

Examination of the results shows two distinct features of the linear-momentum-transfer distribution. First, the reaction cross section is observed to divide into two components consisting of: (1) fragments which are emitted nearly colinearly - these represent peripheral processes, ranging from well-defined few nucleon transfer process at low bombarding energies to increasingly complex events at higher energies, and (2) fragments emitted near or at the angle corresponding to complete fusion followed by fission, as predicted by kinematics - these are associated with central collisions. The distribution of events intermediate between these two extremes is presumably the result of large, but incomplete linear momentum transfer events originating from strongly damped and massive transfer processes. Obviously, these latter processes become increasingly important as the bombarding energy increases.

Nonetheless, it should be noted that even at 20 MeV/u, there is a significant fraction of the cross-section ($\sim 50\%$) which constitutes a well-defined group of events corresponding

to complete (nearly) absorption of the projectile by the target.

A second important feature of the angular correlation systematics is noted when the most probable correlation angle is compared with that predicted by kinematics (assuming complete linear momentum transfer). For the two lowest energies, excellent agreement with complete linear momentum transfer is obtained. At 10.4 MeV/u the experimental most probable angle is about 1.0 degree greater than calculated, corresponding to a value of about 97% of full momentum transfer. At 20 MeV/u this value is shifted 3.0 degrees, corresponding to about 92% of full momentum transfer. In addition the widths of the correlation functions - which are due primarily to dispersions from fragment neutron emission - are broader than expected. We interpret this result as being due to the increasing importance of pre-equilibrium processes involving prompt nucleon emission, which become increasingly important as the bombarding energy is increased. Similar results have been previously observed for the $^{20}\text{Ne} + ^{235}\text{U}$ and $^4\text{He} + ^{233,8}\text{U}$ systems.^{3,4}

The 20 MeV/u results emphasize the difficulties in defining the complete fusion process at energies well above the barrier. Although about 50% of the reaction cross section falls in the central collision peak, a kinematic analysis leads to the conclusion that less than 20% of the cross section is truly complete linear momentum transfer. Hence, it appears that the complete fusion cross section for this system must be rather small and that a broader

definition for reactions involving a strong target-projectile interaction is needed. We suggest that central collision (CC) would be a more general definition of this clearly defined process, which evolves with energy from complete fusion at lower energies. This definition also would provide continuity in the definition of evaporation residues (ER) as complete fusion processes, since pre-equilibrium processes involving central collisions cannot be distinguished from complete fusion followed by statistical decay.

REFERENCES

1. T. Sikkeland, E.L. Haines and V.E. Viola, Phys. Rev.
2. T. Sikkeland and V.E. Viola, Proc. Second Int. Conf. on Reactions between Complex Nuclei (UC Press, Berkeley, 1964).
3. V.E. Viola, et al., Nucl. Phys. A261, 174 (1976).
4. V.E. Viola, et al., Phys. Rev. C 10, 2416 (1974);
W.G. Meyer et al., Phys. Rev., to be published.

Fig. B.1-1:

Fission fragment angular correlation for the system $^{16}\text{O} + ^{238}\text{U}$ at bombarding energies of (a) 6.9 MeV/u, (b) 8.5 MeV/u, (c) 10.4 MeV/u and (d) 20 MeV/u. In Figs. (a)-(c) the correlation is plotted for the detector angle in coincidence with a second detector at -90° . In Fig. (d) the angle between the two fragments, θ_{AB} , is plotted.

2. Studies of Projectile-like Fragments in the $^{16}\text{O} + ^{238}\text{U}$
Reaction at 20 MeV/u. (P. Dyer, T.C. Awes, C.K. Gelbke,
 Michigan State University; B.B. Back, A.C. Mignerey and
 K.L. Wolf, Argonne Nat'l. Lab; H. Breuer and V.E. Viola,
 U. of Maryland, and W.G. Meyer, Lawrence Berkeley Lab).

Projectile residues have been studied in coincidence with angle-correlated fission fragments resulting from reactions induced by 20 MeV/u ^{16}O ions incident on a ^{238}U target at the LBL 88-inch cyclotron. The projectile-like reaction products were identified with a solid-state ΔE - ΔE -E telescope consisting of 27 μm , 70 μm and 3mm elements, respectively. Measurements were performed at 15° in the laboratory system, close to the grazing angle for this reaction. Coincident fragments resulting from the fission of the target residue were detected by two position-sensitive solid-state detectors, as described in the previous section. Gates were placed on various atomic numbers and energies for the projectile-like fragments in order to extract linear momentum transfer distributions parallel to the beam axis.

From a kinematic analysis of the data, it is possible to derive the distribution of missing momenta for reaction products of various Z. In Figure B. 2-1 we show a plot of the missing momentum, P_m , and the fraction of the missing momentum, P_m/P_{total} for Z = 3-8 fragments. In this plot $p_m = 0$ (dashed vertical line) represents a pure transfer reaction, whereas the opposite extreme of pure projectile fragmentation is indicated by the heavy arrow. With decreasing

atomic number of the coincident projectile residue the centroids of the p_m distributions increase. In no case, however, do they agree with either of the extreme situations of transfer or fragmentation. Moreover, from the widths of the p_m distributions one can rule out the possibility that these distributions are due to a simple superposition of pure transfer and pure fragmentation processes. Rather it appears that we are confronted with an intermediate type of reaction. It should be noted that part of the widths of the p_m distributions is due to the smearing of the fission angles by neutron evaporation. The mean fission angles and mean p_m , however, are not affected by isotropic neutron evaporation.

