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NUCLEAR CHEMISTRY PROGRESS REPORT

V. E. Viola, Jr.
Department of Chemistry
University of Maryland
College Park, Maryland 20742

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II. Nuclear Reaction Mechanism Studies

A. Elastic Scattering

1. Elastic Scattering of ^{40}Ar and ^{84}Kr on ^{209}Bi and ^{238}U at 7.2 and 8.5 MeV/nucleon (J. R. Birkelund, J. R. Huizenga, H. Freiesleben, K. L. Wolf, J. P. Unik and V. E. Viola, Jr.; Phys. Rev. 13C, 133 (1976)).

Cross sections for elastic scattering of ^{40}Ar on targets of ^{209}Bi and ^{238}U were measured at the SuperHILAC at energies of 286 and 340 MeV. Cross sections for the elastic scattering of ^{84}Kr on ^{209}Bi were measured at energies of 600 and 712 MeV.

Analysis of these elastic scattering data is complicated by the presence of few nucleon transfer events which give rise to scattered particles of energy close to the energy of the elastically scattered projectile. Hence, it is essential that future data be collected with a high energy resolution if the detailed shape of the elastic scattering angular distribution is to be examined. Because of the rapid decrease in the ratio $\sigma_{\text{el}}/\sigma_{\text{Ruth}}$ near the quarter point, it is still possible to extract from elastic scattering values of the total reaction cross section for heavy ion reactions to within $\pm 10\%$, even from data taken with moderate energy resolution ($\sim 2\%$). These are listed for these systems in Table I.

Comparison of optical and Fresnel scattering models used to fit heavy ion elastic scattering data indicates that the Fresnel model reproduces the gross features of the elastic scattering angular distributions at angles not too far from the quarter point. For heavy ions the Fresnel model leads to reasonable estimates of the maximum angular momentum for reacting ions and the total reaction cross section. Further, the Fresnel interaction radii are in good agreement with the optical model strong absorption radii, as shown

in Table II.

The systematics of the variation of the Fresnel interaction radii indicate that the probability of nuclear reactions between heavy ions is a universal function of the separation of their surfaces. Figure 1 shows a plot of the nuclear radius parameter r_0 as a function of $Z_1 Z_2$ of the target-projectile system. Assuming a two-parameter Fermi density distribution for each of the heavy ions with a half-density radius of C_1 , the onset of nuclear reaction between heavy ions occurs at a constant separation distance of 2.9 ± 0.3 fm, where the Fresnel interaction radius is given by $R_{int} = C_1 + C_2 + 2.9$ fm. With a diffuseness parameter of 0.55 fm in the Fermi density distribution, the onset of nuclear reaction between heavy ions is also describable in terms of a universal function of the ratio of the maximum overlap density to the central nuclear density of approximately 5% for each ion.

The radial dependence of the real nuclear potential is obtained from a combination of the nuclear potential at the strong absorption radius derived from optical model fitting of the elastic scattering and the maximum nuclear force between heavy ions as predicted by the liquid drop model. Such a potential may be a reasonable estimate of the internuclear potential at nuclear separation between the liquid drop touching distance and the strong absorption radius.

Fig. 1. Plot of the interaction radius parameter r_0 as a function of $Z_1 Z_2$ for various projectile-target combinations.

Table 1. Parameters deduced from the Fresnel scattering model.

Target	E_{lab} (MeV)	η	$\theta_{\text{c.m.}}^{1/4}$ (deg)	r_0 (fm)	l_{max}	σ_R (mb)
^{40}Ar projectile						
^{209}Bi	340	80.63	47	1.411	185	2382
^{209}Bi	286	87.91	60	1.433	151	1887
^{238}U	340	89.37	51	1.414	187	2336
^{238}U	286	97.44	68	1.411	144	1648
^{84}Kr projectile						
^{209}Bi	712	161.6	50.5	1.37	343	2533
^{209}Bi	600	175.9	66	1.38	270	1880

Table II. Comparison of parameters found from the optical model and the Fresnel model fit to the data.

	E_{lab}	$R_{\text{int}}^{\text{Fresnel}}$ (fm)	Optical model R_{SA} (fm)
Ar projectile			
^{209}Bi	340	13.21	13.30
	286	13.43	13.35
^{238}U	340	13.59	13.60
	286	13.56	13.68
Kr projectile			
^{209}Bi	712	14.16	14.25
	600	14.24	14.28

2. Elastic Scattering of ^{16}O and ^{20}Ne from ^{235}U (W. G. Meyer, R. G. Clark, V. E. Viola, R. G. Sextro and A. M. Zebelman; Z. Phys. A277, 141 (1976)).

The elastic scattering of 140-MeV ^{16}O and 175- and 252-MeV ^{20}Ne from ^{235}U has been measured at the LBL 88-inch cyclotron using a position-sensitive semiconductor detector.

In Table I we compare results for the reaction parameters obtained with Fresnel¹ and optical² model analyses of elastic scattering data, and find the two models give equivalent results concerning the gross features of the reaction. There is no appreciable dependence of the interaction radius on bombarding energy for ^{20}Ne ions between 175 and 252 MeV.

In addition we have compared our total reaction cross section results with ^{16}O - and ^{20}Ne -induced fission of ^{238}U (Ref. 3). In these comparisons we have assumed that σ_f is identical for ^{235}U and ^{238}U within the experimental limits of error, and that the maximum orbital angular momentum determined from the σ_f values, ℓ_{sc} , is determined by a sharp cutoff model. Because of the high fissionability of uranium, it is generally assumed that nearly all inelastic channels lead to fission, so that $\sigma_f = \sigma_R$. However, cross sections as high as 100 mb have been observed for one- and two-nucleon transfer reactions in bombardments of ^{238}U with very heavy ions such as ^{40}Ar and ^{84}Kr at energies near the interaction barrier. Given the lack of knowledge concerning the few-nucleon transfer cross sections, both the Fresnel and optical model values for σ_R can be considered to be in good agreement with the measured cross section for the inelastic channels; i.e. primarily σ_f .

The comparisons in Table I demonstrate that for a given energy the orbital angular momentum that characterizes the minimum impact parameter for elastic scattering is essentially the same, regardless of the model. The interaction radii determined from the Fresnel and optical model fits are in good agreement with one another, in addition to being energy independent, as previously mentioned. The preceding conclusions are for the most part the same as those derived for ^{40}Ar and ^{84}Kr projectiles in Reference 4. In addition, our values of R_{int} agree well with the value of $R_{\text{int}}=12.7$ fm predicted by a generalized relationship for determining total reaction cross sections in Reference 4.

The agreement between the various types of data in Table I in predicting the gross features of the target-projectile interaction suggests that the interaction radius concept can be generalized for use in predicting total reaction cross sections and maximum angular momenta for ^{20}Ne and ^{16}O reactions with heavy elements. From the relationship

$$\sigma_R = \pi R^2 (1 - V/E_{\text{cm}}), \quad (1)$$

where $V=Z_1 Z_2 e^2/R$ and E_{cm} is the center-of-mass energy of the projectile, an excellent fit to the experimental total reaction cross section data for ^{20}Ne and ^{16}O bombardments of uranium above 120 MeV and 100 MeV, respectively, is obtained if one simply sets $R=R_{\text{int}}=12.75$ fm for ^{20}Ne and 12.60 fm for ^{16}O , as determined from the Fresnel scattering analysis. Comparison of Equation (1) with the experimental data is shown in Figure 1. This can be further generalized to ^{20}Ne - and ^{16}O -induced reactions on other heavy targets by substituting our result for r_0 into Equation (1); i.e. $R=r_0 (A_T^{1/3} + A_P^{1/3})$ with $R_0=1.44$ fm for ^{20}Ne and 1.45 fm for ^{16}O .

- 1) Frahn, W.E., Venter, R.H.: Ann. Phys. 24, 243 (1973); Frahn, W.E.: Phys. Rev. Lett. 26, 358 (1971); Frahn, W.E: Ann. Phys. 72, 524 (1972).
- 2) Igo, G: Phys. Rev. 115, 165 (1959); Drisko, R.M., Satchler, G.R., Bassel, R.H.: Phys. Lett, 5, 347 (1963).
- 3) Viola, V.E., Jr., Sikkeland, T.: Phys. Rev. 128, 707 (1962).
- 4) Birkelund, J.R. Huizenga, J.R. Freiesleben, H., Wolf, K.L., Unik, J.P. Viola, V.E, Jr.: Phys. Rev. C13, 133 (1976).

Fig. 1. a Lower Curve: Total reaction cross section for the ^{20}Ne + uranium system as a function of bombarding energy using $R_{int}=12.75$ fm (solid line). Solid points are total fission cross sections from Reference 3 and open points are from this work. b Upper Curve: Same as (a) except for ^{16}O projectiles and $R_{int}=12.6$ fm

Table I. Comparison of values for the total reaction cross section, maximum orbital angular momentum and strong absorption radius for ^{235}U target as determined from (1) fission total cross section measurement (1); assuming $\sigma_f = \sigma_R$ and a sharp cutoff (SC) model; (2) Fresnel scattering analysis; and (3) optical model analysis

	140-MeV ^{16}O	175-MeV ^{20}Ne	252-MeV ^{252}Cf
σ_f	1,790 $\pm$ 70 mb	1,800 $\pm$ 70 mb	2,730 $\pm$ 110 mb
σ_R (Fresnel)	1,830 $\pm$ 80 mb	1,900 $\pm$ 40 mb	2,810 $\pm$ 140 mb
σ_R (optical)	-	2,060 mb	2,920 mb
l_{sc}	72.1	89.4	132
l_{max} (Fresnel)	72.9	91.8	134
$l_{1/2}$ (optical)	-	93.8	136
R_{int} (Fresnel)	1.6 $\pm$ 0.2 fm	12.8 $\pm$ 0.2 fm	12.7 $\pm$ 0.3 fm
R_{SA} (optical)	-	13.0 $\pm$ 0.2 fm	12.8 $\pm$ 0.3 fm

B. Damped Collision Processes

1. Study of the Reaction $^{209}\text{Bi} + ^{136}\text{Xe}$ (W.U. Schröder, J.R. Birkelund, J.R. Huizenga, K.L. Wolf, J.P. Unik and V.E. Viola; Phys. Rev. Lett 36, 514 (1976))

The charge, kinetic energy and angular distributions of reaction products formed during bombardments of ^{209}Bi with 1130-MeV ^{136}Xe ions have been studied with solid state counter telescope arrays at the LBL SuperHILAC.

The experimental elastic scattering data were fitted with Fresnel and optical models. The reaction cross sections determined from the Fresnel model, $\sigma_R = \pi \lambda^2 (1_{\text{max}} + 1)^2$, and optical model,

$$\sigma_R = \pi \lambda^2 \sum_{l=0}^{l_{\text{max}}} (2l + 1) T_l,$$

are 2700 ± 120 and $2780 \pm \text{mb}$, respectively. The Fresnel interaction radius and the optical-model strong-absorption radius are approximately equal and give a value $R = 15.2 \pm 0.3 \text{ fm}$. This radius corresponds to a value of $r_0 = 1.37 \text{ fm}$ [where $r_0 = R / (A_p^{1/3} + A_t^{1/3})$]. If the interaction or strong-absorption radius are approximately equal and give a value $R = C_p + C_t + S$ (where C_p and C_t are the electron-scattering half-density radii for a two-parameter Fermi charge distribution for the projectile and target, respectively), the constant S determined from the present experiment is $2.9 \pm 0.3 \text{ fm}$. Hence, the interaction radius measured for this very heavy projectile-target system ($Z_p Z_t = 4482$) is in good agreement with the relationship $R = (C_p + C_t + 3.2) \pm 0.3 \text{ fm}$ derived for the interaction radii of lighter systems ($Z_p Z_t \leq 2988$)¹.

The differential reaction cross section for the lighter-mass product from the reaction $^{209}\text{Bi} + ^{136}\text{Xe}$ at 1130 MeV is displayed in Fig. 1 as a function of laboratory angle. As can be seen in this figure, the differential cross section is very strongly peaked at an angle of 30° in the laboratory frame. The integral of the differential reaction-cross-section data is 2840 ± 150 mb, in good agreement with the total reaction cross section determined from elastic scattering.

The experimental ΔE - E distributions were converted to Z - E distributions by using an energy-loss function for ^{136}Xe ions measured in this experiment and, in addition, relative values of $\Delta Z/\Delta E$ from Northcliffe and Schilling.² A constant ratio of $Z/A = 0.397$ was assumed for the reaction products. Examples of the charge distributions of the Xe-like fragment as a function of kinetic energy are shown in Fig. 2 for $\theta_{\text{lab}} = 30^\circ$. The different Z distributions of Fig. 2 correspond to the kinetic energy bins listed in Table 1. The differential cross sections and the centroids $\langle Z \rangle$ and widths (FWHM) of the Z distributions as a function of energy loss are summarized in Table 1. The curves of Fig. 2 are Gaussian fits to the charge-distribution data.

As the bin number increases more kinetic energy is lost in the collision and, as displayed in Fig. 2, the charge distribution broadens. One of the surprising features of the data is that even for large kinetic-energy losses, the Z distribution remains Gaussian in shape and its centroid stays nearly at Xe. Only for the last bin, where some 300 MeV of kinetic energy is lost, has $\langle Z \rangle$ increased by more than 1 unit. This result

differs from that for ^{84}Kr -induced reactions where the centroid in Z is shifted to larger values corresponding to net transfer of mass from the target to the projectile. Based on potential energies of the two-nucleus intermediate systems, the driving force for mass transfer to the projectile is much greater for the reaction $^{209}\text{Bi} + ^{84}\text{Kr}$ than for the reaction $^{209}\text{Bi} + ^{136}\text{Xe}$.

In summary, the charge distributions are interpreted in terms of a strong contact collisions between the two complex nuclei resulting in a two-body intermediate system where the two nuclei cling together temporarily but do *not* actually fuse together. The reaction products "remember" to some extent their initial charges and masses as well as their direction of motion. During the time of contact of the two nuclear surfaces, translational energy is converted into internal energy and nucleon transfer occurs between the fragments. Accordingly, the broader Z distributions correspond to longer interaction times and larger kinetic-energy losses.

- 1) J.R. Birkelund, J.R. Huizenga, H. Freiesleben, K.L. Wolf, J.P. Unik, and V.E. Viola, Jr., Phys. Rev. 13C, 133 (1976).
- 2) L.C. Northcliffe and R.F. Schilling, Nucl. Data, Sect. A 7, 233 (1970).