To obtain more information, we set gates on different energy bins for the projectile residues and determined, for each gate, the average parallel momenta of the outgoing projectile and target residues, (p_3) and (p_R) . The resulting relation between (p_R) and (p_3) is shown in Fig. B 2-2. For the purpose of orientation, the two-body transfer limit, $p_{tr} \equiv p_1 - p_3$, is shown by the solid line. We observe an approximately linear dependence of (p_R) on (p_3) , which shows that (p_R) is about 65% of the momentum transfer expected for a transfer reaction. This linear dependence on (p_3) is significantly more pronounced than any remaining dependence on the atomic number of the projectile residues. The reaction appears to be dominated by an intermediate process which is observed for a large dynamic range of

energies and atomic numbers of the outgoing projectile residues. From the rather unique dependence of this process on the parallel momentum of the projectile residue and the forward direction of the missing momentum it appears that the mechanism of momentum transfer and energy dissipation at projectile energies of about 20 MeV/nucleon is closely connected with the fast emission of a "jet" of particles preferentially into the forward direction.

Fig. B.2-1

Distributions of the missing parallel momentum $p_m^||$ for different projectile residues.

Fig. B.2-2

Dependence of the average parallel recoil momentum $\langle p_R^|| \rangle$ on the average parallel momentum $\langle p_3^|| \rangle$ of the projectile residue. The error bars include statistical errors and an estimate of the uncertainty due to the choice of θ_m .

3. Spectra of Light Ions in Coincidence with Angle-
Correlated Fission Fragments in the $^{16}\text{O} + ^{238}\text{U}$
Reaction at 20 MeV/u (T.C. Awes, P. Dyer and C.K.
 Gelbke, Michigan State U.; B.B. Back, A.C. Mignerey
 and K.L. Wolf, Argonne Nat'l. Lab., and H. Breuer
 and V.E. Viola, U. of Maryland).

Energetic light particles (H and He) have been measured in coincidence with angle-correlated fission fragments produced in the $^{16}\text{O} + ^{238}\text{U}$ reaction at 20 MeV/u. Central and peripheral collisions are distinguished on the basis of the projectile-to-target linear momentum transfer deduced from the fission fragment angular correlation. The experiments were performed at the LBL 88-inch cyclotron and the angle-correlated fission fragments and projectile-like fragments were detected as described in the previous two sections. Light particle (H and He) were detected at 14° with a ΔE -E telescope consisting of a 350 μm thick semiconductor ΔE detector and a 4 cm thick NaI E detector.

The fission yields as a function of the fission fragment correlation angle, θ_{AB} , are shown for the inclusive spectra in Fig. B. 3-1. The associated momentum-transfer scale was obtained by assuming symmetric fission of the compound nucleus ^{254}Fm . The inclusive distribution shows two groups which we associate with central ($\theta_{AB} \sim 148^\circ$) and peripheral ($\theta_{AB} \sim 173^\circ$) collisions. From the specific H and He yields as a function of correlation angle in Fig. B. 3-1, it is observed that the probability for the emission of energetic light particles is high for both

central and peripheral collisions. Of particular interest, it is noted that the p, d, t and α yields at 14° are all within a factor of 2-3 of one another - in marked contrast with inclusive spectra studies with ^4He ions,¹ where p and α yields are of much greater relative importance at 20 MeV/u.

The energy spectra of H and He ions observed at 14° are compared for central and peripheral collisions in Fig. B. 3-2. Although substantial differences are apparent at low energies, at high energies the slopes of the spectra are identical within the limits of error. This striking result supports a mechanism in which promptly emitted particles are produced at a very early stage (pre-equilibrium) in the projectile-target interaction, thus yielding spectra that are independent of the final fate of the colliding nuclei.^{2,3} On the other hand, the data do not support models (e.g. fireball⁴) which treat the target nucleus as a spectator in the collision.

In summary, these studies demonstrate that light-ion emission in the reaction of 20 MeV/u ^{16}O ions with ^{238}U is dominated by pre-equilibrium processes and involves large momentum transfers to the target nucleus. This result has previously been inferred for lighter projectiles from the study of 12-35 MeV/u ^4He ions on ^{233}U . The remarkable similarity of the slopes of the spectra for energetic H and He ions for both central and peripheral collisions further supports a pre-equilibrium source for light ions formed in these reactions. On the basis of these results it is

possible to conclude that the energetic emission of protons from a hot source moving with a velocity intermediate between projectile and target velocities is not a mechanism of major importance in these reactions.

REFERENCES

1. C.C. Chang and H. Holmgren, private communication.
2. V.E. Viola et al., Phys. Rev. C 10, 2416 (1974);
W.G. Meyer et al., Phys. Rev. C, to be published.
3. J. Bondorf, Proc. Workshop on High Resolution Heavy-Ion Physics at 20-100 MeV/A, p. 37 (1978).
4. G.D. Westfall et al., Phys. Rev. Lett. 37, 1202 (1976).

Fig. B.3-1:

Folding angle distributions between two outgoing fission fragments. The kind of additional coincidence condition is given in the figure. For the ratio of the parallel recoil momentum p_R and the beam momentum p_{11} fission of ^{254}Fm has been assumed.

Fig. B.3-2:

Light particle spectra measured at 14° in coincidence with central ($\theta_{AB} < 160^\circ$) and peripheral ($\theta_{AB} > 160^\circ$) reactions. The solid lines correspond to the spectral shape $\exp(-E/T)$, with $T = 13$ MeV.

4. Studies of the $^4\text{He} + ^{233}\text{U}$ Reaction between 12-35 MeV/u
(V.E. Viola, B.G. Glagola and S.M. Read, U. of Maryland,
and W.G. Meyer, Lawrence Berkeley Lab.).