Table 1. Centroid and FWHM of the charge distribution of the Xe-like fragment for various energy bins measured at a laboratory angle of 30° for the reaction $^{209}\text{Bi} + ^{136}\text{Xe}$ at 1130 MeV (laboratory energy). Both energies are given to the middle of the bin and the total-kinetic-energy (TKE) values (c.m.) are corrected for neutron emission.

Bin	E_{lab} (MeV)	TKE _{c.m.} (MeV)	$d\sigma/d\Omega$ (mb/sr)	$\langle Z \rangle$	FWHM
1	946	684		54	3.3 ± 0.2
2	926	662	1410	54.1 ± 0.1	4.0 ± 0.2
3	896	640	1095	54.0 ± 0.1	4.6 ± 0.2
4	857	605	700	54.8 ± 0.1	4.5 ± 0.2
5	818	575	553	54.8 ± 0.2	5.4 ± 0.2
6	779	540	515	54.8 ± 0.2	6.3 ± 0.2
7	740	510	471	55.1 ± 0.2	7.8 ± 0.3
8	700	475	405	55.0 ± 0.2	8.3 ± 0.2
9	661	442	313	55.1 ± 0.2	11.1 ± 0.3
10	622	410	234	55.4 ± 0.3	14.3 ± 0.5
11	583	375	160	57.1 ± 0.5	16.8 ± 1.0

Fig. 1 Angular distribution for 1130-MeV ^{136}Xe ions incident on ^{209}Bi .

FIG. 2. Charge distributions of the Xe-like fragment formed in the reaction $^{209}\text{Bi} + ^{136}\text{Xe}$ at 1130 MeV (laboratory energy) as a function of the fragment kinetic energy. The fragment kinetic energy decreases as the bin number increases. The error bars represent the square root of the counts per Zchannel.

2. Energy Dissipation and Nucleon Transfer in Heavy-Ion Reactions (J.R. Huizenga, J. R. Birkelund, W.U. Schröder, K.L. Wolf and V.E. Viola; Phys. Rev. Lett. 37, 885 (1976))

In furthering our understanding of heavy-ion reactions it is crucial to know the relationship between energy dissipation and particle diffusion and, in particular, the relative time scales on which these two processes occur. It is often assumed that the time scale for the energy dissipation is very short compared to the time scale for particle diffusion. Recent experimental results¹ show that the energy dissipation and particle diffusion are strongly correlated and, hence, that the above assumption concerning time scales is not valid for all heavy-ion reactions.

Proton distributions of projectilelike fragments, studied at the Lawrence Berkeley Laboratory SuperHILAC with semiconductor counter telescopes, are discussed in this article for the reactions $^{209}\text{Bi} + ^{136}\text{Xe}$, $^{165}\text{Ho} + ^{136}\text{Xe}$, $^{209}\text{Bi} + ^{84}\text{Kr}$, and $^{165}\text{Ho} + ^{84}\text{Kr}$ at bombarding energies of 8.3 to 8.5 MeV/nucleon. A qualitative correlation between the kinetic energy dissipation and the width of the proton distribution was first observed for the $^{209}\text{Bi} + ^{136}\text{Xe}$ reaction.¹ The width of the proton distribution, defined by the variance σ_z^2 , was determined at each energy by fitting a Gaussian function to the experimental data. More asymmetric proton distributions observed for the Kr-induced reactions, as compared to Xe-induced reactions, are consistent with the underlying potential energy surfaces of these reactions.

The correlation between the measured variance of the proton distribution and the amount of kinetic energy loss for the above four reactions is shown in Fig. 1. The variance of the proton distribution, σ_z^2 , increases with increasing amounts of total kinetic energy loss. In addition, the slope of the energy dissipation as a function of the variance σ_z^2 is largest for small values of the variance and decreases as the variance increases. The values of σ_z^2 in Fig. 1 for the Kr-induced reactions are included only for total kinetic energy losses less than about 200 MeV. For the Xe-induced reactions, σ_z^2 is, within experimental error, independent of angle for events of the same energy loss. This is nearly true also for the Kr-induced reactions with the smaller energy losses mentioned above.

In order to investigate in more detail the correlation of σ_z^2 and energy loss shown in Fig. 1, a simple diffusion theory is introduced which has recently been employed to explain the mass and proton distributions of reaction products from damped collisions.² The formulation of Nörenberg is followed in which the occupation probabilities,

$$P(Z, t) = (4\pi\mathcal{D}_z t)^{-1/2} \times \exp [-(Z - Z_0 - v_z t)^2 / 4\mathcal{D}_z t]. \quad (1)$$

The quantity $Z - Z_0$ stands for the number of protons transferred during the interaction time t . The parameters v_z and $\mathcal{D}_z$ are constants and represent average proton drift and diffusion coefficients, respectively. The variance, σ_z^2 , of this distribution is given by $2\mathcal{D}_z t$.

The nearly constant value of Z for the Xe-induced reactions indicated that the drift coefficient v_z in Eq. (1) is small. If the diffusion theory is valid for proton transfer at all stages of the process and D_z is a constant, then the abscissa of Fig. 1 converts to a time scale, with the interaction time given by $t = \sigma_z^2 / 2D_z$. On the other hand, under the assumption of the sharp cutoff model and a monotonic decrease of l with energy loss, starting with the grazing angular momentum and zero energy loss, a deflection function $\theta(l)$ can be calculated from the experimental reaction data. From a comparison to the Coulomb deflection function, angular-momentum-dependent interaction times can be estimated. For example, for the $^{165}\text{Ho} + ^{84}\text{Kr}$ reaction, 10 units σ_z^2 correspond to $(7 \pm 3) \times 10^{-22} \text{ sec.}^3$ This relationship changes slightly for the other reactions. From the earlier relationship between σ_z^2 and the interaction time t for the $^{165}\text{Ho} + ^{84}\text{Kr}$ reaction, a value of the proton diffusion coefficient $D_z = (0.7 \pm 0.3) \times 10^{22} \text{ sec}^{-1}$ is deduced.

It is important to emphasize the continual range of total kinetic energy damping for these very-heavy-ion reactions. This is illustrated in Fig. 2 where the differential cross section in millibarns per MeV of total kinetic energy loss is plotted versus the total kinetic energy loss. For the Xe-induced reactions, the integral of the plotted differential cross section gives the total reaction cross section. However, in the case of the $^{165}\text{Ho} + ^{84}\text{Kr}$ reaction some 700 mb of the cross section is in the range $\theta_{\text{c.m.}} < 20^\circ$ and missing in this figure. In addition, these events are relatively strongly damped.³ The kinetic

energy loss indicated by each arrow in Fig. 2 is based on a final kinetic energy equivalent to the Coulomb energy at the strong absorption radius R_{SA} . One observes that the peak in the cross section of each Xe-induced reaction is at an energy loss considerably less than that for events with final kinetic energy equal to $E_{Coul}(R_{SA})$. However, with a large number of γ waves and a range of separation distances it is not possible to disentangle the contributions to the observed kinetic energy due to the Coulomb energy and the translational energy at separation.

- 1) W.U. Schröder, J.R. Birkelund, J.R. Huizenga, K.L. Wolf, J.P. Unik, and V.E. Viola, Jr., Phys. Rev. Lett. 36, 514 (1976).
- 2) W. Nörenberg, Phys. Lett. 52B, 289 (1974), and Z. Phys. A274, 241 (1975).
- 3) K.L. Wolf and C.T. Roche, in Proceedings of the Symposium on Macroscopic Features of Heavy-Ion Collisions, Argonne National Laboratory, 1-3 April 1976 (to be published).

Fig. 1. Total kinetic energy loss in MeV as a function of the variance, σ_z^2 , of the proton distribution of the projectile-like fragment. All values of the variance are determined from angle-integrated data. The abscissa is a time scale where 10 units in σ_z^2 correspond to $(7 \pm 3) \times 10^{-22}$ sec for the $^{165}\text{Ho} + ^{84}\text{Kr}$ reaction (see text). Estimated errors are included for selected points.

Fig. 2. Differential cross section, $d\sigma/dT_{\text{loss}}$, for events of various degrees of kinetic energy damping T_{loss} . Each arrow corresponds to the kinetic energy loss for an event with final kinetic energy equal to that of the Coulomb energy at the separation distance of the strong absorption radius

3. Strongly Damped Collisions in the $^{84}\text{Kr} + ^{209}\text{Bi}$ Reaction. (V.E. Viola, Jr., K.L. Wolf, J.P. Unik, J.R. Huizenga, J. Birkelund and H. Freiesleben).

Information on strongly damped collisions (SDC) is presented for bombardments of ^{209}Bi with ^{84}Kr ions from the Berkeley SuperHILAC. This process accounts for a significant fraction of the reaction cross section in interactions between heavy target nuclei and projectiles of ^{40}Ar and heavier.¹⁻³ The exit channel properties of the strongly damped collisions exhibit the following features: (1) two fragments are emitted with masses near those of the target and projectile, although exchanges of several nucleons can occur; (2) strong damping of the energy degree of freedom is observed; fragment energies are characteristic of deformed fission fragments, representing an attenuation of 100-150 MeV in the entrance channel energy, and (3) the angular distribution for the ^{84}Kr -like product is strongly peaked at an angle near the classical grazing angle. Measurements have been conducted with 600-MeV and 714-MeV ^{84}Kr ions. These are compared with the work of Hanappe et al.¹ at 525 MeV.

The center-of-mass differential cross sections for the light fragments from the SDC process are compared in Fig. 1. The sharp peaking of the angular distributions is indicative of a direct reaction mechanism, and the decrease in $d\sigma/d\Omega$ at forward angles implies that the target-projectile system remains intact for considerably less than one revolution. The most probable peak angle for the strongly damped collision process is

found to shift to progressively forward angles as the bombarding energy is increased. Further, near the interaction barrier (≈ 450 -MeV lab energy for this system³), the angular distribution peak occurs at an angle greater than the classical grazing angle,¹ whereas for the higher energies,² the peak angle is inside the grazing angle. These results suggest that as the ^{84}Kr energy is increased, the projectile penetrates more deeply into the target-nucleus; hence, producing longer target-projectile sticking times. Analysis of the elastic scattering³ and strongly damped collision data give the following results:

E_{Kr} (MeV)	σ_{R} (mb)	ℓ_{max}	σ_{SDC} (mb)	$\sigma_{\text{SDC}}/\sigma_{\text{R}}$
525 (Ref. 1)	920	176	~ 600	~ 0.65
600 (Ref. 2)	1800	263	~ 1500	~ 0.83
714 (Ref. 2)	2500	337	> 1900	> 0.75

These data demonstrate the increasing importance of the strongly damped collision process as the bombarding energy increases.

More detailed information on the properties of the products are obtained from correlated fragment data. In Fig. 2(a) a contour plot of the pre-neutron emission total kinetic energy in the c.m. system is presented as a function of mass for the 600-MeV bombardment with the defining detector placed at 87° (c.m.). The average total kinetic energy (TKE) is observed to be about 275-MeV, compared to an energy of 430-MeV for elastically scattered ^{84}Kr ions. Analysis of similar plots at other angles demonstrates that the average TKE remains nearly constant as a function of angle, with a slight increase at forward angles. Fig. 2(b)

compares mass distributions for the SDC process at 87° (c.m.) and 51° (c.m.) in the 600-MeV bombardment. The grazing angle is 67° (c.m.) For angles well outside the grazing angle, considerably more mass exchange is observed. The direction of mass flow is from the target to projectile, consistent with liquid drop expectations.³ This result suggests that these fragments are the result of low impact-parameter collisions where longer contact time permits greater mass exchange to occur.

The SDC process is interpreted in terms of the near balance between the attractive nuclear force, dV_N/dr , and the repulsive effects of the Coulomb and centrifugal forces, $d(V_C + V_\ell)/dr$, in the $^{209}\text{Bi}-^{84}\text{Kr}$ system. Because only a small number, if any, of the lowest entrance channel ℓ -waves have potential minima in these collisions, complete fusion of the target and projectile is very improbable.

- 1) F. Hanappe, M. Lefort, G. Ngo, J. Peter, and B. Tamain, Phys. Rev. Lett. 32, 738 (1974).
- 2) K.L. Wolf, J.P. Unik, J.R. Huizenga, J. Birkelund, H. Freiesleben and V.E. Viola, Jr. Phys. Rev. Lett. 33, 1105 (1974).
- 3) J.R. Huizenga, University of Rochester Report UR-NSRL-90, 1974; Nucleonika, 20, 291 (1975).

Fig. 1. Center-of-mass angular distributions for the light-mass fragment from the strongly damped collisions.

Fig. 2. (a) Contour plot of the kinetic energy (c.m.) versus fragment mass for the 600 MeV data with the defining detector at 59° (lab) with an energy window around the strongly damped peak of the light fragment. (b) Mass distributions for strongly damped collisions when the light fragment is detected at 59° (lab), solid curve, and 34° (lab), dashed curve.

4. Effect of Static Target Deformation on the Reaction of ^{84}Kr Ions with ^{144}Sm and ^{154}Sm (R.L. Boudrie, K.L. Wolf, C.T. Roche, J.R. Birkelund, W.U. Schröder, J.R. Huizenga and V.E. Viola; BAPS 21, 969 (1976)).

Measurements of elastic scattering and inelastic processes have been made for 475, 605, 720 MeV krypton ions interacting with the nearly spherical nuclide ^{144}Sm , and with ^{154}Sm , a nuclide with a large prolate deformation. Complete angular distributions of reaction products were measured using dE/dX Z-identification. The most significant observed differences between reactions on the two targets are in the angular distributions and energy spectra of products from strongly damped collisions. An enhanced yield of fully damped products is observed at angles forward of the grazing angle for bombardment of the highly deformed ^{154}Sm target nuclide compared to ^{144}Sm at each bombarding energy. In Fig. 1 a comparison between the angular distributions for the two targets is shown. This effect, which is most prominent at incident energies of 475 and 605 MeV, is interpreted in terms of a deformed nuclear potential and a more spherical Coulomb potential in the entrance channel. The role of the neutron-to-proton ratio of the target nuclide must also be considered in this regard.

Fig. 1. Laboratory angular distribution for 605-MeV $^{84}\text{Kr} + ^{154}\text{Sm}$ (solid line) compared with 605-MeV $^{84}\text{Kr} + ^{144}\text{Sm}$ (dotted line).