Fission fragment angular correlation measurements have been performed on the $^{233}\text{U} + ^4\text{He}$ system at energies between 12-35 MeV/u in order to obtain an understanding of the macroscopic features of the target-projectile interaction mechanism. The salient features of these studies have been described previously.¹ In an effort to provide a more quantitative description of the measured linear momentum transfer distributions for this reaction, we have compared the experimental results with existing models for collisions between complex nuclei.^{2,3} In comparisons with a proximity potential model which includes one-body energy dissipation,² we find that the experimental complete fusion cross section (complete linear momentum transfer) is much smaller than predicted. The predictions do, however, account for the central collision cross section (50-100% linear momentum transfer) quite well.

In view of the above interpretation, it is of interest to compare the present experimental results with the predictions of the intranuclear cascade code, which explicitly includes two-body energy dissipation. The code of Chen, et al.,² has recently been modified to permit calculations for reactions induced by deuterons and alpha particles, as well as for the existence of d and α clusters in the target nucleus.⁴ In Fig. B. 4-1 the experimental fission-fragment angular correlation for 140-MeV alpha particles incident on

^{233}U is plotted along with predictions of the intra-nuclear cascade code. The calculations assumed one alpha-particle cluster in the ^{233}U target (not a very sensitive parameter) and did not allow for refraction and reflection at the nuclear surface. Two assumptions were made concerning alpha-particle collisions in the cascade: one which permitted the alpha particle to breakup and the other which allowed no-breakup. From the linear momentum transfer distribution and corresponding excitation energies predicted for the residual heavy nuclei, the fission fragment angular correlation was then calculated. This calculation included dispersion effects due to neutron emission from the fragments.

Qualitatively, the calculations reproduce the basic features observed in the data, i.e., distinct complete (or nearly so) fusion and peripheral components, plus a substantial fraction of events that are characterized by a large, but incomplete linear momentum transfer. Clearly, the no-breakup assumption for alpha-particle cascades provides a better fit to the data. However, since the treatment of the ion-ion potential is very approximate in the intranuclear cascade model, one cannot expect to reproduce the exact details of the data with such a calculation, especially at the low energies for which the model is applied here. Nonetheless, the calculations do reinforce the previous conclusion that the effects of two-body energy dissipation must be incorporated into models which hope to describe collisions induced by complex nuclei above 10 MeV/nucleon.

REFERENCES

1. V.E. Viola et al., Phys. Rev. C10, 2416 (1974);
W.G. Meyer et al., Phys. Rev., to be published.
2. J.R. Birkelund et al., Phys. Rev. Lett. 40, 1123 (1978).
3. K. Chen et al., Phys. Rev. 166, 949 (1968).
4. R.A. Moyle et al., to be published.

Fig. B.4-1:

Comparison of the experimental fission fragment angular correlations at 140 MeV with predictions based on the intra-nuclear cascade model. The solid line refers to cascades which allow alpha-particle breakup; the dashed line refers to a no-breakup assumption.

5. Measurement of Total Heavy Fragment Mass, Energy and Angular Distributions for the ${}^4\text{He} + {}^{12}\text{C}$ and ${}^4\text{He} + {}^{27}\text{Al}$ Reactions (A. Gökmen, B.G. Glagola, H. Breuer and V.E. Viola).

Increasing emphasis is currently being placed on both the theoretical and experimental description of nuclear reactions in the transitional energy region between 10-100 MeV/u. In order to obtain a detailed description of the product yields for reactions of this type, we have initiated a study of the ${}^4\text{He} + {}^{12}\text{C}$ and ${}^4\text{He} + {}^{27}\text{Al}$ reactions from 10-40 MeV/u. The ${}^{12}\text{C}$ data are also of interest for astrophysical problems.

The experimental program involves the measurement of complete mass, energy and angular distributions for all products with $A > 4$ in the above reactions. Element identification for $Z \leq 6$ is also obtained using a ΔE -E semiconductor telescope which employs a 15 μm ΔE and a 700 μm E detector. Fragment masses are identified with a channel-plate time-of-flight system consisting of a channel-plate start signal and a semiconductor stop and E signal. This system has achieved a timing resolution of 140 psec. In Fig. B. 5-1 mass spectra obtained with a flight path of 22cm are shown for the ${}^4\text{He} + {}^{12}\text{C}$ and ${}^4\text{He} + {}^{27}\text{Al}$ reactions at 20 MeV/u.

It is observed that the yield patterns in the ${}^4\text{He} + {}^{27}\text{Al}$ case exhibit a preference for the formation of $A = 4n$ products. In addition examination of the energy spectra as a function of bombarding energy clearly shows the transition

from final products dominated by two-body processes to more complex processes characteristic of multi-body final states. /

Bombardments have been performed at 40, 60, 80, 120, 140 and 160 MeV and the data are currently being analyzed. The ${}^4\text{He} + {}^{12}\text{C}$ system will be compared with predictions which employ (1) the intranuclear cascade code modified for α and d clusters¹ in the interaction stage, followed by (2) decay of the excited residuals via a Fermi breakup mechanism which allows for multibody final states (discussed below). The ${}^{27}\text{Al} + {}^4\text{He}$ data will also employ the intranuclear cascade code in the interaction stage followed by a standard evaporation code for de-excitation of the residual nuclei.

1. R.A. Moyle, et al., to be published.

Fig. B.5-1:

Mass spectrum of all product nuclei with $E > 1$ MeV measured at 12° for bombardment of ^{12}C with 80 MeV ^4He pions.

Fig. B.5-2:

Mass spectrum of product nuclei with $E = 15-20$ MeV measured at 20° for bombardment of ^{27}Al with 80 MeV ^4He ions.