5. Interaction Times for Damped Heavy-Ion Collisions

(W.U. Schröder, J.R. Birkelund, J.R. Huizenga,
K.L. Wolf and V.E. Viola; Phys. Rev. C16 (1977))

Angular-momentum dependent interaction times for damped heavy-ion reactions have been deduced from experimental angular distributions for reactions of 8.5 MeV/nucleon ^{84}Kr and ^{136}Xe ions with ^{165}Ho and ^{209}Bi targets. The data were obtained using semiconductor detector counter telescopes operating in a singles mode. The angular momentum is related to the experimental

cross section by means of a sharp cutoff model of the form

$$\ell_i = \left[(\ell_j + 1)^2 - \frac{\Delta\sigma_{ij}}{\pi\lambda^2} \right]^{1/2} - 1$$

where $\Delta\sigma_{ij} = \sigma_j - \sigma_i$ is the cross section for products measured in the total kinetic energy window between E_i and E_j . It is assumed that the maximum angular momentum, $\ell_{\max}$, is associated with zero kinetic energy loss; i.e. elastic scattering.

From such an analysis, deflection functions can be constructed from experimental data, as shown in Fig. 1 where both the Coulomb deflection function and the experimental deflection function are compared. The most probable angle of emission is assumed to correspond to the maximum cross section ridge for a given kinetic energy loss. The interaction time is then given by

$$t(\ell) = \Delta\theta(\ell) \quad (\ell)/\hbar\ell$$

where $\Delta\theta(\ell)$ is the difference between the Coulomb and experimental deflection functions. From the deduced interaction times it is then possible to derive diffusion coefficient information from a Fokker-Planck equation and experimental widths of the fragment charge distributions. In Table 1 the diffusion coefficients D_z for three systems are tabulated, depending on whether one assumes a sticking model or a non-sticking model for the moment of inertia, I . These values are larger than those reported by Nörenberg¹ but comparable to those of Moretto and Schmitt.²

1) W. Nörenberg, Caen Conference, 1976.

2) Moretto and Schmitt, *ibid.*

Table 1

Reaction	Dz Sticking Model	Dz Non-Sticking Model
$^{209}\text{Bi} + ^{136}\text{Xe}$	0.51	1.1
$^{209}\text{Bi} + ^{84}\text{Kr}$	0.44	0.87
$^{165}\text{Ho} + ^{84}\text{Kr}$	0.40	0.74

Fig. 1: Deflection functions for $^{165}\text{Ho} + ^{84}\text{Kr}$ and $^{136}\text{Xe} + ^{209}\text{Bi}$ reactions. Dashed line is the Coulomb deflection function and the solid line is that extracted from experimental data.

6. Neutron Emission Studies in the Reaction of 500-MeV
 ^{56}Fe Ions with ^{165}Ho (D. Hilscher, K.L. Wolf,
J. Birkelund, A. Mignorey, W. Wilcke, J.R. Huizenga
and V.E. Viola)

The spectrum of neutrons in coincidence with projectile-like fragments has been measured for the reaction of 500-MeV ^{56}Fe ions with a ^{165}Ho self-supporting target. The experimental arrangement consisted of three counter telescopes mounted inside the SuperHILAC 30-inch scattering chamber and two NE213 neutron detectors mounted outside the chamber. The neutron detectors were gated by one of the telescopes and the other two telescopes were used to study fragment charge, energy and angular distributions. The beam optics were controlled with two sets of remote-controlled, 4-jaw collimators placed upstream from the last bending magnet in front of the scattering chamber. A special Faraday cup extension tube placed the beam stop approximately 5 meters downstream from the target and outside the concrete shielding walls of the experimental area (after boring the appropriate hole). Additional neutron shielding was also placed between the beam stop and the neutron detectors. With this arrangement the neutron detector counting rate with the beam on was in general less than 20% of that with the beam off.

Measurements of neutron time-of-flight energy spectra were made as a function of the neutron detector angle with respect to a fixed telescope angle. Telescope angles at the

peak angle for damped collisions were measured, as well as angles outside and the peak. Some out-of-plane spectra were also taken. A sample spectrum is shown in Fig. 1 in which both the telescope and neutron detector angle is 20° with respect to the beam axis. The lower figure represents the gross spectrum of neutrons and gammas, the middle spectrum is for neutrons only and the upper for gamma rays only, as gated by a pulse-shape discriminator. In comparison with non-colinear angles, this spectrum is much harder, as expected from kinematics.

This report represents preliminary data and more detailed analysis awaits future sorting. It is hoped that the data will provide valuable information with respect to the energy dissipation process in damped collisions.

Fig. 1. TAC spectrum from NE213 detector. Lower curve is gross spectrum; middle curve is for neutrons, and upper curve is for gamma rays. The upper two curves were obtained by gating the spectra with a pulse shape discriminator.

7. Experimental Study of the $^{20}\text{Ne} + \text{Cu}$, $^{40}\text{Ar} + \text{Cu}$ and $^{40}\text{Ar} + \text{Ag}$ Reactions at 170-MeV Bombarding Energy

(G. J. Mathews, R. C. Jared[†] and L. G. Moretto[†])

A study of the $^{20}\text{Ne} + \text{Cu}$, $^{40}\text{Ar} + \text{Cu}$ and $^{40}\text{Ar} + \text{Ag}$ reactions at 170-MeV laboratory energy has been performed in order to investigate the effects of the excitation energy above the Coulomb barrier on the fragment charge and angular distributions. The measurements were carried out using a ΔE -E telescope with a gas ionization ΔE detector at the LBL 88-inch cyclotron and SuperHILAC. It was found that the charge distributions of the fragments broaden and the angular distributions become more forward peaked as the energy above the barrier increases. Also, it is observed that for fragment Z values far from the projectile, the angular distributions tend to convert to $1/\sin \theta$. A model which employs classical trajectories and nucleon diffusion during the lifetime of the intermediate complex formed in these collisions is employed to fit the salient features of the data. Fits to the data are shown in Figs. 1(a), (b) and (c). For the $^{40}\text{Ar} + \text{Cu}$ system - the only case where quasi-elastic and strongly damped components can be readily separated - the agreement is good. In the case of $^{20}\text{Ne} + \text{Cu}$, the results indicate an underestimated drift velocity for $^{40}\text{Ar} + \text{Ag}$, the quasielastic contribution is very strong because the energy is very near the barrier; hence the widths are much narrower than calculated.

[†] Nuclear Sciences Division, Lawrence Berkeley Laboratory.

Fig. 1. Comparison of experimental and calculated charge distributions for (a) 170-MeV $^{40}_{18}\text{Ar} + ^{29}_{29}\text{Cu}$, (b) 170-MeV $^{20}_{10}\text{Ne} + ^{29}_{29}\text{Cu}$ and (c) 170-MeV $^{40}_{18}\text{Ar} + ^{47}_{47}\text{Ag}$.

C. Fusion Studies

1. Limits on the Complete Fusion Cross Section for

^{84}Kr and ^{136}Xe -Induced Reactions (K.L. Wolf,

J.P. Unik, V.E. Viola, J.R. Birkelund, J.R.

Huizenga, W.U. Schröder and H. Freiesleben)

Upper limits for complete fusion cross sections have been determined for reactions of ^{84}Kr and ^{136}Xe ions with targets of $^{\text{nat}}\text{Ag}$, ^{165}Ho , ^{197}Au , ^{209}Bi and ^{238}U . Projectile energies ranged from 5.9 to 8.5 MeV/nucleon. The fragment-fragment angular correlation technique was used to obtain the fusion limits under the assumption that all fusion reactions resulted in binary fission. This measurement involved the use of a collimated defining detector (or detector telescope) in coincidence with a 1.5 cm x 5 cm surface barrier position-sensitive detector. From the fragment energies and angles, fragment mass distributions were derived on the basis of kinematics. The data were corrected for pulse-height defect effects and neutron emission from the excited fragment.

In extraction of fusion-fission yields it was assumed that the mass distribution of the fragments was symmetric and that the angular distribution followed $1/\sin\theta$. Yields were determined at angles as far outside the peak of the angular distribution for strongly damped collision events. Nonetheless, it was never possible to eliminate contamination of the spectra with strongly damped events.

This is demonstrated in Fig. 1 where the mass-energy contours for bombardment of ^{165}Ho , ^{197}Au and ^{209}Bi with 7.2

MeV/nucleon ^{84}Kr ions are shown. For the lightest system (Kr + Ho) the strongly damped and fusion-fission events show relatively clear separation, although it is clear that some damped events (masses near the target and projectile) are present in the spectra. For the heavier targets the situation is much more poorly defined due to extensive mass diffusion in the strongly damped collisions. In general it is observed that as the bombarding energy increases and the target-projectile mass increases, it becomes increasingly difficult to separate the two processes. Furthermore, even those events defined as fusion-fission may contain contributions from processes in which a compound nucleus cannot be formed due to the rotational energy of the system.¹

The measurements have demonstrated the essential binary nature of collisions between very heavy nuclei. Calculation of the angular correlation centroids and widths are in good agreement with the observed results and indicate that the probability for ternary (as distinguished from sequential) events is small in these systems. The values for the experimental fusion cross sections are given in Table I where they are also compared with several theoretical predictions.¹⁻⁴ The dependence of the fusion cross section on bombarding energy is small except near the barrier and is seen to decrease as the mass of the target-projectile system increases. In all cases the fission-fusion cross section is but a small fraction of the total reaction cross section. In comparison with theoretical values, one finds that in general, the fusion-fission cross sections

exceed those predicted by the rotating liquid drops limit¹; but are much smaller than those predicted by the fusion models.²⁻⁴ In the former case, it may be that our data include events which have undergone a few rotations, but have been unable to fuse; hence, the data and predictions are not necessarily contradictory. In the latter case the data seem to be in disagreement with theory and hence indicate the need for more realistic models.

- 1) S. Cohen, F. Plasil and W.J. Swiatecki, Ann. Phys. 82, 557 (1974); C.E. Rosenkilde, J. Math. Phys. 8, 98 (1967).
- 2) R. Bass, Nucl. Phys. A231, 386 (1974).
- 3) C. Ngo, B. Tamain, J. Galin, M. Beiner, Nucl. Phys. A240, 353 (1975).
- 4) D.H.E. Gross and H. Kalinowski, Phys. Lett. 48B, 302 (1974); private communication.

TABLE 1: Comparison of experimental and predicted complete fusion cross sections.

Target	Projectile	E_{lab} (MeV)	E_{CR} (MeV)	σ_{CF}^{exp}	(1) σ_{LD}	(2) σ_{CF}	(3) σ_{CF}	(4) σ_{CF}
$^{165}_{Ho}$	$^{84}_{Kr}$	602	399	*320 $\pm$ 50	151	685	1148	504
	$^{64}_{Kr}$	714	473	*440 $\pm$ 50	127	576	1497	671
$^{197}_{Au}$	$^{84}_{Kr}$	530	372	≤ 15	83	502	596	139
	$^{84}_{Kr}$	598	419	*210	73	506	938	326
$^{209}_{Bi}$	$^{84}_{Kr}$	530	378	≤ 15	43	453	501	52
	$^{84}_{Kr}$	598	427	*177 $\pm$ 20	38	454	863	288
	$^{84}_{Kr}$	714	509	*240 $\pm$ 30	32	381	1321	484
$^{238}_{U}$	$^{84}_{Kr}$	530	392	≤ 21	0	411	301	0
	$^{84}_{Kr}$	598	442	≤ 31	0	364	708	152
$^{nat}_{Ag}$	$^{136}_{Xe}$	1124	498	*121 $\pm$ 19	115	497	1508	605
Ho	$^{136}_{Xe}$	1130	619	*110 $\pm$ 20	10	137	1419	440
$^{209}_{Bi}$	$^{136}_{Xe}$	1130	685	<320	0	0	1235	198

a. Rotating liquid drop limit, Ref. 13

b. Bass, Ref. 3

c. Critical radius, Ref. 4

d. Gross, Ref. 5

* May include products from the strongly damped collision process.

Fig. 1. Comparison of mass versus total kinetic energy distributions for events observed in defining detector for 7.2 MeV/nucleon ^{84}Kr ions incident upon ^{165}Ho , ^{197}Au and ^{209}Bi .

2. Complete Fusion Studies of the $^{20}\text{Ne} + ^{235}\text{U}$
System (V.E. Viola, R.G. Clark, W.G. Meyer,
A.M. Zebelman and R.G. Sextro; Nucl. Phys. A261,
174 (1976)).

The probability for complete fusion has been measured for the $^{20}\text{Ne} + ^{235}\text{U}$ system at bombarding energies of 175 and 252 MeV at the LBL 88-inch cyclotron. The fission fragment angular correlation technique was used to obtain both the absolute cross section for complete fusion and relative cross section for the ratio of complete fusion to incomplete fusion processes. Total reaction cross sections were also determined from elastic scattering measurements. Values of $\sigma_R = 1900 \pm 40$ and 2810 ± 140 mb were obtained at 175 and 252 MeV, respectively. These measurements yield $\sigma_{CF}/\sigma_R = 0.74 \pm 0.05$ at 175 MeV and 0.48 ± 0.06 at 252 MeV. These results are summarized in Table I.

These studies of the probability for complete linear momentum transfer in $^{20}\text{Ne} + ^{235}\text{U}$ reactions demonstrate the increasing importance of incomplete momentum transfer reactions as the projectile energy is increased. In particular, at the highest energy studied here, there appears to be a significant probability for processes in which there is high, but not complete, transfer of linear momentum to the fissioning system. This result is similar in nature to the behavior of heavy fissioning systems produced in ^4He ion bombardments at energies above 10 MeV/nucleon¹).

Under the assumption that the high linear momentum transfer component of the angular correlation functions studied here can

be associated with a complete fusion process, critical angular momenta are derived that compare fairly well with the entrance channel limits of ref. ²⁻⁴). These are shown in Fig. 1. Our l_c values do not show as strong an energy dependence as these predictions, but do not agree with the constant value of l_c calculated by Wilczynski. On the other hand, the limiting angular momentum results based on the above assumption disagree strongly with the predictions of Plasil *et al.*⁵ and Rosenkilde⁶ for the angular momentum limits of a rotating liquid drop. However, the calculated and experimental centroids of the most probable peaks in our angular correlation functions do not agree at higher bombarding energies. These discrepancies may be due to the presence of high linear momentum transfer, incomplete fusion reactions and/or light charged particle emission. If so, our experimental values of l_c will be lowered to give better agreement with the rotating liquid drop limit. At the same time a lower value of the saturation value for the critical angular momentum in the entrance channel is implied.