6. Calculation of $Z \geq 3$ Mass, Energy and Angular Distributions
in the $p + {}^{12}\text{C}$ Reaction (A. Gökmen, B. G. Glagola, G. J.
 Mathews and V. E. Viola)

Reactions between light projectiles (e.g., p, α) and light target nuclei (e.g., C, O) at energies above 10 MeV/u may be described in two stages. The first involves the excitation of the target nucleus by two-body interactions between the incident particles and individual nucleons in the target nucleus. As a result, the system can emit particles at a pre-equilibrium stage or proceed towards an equilibrium state. The second stage of the reaction involves the de-excitation of a highly excited residual nucleus. For heavy target-projectile systems the evaporation model is widely used. However, if the excitation energy is large compared to the total binding energy of the residual nucleus such as that which results from bombardment of ${}^{12}\text{C}$ or ${}^{16}\text{O}$ by energetic p or α 's, the de-excitation is likely to be more sudden and to follow the Fermi statistical pattern.¹

In the Fermi break-up mode of de-excitation the energy is instantaneously distributed to all degrees of freedom, and various possible disintegrations occur according to their statistical weight^{2,3}. The distribution function takes into account energy and momentum conservation, the spin of emitted particles and also the indistinguishability of identical particles in the process.

An excited residual nucleus A^* with an energy E_A^* will undergo decay into n particles;

$$A^* \rightarrow b + c + \dots + n$$

where b, c, -- n are resultant particle-stable nuclei (e.g., n, p, d, t, α , -- etc)

The input data for the calculations are:

- (1) Mass excesses of all nuclei involved in the reaction.
- (2) The residual nuclei produced by the cluster cascade code and their excitation energy, momentum and angle of emission spectra.
- (3) All particle-stable nuclei that can be formed in the reaction and their spectrum of excited states.

The calculation is performed according to the following procedure:

- (1) For a given residual nucleus all energetically possible decay channels (i.e., total energy released in the channel is positive) are selected by the distribution function.
- (2) The probability of decay of the residual nucleus to each channel is determined by normalizing the distribution function.
- (3) The decay channel is selected by comparing with a random number.
- (4) The kinematic behavior of each breakup is calculated and stored in a table, and
- (5) The calculations are repeated through Step (1) for other residual nuclei.

Calculations with this de-excitation code for the $^{12}\text{C}(p, \text{HI})$ reaction have been carried out. Calculated differential cross

sections are compared with experimental data in Fig. B.6-1 (a)-(d). It is common in all graphs that the differential and total reaction cross sections are over estimated. However, the angular distributions of fragments are predicted to be quite similar to the experimental data.

REFERENCES

1. E. Fermi, Prog. Theor. Phys., 5, No. 4, 570 (1950).
2. J. V. Lepore and R. N. Stuart, Phys. Rev. 94, 1724 (1954).
3. T. Erickson, Nuova Cimento, 21, 605 (1961).

Fig. B.6-1(a)

Fig. B.6-1(b)

Fig. B.6-1(c)

Fig. B.6-1(d)

Fig. B.6-1:

Comparison of calculated angular distribution and total cross section results using the cluster intranuclear cascade phys. Fermi breakup model with experimental data for the 100 MeV $p + {}^{12}\text{C}$ reaction. Curves are as follows: (a) $A=6$, (b) $A=7$, (c) $A=10$ and (d) $A=11$.

7. DWBA Analysis of the $\alpha + \alpha$ Reaction at 10-40 MeV/u

(B. G. Glagola, A. Nadasen, N. S. Chant and V. E. Viola).

In order to provide a deeper understanding into the nuclear structure of light elements and the underlying reaction mechanism we have measured the production of the $A = 6$ and 7 isobars in the $\alpha + \alpha$ reaction.¹ Using alpha-particle beams in the energy range from 61.5 to 158.2 MeV from the University of Maryland Cyclotron, energy and angular distributions have been measured for the $A = 6$ and 7 reaction products. These data 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 energies.

Fig. B.7-1 shows the center-of-mass (com) angular distributions of the $\alpha(\alpha, {}^6\text{Li(g.s.)})d$ reaction and results of calculations using the Exact Finite Range Nucleon Transfer Code (MARY) of N. S. Chant².

The $\alpha + \alpha$ optical potentials were calculated from the energy-dependent analysis of the $\alpha + \alpha$ elastic scattering volume integrals.³ These potentials are found to be consistent with those of $\alpha + {}^{12}\text{C}$ ⁴ and $\alpha + {}^{24}\text{Mg}$.⁵ For the $d + {}^6\text{Li}$ exit channel, three sets of potentials based on the systematics reported by Hinterberger, et al,⁶ were used: (1) Energy independent $d + {}^{12}\text{C}$ ($E_d = 52$ MeV for all calculations); (2) energy dependent $d + {}^{12}\text{C}$; and (3) energy dependent $d + {}^6\text{Li}$. Although the lightest target used in reference 6 was ${}^{12}\text{C}$, potential set 3 was obtained by extending the potentials to ${}^6\text{Li}$ based on the reported mass dependence. It should be noted, however, that the Hinterberger potentials have no energy dependence for the imaginary part of the potential.

As can be seen from the figures, the calculations using the energy-independent $d + {}^{12}\text{C}$ potential for the exit channel reproduces the shape of the ${}^6\text{Li}$ angular distribution quite well, but there are major problems with the magnitude, particularly at the lower energies. As expected, the energy-dependent potentials result in substantial improvement of the fit to the experimental data. Extrapolation to the $d + {}^6\text{Li}$ potential provides further improvement. One major problem that becomes immediately obvious when using the energy-dependent potentials, however, is that the fit to the shape of the 60 MeV data has deteriorated even though there is an improvement in magnitude. The calculations exhibit oscillations not present in the data. This could be the result of using a weak absorption potential. This discrepancy might be resolved by introducing an energy dependence into the imaginary part of the potential. Work along this line is presently in progress.

Overall it can be seen that the calculations are in good agreement with the systematic trends of the ${}^6\text{Li}$ angular distribution over a wide energy range. Also, the $\alpha(\alpha, {}^6\text{Li}(\text{g.s.})){}^2\text{H}$ reaction can be described well in terms of a two-nucleon transfer reaction mechanism in the distorted-wave Born Approximation. Thus far no attempt has been made to explain the $\alpha(\alpha, {}^7\text{Li})\text{p}$ and $\alpha(\alpha, {}^7\text{Be})\text{n}$ data over the same energy range in terms of a three nucleon transfer reaction. These calculations are planned in the near future.

REFERENCES

1. B. G. Glagola, University of Maryland Technical Report No. MNC-5172-0012 (1978).
2. N. S. Chant, Nucl. Phys. A211, 269 (1973).
3. A. Nadasen, P. G. Roos, B. G. Glagola, G. J. Mathews, V. E. Viola, H. G. Pugh and P. Frisbee, Phys. Rev. C18, 2792 (1978).

4. S. M. Smith, et al., Nucl. Phys. A207, 273 (1973).
5. P. P. Singh, P. Schwandt, and G. C. Yang, Phys. Lett. 59B, 113 (1975); G. C. Yang, Ph.D. Thesis, Indiana University, 1975 (unpublished).
6. Hinterberger, et al., Nucl. Phys. A111, 265 (1968).

Fig. B.7-1 (a)

Fig. B.7-1:

Comparison of calculated $(\alpha, {}^6\text{Li})^2\text{H}$ center-of-mass angular distributions with the experimental data. The triangles are experimental data; the dotted line (...) is for the energy-independent $d + {}^{12}\text{C}$ potential; the dashed line (---) is for the energy-dependent $d + {}^{12}\text{C}$ potential and the solid line (-) is for the energy-dependent $d + {}^6\text{Li}$ potential.

Fig. B.7-1 (b)

Fig. B.7-1 (c)

Fig. B.7-1 (d)

C. Nuclear Astrophysics

1. Cross Sections for A = 6 and 7 Isotopes in the ${}^4\text{He} + {}^4\text{He}$ Reaction (B.G. Glagola, G.J. Mathews, H. Breuer, V.E. Viola, P.G. Roos and A. Nadasen, U. of Maryland, and Sam M. Austin, Michigan State U.).

Cross sections have been measured for the production of ${}^6\text{He}$, ${}^6\text{Li}$, ${}^7\text{Li}$ and ${}^7\text{Be}$ in the astrophysically important ${}^4\text{He} + {}^4\text{He}$ reaction between 61.5 and 158.2 MeV. In Fig. C. 1-1 we have plotted the ratio of the total cross section for A = 7 products to that for A = 6, as a function of ${}^4\text{He}$ bombarding energy.

From examination of Fig. C. 1-1 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 simultaneously reproducing the experimental ${}^7\text{Li}/{}^6\text{Li}$ and ${}^{11}\text{B}/{}^{10}\text{B}$ ratios with single-component models which involve galactic-cosmic-ray or stellar-flare particle spectra. In addition, more rigorous constraints on the amount of ${}^6\text{Li}$ and ${}^7\text{Li}$ that can be synthesized by such mechanisms are now imposed on model calculations.

Under any circumstances, there is no question of the need for a low-energy mechanism for ${}^7\text{Li}$ production in nature.

Since ${}^7\text{Li}$ is also predicted to be formed in the big bang,¹ it has been argued²⁻⁴ that this may be the additional source of ${}^7\text{Li}$. Indeed, the assumption that the big bang does not produce more ${}^7\text{Li}$ than the presently observed abundance leads to limits on the universal baryon density. These limits are indicated in Fig. C. 1-2 where the ratio of the limit on the big bang abundance of ${}^7\text{Li}$ ($X_{7\text{Li}}^{\text{BB}}$) to that of deuterium (X_D^{BB}) are compared⁴ with calculated big bang abundances as a function of the baryon density of the universe. This analysis implies a universe that is too low in density to permit eventual gravitational collapse. Whether the big bang or mechanisms such as supernova shock waves, novae, neutron stars, or helium-shell flashes constitute this additional source of ${}^7\text{Li}$ remains open to debate, but certainly the present results are consistent with a picture in which ${}^2\text{H}$, ${}^3\text{He}$, and ${}^4\text{He}$, and ${}^7\text{Li}$ are primarily of big bang origin and ${}^6\text{Li}$, ${}^9\text{Be}$, ${}^{10}\text{B}$, ${}^{11}\text{B}$, and a small amount (~10%) of ${}^7\text{Li}$ are produced via galactic-cosmic-ray mechanisms.

These data are also relevant to the understanding of several other problems in astrophysics. For example, the $\alpha + \alpha$ reaction is important in evaluating possible galactic sources of deuterium, which could alter conclusions about the universal baryon density. The interpretation of the composition and energy spectrum of galactic cosmic rays is also affected by these data. The present results argue against a cosmic-ray spectrum shape which emphasizes high-energy α particles, because of the influence on observed ${}^7\text{Li}/{}^6\text{Li}$

ratios this would imply. Finally, these cross sections are essential for the investigation of Li synthesis mechanisms in various cosmological settings, e.g., production on the surfaces of neutron stars and carbon stars.

REFERENCES

1. D.N. Schramm and R.V. Wagoner, Annu. Rev. Nucl. Sci. 27, 37 (1977).
2. H. Reeves, Annu. Rev. Astron. Astrophys. 12, 437 (1974); H. Reeves and J.-P. Meyer, to be published.
3. C.H. King, Sam M. Austin, H.H. Rossner, and W.H. Chien, Phys. Rev. C 16, 1712 (1977).
4. G.J. Mathews and V.E. Viola, Ap. J. 288, 375 (1979).