- 1) See following report II.C.3.
- 2) R. Bass, Nucl. Phys. A231 (1974) 45
- 3) D.H.E. Gross and H. Kalinowski, Phys. Lett. 48B (1974) 302; D.H.E. Gross, private communication
- 4) J. Galin, D. Guerreau, M. Lefort and X. Tarrago, Phys. Rev. C9 (1974) 1018
- 5) S. Cohen, F. Plasil and W.J. Swiatecki, Ann. of Phys. 82 (1974) 557; Proc. 3rd Conf. on reactions between complex nuclei (Univ. of California Press, 1963) p. 325
- 6) C.E. Rosenkilde, J. Math. Phys. 8 (1967) 98

Table I

Properties of fission-fragment angular correlation functions $^{24}\text{Ne} + ^{235}\text{U}$ system

	175 MeV	208 MeV ^{a)}	252 MeV
$\psi_{\text{mp}}(\text{exp})$ (deg)	98.0	95.8	93.7
$\psi_{\text{mp}}(\text{calc})$ (deg)	97.4	94.8	91.6
FWHM (CF in-plane) (deg)	7.2	7.9	10.6
FWHM (CF non-planar) (deg)	7.5		9.2
$E_{\text{total}}^{\text{k}}(\text{exp})$ (MeV)	198 $\pm$ 6		201 $\pm$ 8
$E_{\text{total}}^{\text{k}}(\text{calc})$ (MeV)	198	198	198
$(\sigma_{\text{CF}}/\sigma_{\text{R}})^{\text{b)}}$	0.73 $\pm$ 0.05	0.58 $\pm$ 0.08	
$\sigma_{\text{CF}}(\text{mb})$	1430 $\pm$ 90		1360 $\pm$ 100
$\sigma_{\text{R}}(\text{mb})$	1900 $\pm$ 40	2340 $\pm$ 90	2810 $\pm$ 140
$(\sigma_{\text{CF}}/\sigma_{\text{R}})^{\text{c)}}$	0.75 $\pm$ 0.05		0.46 $\pm$ 0.06

Symbols are defined in text.

a) $^{238}\text{U} + ^{20}\text{Ne}$ system; ref.¹²⁾.

b) Relative ratio of CF to ICF events from total correlation function.

c) Ratio of measured σ_{CF} to σ_{R} from elastic scattering.

Fig. 1. Critical angular momentum, l_c , as a function of bombarding energy. Experimental values are represented by points; dashed line is representative calculation for entrance channel limits based on ref.²⁾, and solid line is rotating liquid drop limit. The two saturations limits for l_c from ref.²⁾ are for limits of zero and infinite tangential fraction.

3. Complete Fusion Cross Sections for Reactions of
12-35 MeV/nucleon ${}^4\text{He}$ Ions with Heavy Target
Nuclei (W.G. Meyer, R.G. Clark and V.E. Viola)

Complete fusion cross sections for the ${}^4\text{He} + {}^{233}\text{U}$ system have been measured at bombarding energies between 49 and 140 MeV by means of the fission fragment angular correlation technique at the University of Maryland Cyclotron. Angular correlations for the (α, f) reaction on ${}^{233}\text{U}$ and ${}^{209}\text{Bi}$ are shown in Fig. 1 for each energy. Table 1 summarizes the properties of these angular correlations and Table 2 compares the fusion cross sections for the ${}^{233}\text{U}$ and ${}^{209}\text{Bi}$ systems as a function of excitation energy.

The results show the importance of reaction mechanism studies in the interpretation of intermediate energy fission data. Previous work¹ indicated that greater than 90% of the reaction cross section occurred via a complete fusion interaction mechanism for systems of intermediate energy ($E \gtrsim 40$ MeV) ${}^4\text{He}$ ions and heavy targets. This work shows that the probability of complete fusion decreases from 72% to 54% over an energy range of 49- to 140 MeV. This energy dependence and the increasing contribution of incomplete-momentum transfer events complicates the analysis of intermediate energy fission data, especially as regards the knowledge of the excitation energy and the angular momentum distribution of the fissioning species. This work has not completely answered the questions involving the dependence of the effective moment of inertia, J_{eff} , on excitation energy.¹

However, it has shown the difficulties inherent in such studies and has indicated the factors which must be considered in future attempts to investigate this dependence.

The comparison of the experimental complete fusion cross sections with the theoretical models used to predict heavy-ion complete fusion cross sections in Table II has shown the need for more sophisticated calculations for use in the interpretation of ^4He reactions. It is not sufficient to use semi-classical approximations when considering ^4He ion interactions. For example, more sophisticated forms of the nuclear potential than those described by Wilczynski² and Bass³ seem to be required. The effect of friction, as used by Gross⁴ in ^4He -ion complete fusion reactions, needs to be thoroughly investigated to see what role and form, if any, the concept of friction has in such reactions. Further, the critical radius approach of Galin *et al*⁵ does not seem to describe the data well either. Clearly a dynamical calculation which takes into account the microscopic structure of the alpha particle and the stepwise energy dissipation process seems to be required in order to account for the complete absorption of ^4He ions in these systems.

- 1) S. S. Kapoor, H. Baba and S. G. Thompson, Phys. Rev. 149, 965 (1966).
- 2) J. Wilczyński, Nucl. Phys. A216, 386 (1973).
- 3) R. Bass, Nucl. Phys. A231 (1974) 45
- 4) D.H.E. Gross and H. Kalinowski, Phys. Lett. 48B (1974) 302; D.H.E. Gross, private communication
- 5) J. Galin, D. Guerreau, M. Lefort and X. Tarrago, Phys. Ref. C9 (1974) 1018

Table I. Summary of Fission Fragment
Angular Correlation Parameters

Reaction	E _{lab} (MeV)	ψ_{mp} (deg) Calculated	ψ_{mp} (deg) Experimental	σ_{CF}/σ_f
$^4\text{He} + {}^{233}\text{U}$	140.0 ^a	76.46	76.52	0.539 $\pm$ 0.054
	69.2 ^b	80.77	80.80	0.607 $\pm$ 0.073
	49.0 ^b	82.16	81.67 ^c	0.724 $\pm$ 0.087
$^4\text{He} + {}^{209}\text{Bi}$	140.0 ^a	74.76	74.82	-----
	69.2 ^b	79.54	79.57	-----
	49.0 ^b	81.12	80.64 ^c	-----

^aAngular Error - $\pm 0.23^\circ$

^bAngular Error - $\pm 0.25^\circ$

^cRelative Angles - no absolute angle normalization

Table II Comparison of Experimental Values of σ_{CF} with
Calculated Values for the $^4\text{He} + {}^{233}\text{U}$ System

E _{lab} (MeV)	Experimental		Wilczyński		Bass ^a		Gross ^b		Galin et al. ^c
	ℓ_c	σ_{CF} (mb)	ℓ_c	σ_{CF} (mb)	ℓ_c	σ_{CF} (mb)	ℓ_c	σ_{CF} (mb)	
140.0	32.3	1342	33.7	1459	41	2030	42	2242	1967
69.2	22.7	1376	----	----	29	2030	--	----	1856
49.0	19.6	1468	----	----	23	1780	--	----	1765
30.0	----	----	----	----	14	1273	12	956	----

^aCourtesy of G. Mathews - private communication.