Fig. C.1-1:

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

Fig. C.1-2:

The ratio of ^7Li to D mass fractions as a function of the present baryon density for a present background temperature of 2.8K. The curve labeled $\xi = 1.0$ corresponds to the standard big bang (ref. 1). The curves labeled $\xi = 0.5, 2.0$ correspond to a scaling of the free expansion trajectory consistent with the range of the observed ^4He abundance.

2. Production Cross Sections for Li, Be and B

Isotopes from the $p + {}^{16}\text{O}$ Reaction at 50-90 MeV

(R.A. Moyle, B.G. Glagola, G.J. Mathews and V.E. Viola,
U. of Maryland).

Cross sections for the production of $A = 6, 7, 9, 10,$ and 11 isobars in the reaction of 50-90 MeV protons with oxygen are reported. Product masses were identified by time-of-flight techniques using either a channel-plate fast-timing device or rf fast timing. Mass, kinetic energy, and angular distributions are reported for the products. The measured cross sections are applied to theories of LiBeB nucleosynthesis which involve galactic-cosmic-ray or stellar-flare reactions as a source of these elements. Both of the models underproduce the observed ${}^7\text{Li}/{}^6\text{Li}$ ratio by an order of magnitude, which supports previous conclusions that an additional source of ${}^7\text{Li}$ is required for its synthesis. However, the models give reasonable agreement for the ${}^{11}\text{B}/{}^{10}\text{B}$, ${}^6\text{Li}/\text{Be}$ and $\text{B}/{}^6\text{Li}$ ratios, although the galactic ray model predicts a ${}^{11}\text{B}/{}^{10}\text{B}$ ratio that is low by a factor of 2. In addition the $\text{B}/{}^6\text{Li}$ ratio is consistent only with a low value for the natural boron abundance.

3. Nucleosynthesis Calculations for the Production of Li, Be and B (S. M. Read, B. G. Glagola and V. E. Viola).

New calculations for the nucleosynthesis of Li, Be and B in nature have been performed, using the most recent observational data as input parameters. These calculations have included:

- (1) A review of the literature and tabulation of all salient cross section (σ_{ijL}) information for the $p + \text{CNO}$, $\alpha + \alpha$ and $\alpha + \text{CNO}$ reactions;
- (2) Generation of standard excitation functions for each product isotope from each reaction based on the systematics of the above data;
- (3) Inclusion most recent elemental and isotopic abundances for the interstellar medium (Ni) and the cosmic ray composition and,
- (4) Calculation of the abundance ratios ${}^7\text{Li}/{}^6\text{Li}$, ${}^{11}\text{B}/{}^{10}\text{B}$, ${}^6\text{Li}/\text{Be}$ and $\text{B}/{}^6\text{Li}$ for models which invoke galactic cosmic rays, stellar flares and monoenergetic shock waves as sources.

Abundances were calculated with the standard expression

$$\frac{dN_L}{dt} = \sum_{i,j} N_i \int_{E_0}^{\infty} \sigma_{ijL}(E) \phi_j(E) S(E, i, j, L) dE$$

where L represents the Li, Be and B isotopes produced in all combinations of interactions between targets, i and projectile j. The function $S(E, j, i, L)$ represents the fraction of products projectiles, j retained by the interstellar medium. Results for galactic cosmic ray and monoenergetic source spectra ($\phi_j(E)$) are presented here.

Calculations for the production of Li, Be and B via interactions between galactic cosmic rays and the interstellar medium employed the ISM abundances of Cameron¹, cosmic ray fluxes of Mitler² and a flux function of the form

$$\phi_j(E) = k (E_0 + E)^{-2.6}.$$

Comparison of this calculation with experimental data is shown in Table C.3-I. It is observed that for the ${}^6\text{Li}/\text{Be}$ and $\text{B}/{}^6\text{Li}$ ratios the results are quite satisfactory. Serious disagreement is observed for the ${}^7\text{Li}/{}^6\text{Li}$ ratio, indicating the need for a low-energy mechanism for ${}^7\text{Li}$ production. The disagreement between calculation and experiment for the ${}^{11}\text{B}/{}^{10}\text{B}$ ratio is also outside experimental error, but could be brought into agreement if a low-energy component were present in the galactic cosmic ray flux.

The monoenergetic source spectrum employs a spectrum for the incident particles of the form

$$\phi_j(E) = \delta(E)$$

and employed values of N_i used by Bodansky³.

The results for this calculation for various values of E are presented in Table C.3-II. The sharp discontinuity in the results between 11 and 12 MeV/u is due to the opening of the $\alpha(\alpha, d){}^6\text{Li}$ channel, which influences ${}^6\text{Li}$ production markedly. It is observed that only for an extremely well-defined energy near 11.5 MeV/u is it possible to reproduce the experimental abundance values with such a model. Hence, the monoenergetic source model, which is associated with supernova shock wave mechanisms, seems to be an unlikely one.

REFERENCES

1. A.G.W. Cameron, Space Science Reviews 15, 121, (1970).
2. H.E. Mitler, Astrophysics Space Science 17, 186 (1972).
3. D. Bodansky et al., Ap. J. 202, 222 (1975).

TABLE C.3-I

	${}^7\text{Li}/{}^6\text{Li}$	${}^{11}\text{B}/{}^{10}\text{B}$	${}^6\text{Li}/\text{Be}$	$\text{B}/{}^6\text{Li}$
Experimental ¹	$12.6^{+0.2}$	$4.05^{+0.10}$	5.3 (2.3)*	2.6 (2.7)*
GCR Calculation	1.3	2.2	4.0	4.1

*represents error factor

TABLE C.3-II

E (MeV/u)	${}^7\text{Li}/{}^6\text{Li}$	${}^{11}\text{B}/{}^{10}\text{B}$	${}^6\text{Li}/\text{Be}$	$\text{B}/{}^6\text{Li}$
8	1.0	9.1	29	29
9	72	3.7	14	11
10	470	3.8	8.5	13
11	248	5.3	6.5	19
12	4.0	4.1	182	0.42
13	1.4	4.8	280	0.25
15	1.7	2.4	116	0.27
20	1.2	1.7	51	0.33
30	0.48	4.0	29	0.80

III. PERSONNEL

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IV. PUBLICATIONS AND ACTIVITIES

A. Published Papers

MEASUREMENT OF ${}^4\text{He} + {}^4\text{He}$ ELASTIC SCATTERING AT 158.2 MeV, A. Nadasen, P.G. Roos, H.G. Pugh, P. Frisbee, B.G. Glagola, G.J. Mathews, and V.E. Viola, Jr., *Phys. Rev. C* 18, 2792 (1978).

PRODUCTION OF $A = 6$ AND 7 ISOTOPES IN THE $\alpha + \alpha$ REACTION, B.G. Glagola, G.J. Mathews, H.F. Breuer, V.E. Viola, Jr., P.G. Roos, A. Nadasen, and Sam M. Austin, *Phys. Rev. Lett.* 41, 1698 (1978).

MECHANISMS OF VERY HEAVY-ION COLLISION: THE ${}^{209}\text{Bi} + {}^{136}\text{Xe}$ REACTION AT $E_{\text{lab}} = 1130$ MeV, W.U. Schröder, J.R. Birkelund, J.R. Huizenga, K.L. Wolf, and V.E. Viola, Jr., *Physics Reports* 45, 301 (1978).

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 V.E. Viola, Jr., *Phys. Rev. C* 19, 631 (1979).

ON THE LIGHT ELEMENT ABUNDANCES, GALACTIC EVOLUTION, AND A MORE SENSITIVE INDICATOR OF THE UNIVERSAL BARYON DENSITY, G.J. Mathews and V.E. Viola, Jr., *Astrophys. J.* 228, 375 (1979).

INCOMPLETE MOMENTUM TRANSFER IN PERIPHERAL HEAVY-ION COLLISIONS AT 20 MeV/A, P. Dyer, T.C. Awes, C.K. Gelbke, B.B. Back, A. Mignerey, K.L. Wolf, H. Breuer, V.E. Viola, Jr., and W.G. Meyer, *Phys. Rev. Lett.* 42, 560 (1979).

SYNTHESIS OF SUPERHEAVY ELEMENTS IN THE r -PROCESS, V.E. Viola, Jr. and G.J. Mathews, *Proc. Int. Sym. on SuperHeavy Elements*, (Pergamon Press), 499 (1979).

STRUCTURE IN THE ENERGY SPECTRA OF THE FRAGMENTS PRODUCED IN DAMPED HEAVY-ION REACTIONS, D. Hilscher, J.R. Birkelund, A.D. Hoover, W.U. Schröder, W.W. Wilcke, J.R. Huizenga, A. Mignerey, K.L. Wolf, H.F. Breuer, and V.E. Viola, accepted for publication in *Phys. Rev.*

ENERGY SPECTRA OF LIGHT IONS FOR CENTRAL AND PERIPHERAL COLLISIONS OF 20-MeV/u ${}^{16}\text{O} + {}^{238}\text{U}$, C.K. Gelbke, T.C. Awes, B.B. Back, A.C. Mignerey, K.L. Wolf, P. Dyer, H. Breuer and V.E. Viola, Jr., submitted to *Physics Letters*.

NEUTRON EMISSION FROM THE ${}^{165}\text{Ho} + {}^{56}\text{Fe}$ REACTION AT 8.5 MeV/A, D. Hilscher, J.R. Birkelund, A.D. Hoover, W.U. Schröder, W.W. Wilcke, J.R. Huizenga, A. Mignerey, K.L. Wolf, H. Breuer, and V.E. Viola, Jr., accepted for publication in *Phys. Rev.*

CORRELATED CHARGE EXCHANGE AND N/Z EQUILIBRATION IN REACTIONS INDUCED BY 8.5 MeV/A ${}^{56}\text{Fe}$ IONS, H.F. Breuer, B.G. Glagola, V.E. Viola, A. Mignerey, K.L. Wolf, J. Birkelund, D. Hilscher, W.U. Schröder, W.W. Wilcke, and J.R. Huizenga, *Phys. Rev. Lett.* 43, 191 (1979).

NUCLEOSYNTHESIS OF THE CHEMICAL ELEMENTS, V.E. Viola, Jr.,
Sym. on Cosmochemistry and the Origin of Life, (University of
 Mexico), to be published.

THE PARTICLE-HOLE SPECTRA OF ^{16}O AND ^{16}N AS OBSERVED IN PICK-UP REACTIONS
 FROM ^{17}O , G. Mairle, G. J. Wagner, P. Doll, K. T. Knöpfle, and H. Breuer,
 Nucl. Phys. A299, 39 (1978).

DOMINANCE OF α DECAY FROM THE ISOSCALAR GIANT QUADRUPOLE RESONANCE ON
 ^{16}O , K. T. Knöpfle, G. J. Wagner, P. Paul, H. Breuer, C. Mayer-Böricke,
 M. Rogge, and P. Turek, Phys. Lett. 74B, 191 (1978).

IS THERE AN ISOSCALAR "GIANT" QUADRUPOLE RESONANCE IN ^{12}C , H. Riedesel,
 K. T. Knöpfle, H. Breuer, P. Doll, G. Mairle, and G. J. Wagner, Phys.
 Rev. Lett. 41, 377 (1978).

B. Published Abstracts

STUDY OF THE $^{56}\text{Fe} + ^{209}\text{Bi}$ REACTION AT 385- AND 480-MeV, H. F. Breuer,
 B. G. Glagola, V. E. Viola, A. Mignerey, D. Raich, K. L. Wolf, J. R.
 Birkelund, D. Hilscher, J. R. Huizenga, and W. U. Schröder, Bull. Am.
 Phys. Soc. 23, 958 (1978).

MOMENTUM TRANSFER IN PERIPHERAL REACTIONS OF 20 MeV/A ^{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, Bull. Am. Phys. Soc. 23, 958 (1978).

CROSS-SECTION MEASUREMENTS FOR THE $\alpha+\alpha$ AND $p + ^{16}\text{O}$ REACTION AT INTERMEDIATE
 ENERGIES, B. G. Glagola, G. J. Mathews, A. Nadasen, R. A. Moyle, P. G.
 Roos, H. F. Breuer, V. E. Viola, and Sam M. Austin, Topical Conf. on
 Cosmic Ray Astrophysics, Durham, NH, September (1978).

NEW CALCULATIONS OF THE COSMIC-RAY NUCLEOSYNTHESIS OF Li, Be AND B, G. J.
 Mathews, B. G. Glagola, S. M. Read, and V. E. Viola, Topical Conf. on
 Cosmic Ray Astrophysics, Durham, NH, September (1978).

NEUTRON EMISSION FROM THE REACTION $^{165}\text{Ho} + ^{56}\text{Fe}$ AT 8.5 MeV/A, J. R.
 Birkelund, D. Hilscher, A. D. Hoover, W. U. Schröder, W. W. Wilcke, J. R.
 Huizenga, A. Mignerey, K. L. Wolf, H. Breuer, and V. E. Viola, 3rd Nat.
 Cong. of Australian Institute of Physics, January (1979).

CROSS-SECTION MEASUREMENTS FOR ^6He , $^6,^7\text{Li}$ AND ^7Be IN THE $\alpha+\alpha$ REACTION
 AT 61.5-159 MeV, B. G. Glagola, H. F. Breuer, G. J. Mathews, A. Nadasen,
 P. G. Roos, V. E. Viola, and Sam M. Austin, Bull. Am. Phys. Soc. 24,
 593 (1979).

MODIFICATION OF THE INTRANUCLEAR CASCADE CODE TO INCLUDE d AND INTER-ACTIONS, V. E. Viola, B. G. Glagola, G. J. Mathews, and R. A. Moyle, Bull. Am. Phys. Soc. 24, 615 (1979).

CENTRAL AND PERIPHERAL REACTIONS OF 20 MeV/A ^{16}O WITH ^{238}U , B. B. Back, A. Mignerey, K. L. Wolf, C. K. Gelbke, T. C. Awes, P. Dyer, H. Breuer, V. E. Viola, W. G. Meyer, Bull. Am. Phys. Soc. 24, 628 (1979).

STRUCTURE IN THE ENERGY SPECTRA FROM THE REACTION $^{56}\text{Fe} + ^{56}\text{Fe}$ AT 8.5 MeV/n, A. C. Mignerey, K. L. Wolf, J. R. Birkelund, D. Hilscher, W. U. Schröder, W. W. Wilcke, J. R. Huizenga, V. E. Viola, and H. Breuer, Bull. Am. Phys. Soc. 24, 629 (1979).

STUDY OF THE REACTION $^{165}\text{Ho} + ^{56}\text{Fe}$ AT 8.5 MeV/amu, A. D. Hoover, D. Hilscher, J. R. Birkelund, W. U. Schröder, W. W. Wilcke, J. R. Huizenga, A. Mignerey, K. L. Wolf, H. Breuer, and V. E. Viola, Jr., Bull. Am. Phys. Soc. 24, 629 (1979).

STUDY OF Z AND A DISTRIBUTIONS AS A FUNCTION OF ENERGY DAMPING FOR REACTIONS OF ^{56}Fe WITH ^{165}Ho AND ^{209}Bi , H. F. Breuer, B. G. Glagola, V. E. Viola, A. Mignerey, K. L. Wolf, J. R. Birkelund, D. Hilscher, J. R. Huizenga, U. Schroeder, and W. Wilcke, Bull. Am. Phys. Soc. 24, 629 (1979).

STARKE DER ISOSCALAREN QUADRUPOLE-RIESENRESONANZ IN ^{12}C : LÖSUNG DES PROBLEMS DURCH MESSUNG IHRES TEILCHENZERFALLS, H. Breuer, P. Doll, G. Mairle, H. Reidesel, K. Schindler and G. Wagner, VDPG (1979).

STUDY OF THE $^{209}\text{Bi} + ^{56}\text{Fe}$ REACTION AT 385 AND 480 MeV, V. E. Viola, H. Breuer, B. Glagola, K. L. Wolf, A. C. Mignerey, J. Birkelund, D. Hilscher, J. R. Huizenga, U. Schröder and W. W. Wilcke, paper 188, Nuclear Chemistry and Technology Division, ACS/CSJ Chemical Congress, Honolulu. (1979).

C. PROFESSIONAL ACTIVITIES

Chairman-Elect, ACS Division of Nuclear Chemistry and Technology, 1979

Executive Committee, Hollifield Heavy Ion Research Facility, 1979

University Senate Committee on Honors and Prizes, 1978-79

Chemistry Department Faculty Advisory Committee, 1978-79

Chemistry Department Admissions Committee, 1978-79

University of Maryland Research Professor, Spring, 1979

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