^bCourtesy of D.H.E. Gross - private communication.

^cCourtesy of M. Lefort who supplied the following relationship and constants,

$$\sigma_{CF} = \pi [1.05(A_1^{1/3} + A_2^{1/3})]^2 \cdot [1 - (-14.8 + 0.11961 \cdot z_1 z_2) / E_{c.m.}] - \text{private communication.}$$

Fig. 1 Angular correlation function for $^4\text{He} + ^{233}\text{U}$ at 49.0, 69.2 and 140 MeV.

D. Light-Ion Studies

1. Fragments from Uranium Irradiated by 2.1 GeV/nucleon Deuterons and Alpha Particles (A.M. Zebelman, A.M. Poskanzer, J.D. Bowman, R.G. Sextro and V.E. Viola; Phys. Rev. 11C, 1280 (1975)).

Energy spectra at 90° in the laboratory were obtained for He, Li, Be, and B fragments from a uranium target irradiated with 4.9 GeV protons and 2.1 GeV/nucleon deuterons and α particles from the LBL Bevatron. Data at 25° and 155° were also obtained with the proton and α particle beams. These are shown in Fig. 1. In comparing the incident deuteron data with the incident proton data, it was found that the cross sections were a factor of 1.5 higher but the shapes of the energy spectra were unchanged. However, with incident α particles it was found that the cross sections were a factor of 3 to 4 larger, and the energy spectra were somewhat broadened indicating that the effective Coulomb barriers are 15% lower, and the apparent temperatures 1.5 MeV higher. It is concluded that in the α particle irradiations the deposition energies are larger than with either incident protons or incident deuterons.

Fig. 1. Laboratory energy spectra at 90° for α and proton irradiations. The incident proton data are shown as dashed curves and have been normalized at their peaks to the incident α data.

2. Search for "Shock Wave" Effects in Reactions of 35 -MeV/nucleon ^4He Ions with ^{238}U (W.G. Meyer and V.E. Viola)

According to theoretical estimates, the energetic threshold for nuclear shock waves should occur at a projectile velocity of about 20 MeV/nucleon . At present experimental efforts to demonstrate the existence of such effects with heavy ions have utilized projectile with energies well above this threshold (>200 MeV/nucleon)

and have been inconclusive.^{1,2} Efforts to study threshold effects in the energy region 20-100 MeV/nucleon have been restricted by the fact that no accelerators exist which can produce heavy ions in this energy range. The only complex projectile available in this energy range is ${}^4\text{He}$ and it was the purpose of this research to search for such effects.

The experiments reported here involved studies of the angular and energy distributions of heavy fragments emitted from bombardment of ${}^{233}\text{U}$ with 35 MeV/nucleon ${}^4\text{He}$ ions. The fragments were detected with a $4\mu\text{m}$ ΔE and $30\mu\text{m}$ E detector telescope which was calibrated with ${}^{252}\text{Cf}$ and ${}^{241}\text{Am}$ sources. Measurements extended from 7.5° to 172.5° in the laboratory system. In Fig. 1 is shown a sample spectrum from the ΔE detector which demonstrates the expected fission fragment peak, plus light charged particles. Analysis of the light charged particle angular distributions showed the products to be strongly forward peaked, which can be attributed to carbon and fluorine in the target. Table 1 lists the angle integrated cross sections for light fragments as a function of energy. Evidence for collective effects would consist of energetic light ions of $Z \sim 10-20$ in the range of 50-100 MeV of energy. As is observed, the yield for such products drops off rapidly with energy. Hence, we conclude that no unusual effects are present in this particular system.

- 1) H.G. Baumgardt, J.U. Schott, Y. Sakamoto, E. Schopper, J. Hoffman, W. Schied and W. Greiner, *Z. Phys.* A273, 359 (1975).
- 2) A.M. Poskanzer, R.G. Sextro, A.M. Zebelman, H.H. Gutbrod, A. Sandoval, and R. Stock, *Phys. Rev. Lett.* 35, 1701 (1975).

Table 1

Cross sections for fragments produced in reactions of 35-MeV/nucleon ^4He ions with ^{233}U . Coulomb energies for the fragments are calculated assuming fragment charge center separations typical of fission fragments (Ref. 11).

	$Z = 9-10$	$Z = 9-16$	fission fragments
$\sigma(E_{\text{HI}} = 20 \text{ MeV})$	5 mb	8 mb	-
$\sigma(E_{\text{HI}} = 30 \text{ MeV})$	600 μb	900 μb	-
$\sigma(E_{\text{HI}} = 40 \text{ MeV})$	30 μb	120 μb	2.5 barns

Fig. 1. Energy spectrum in $4\mu\text{m}$ detector at 7° to beam axis for 140 MeV $^4\text{He} + ^{233}\text{U}$.

3. Inclusion of α and d Clusters in Intranuclear Cascade Calculations (R.A. Moyle, G.J. Mathews, B.G. Glagola and V.E. Viola)

The intranuclear cascade calculation of Fraenkel, et al.¹, has been expanded to include cascade interactions with alpha-particle and deuteron clusters in the targets nucleus. Experimental cross sections for d-N, d-d, d- α , α -N and α - α scattering have been added to the N-N cross sections of the original GRACE¹ code. Spectroscopic factors for the clusters are a program option. For heavy target nuclei the EVA¹ evaporation code continues to be used for calculations of the de-excitation of the post-cascade residuals. For lighter nuclei ($A < 20$), the evaporation code has been replaced by a Fermi breakup calculation which allows multiparticle breakup. In this code all bound states of the possible residual nuclei are included in the breakup probability functions. The kinematic behavior of each interaction is catalogued, thus providing angular and energy distributions of the final products.

The primary purpose of these modifications is to provide (1) a more realistic calculation for fitting spallation data from heavy target nuclei at high excitation energies (but below the pion threshold) and (2) a better description for light-ion nuclear reactions in light targets for astrophysical and biomedical purposes - the present calculations being inadequate for such purposes.

1) K. Chen, Z. Fraenkel, et al., Phys. Ref. 166, 949 (1968).

III. Nuclear Astrophysics

A. r-Process Nucleosynthesis of Superheavy Elements and Nuclear Mass Tables (G.J. Mathews and V.E. Viola; Nature 261, 382 (1976)).

The r-process is the sequence of rapid neutron captures and subsequent β decays responsible for the build up of many of the heavier nuclei in nature.¹ In particular, the r-process is probably the only natural mechanism for the formation of nuclei with $Z \geq 83$ and $A \geq 210$. Because of this, there has been considerable speculation concerning the possibility of forming superheavy nuclei ($A \sim 290-300$) in the r-process environment.

Nuclear masses enter into a calculation of the r-process in two important ways. First of all, the neutron binding energies are used in the determination of the r-process path. In a static r-process calculation one assumes an $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium. The high neutron flux responsible for this equilibrium presumably arises from violent stellar processes such as a super-nova. The Saha equation can be applied to describe the statistical equilibrium between neutron emission and capture. Thus, the relative isotopic abundances are given by

$$\frac{\eta_n N(Z, A-1)}{N(Z, A)} = \frac{(2\pi\mu kT)^{3/2}}{h^3} \left[\frac{G_n(Z, A-1)}{G(Z, A)} \right] \exp \left[\frac{-B_n(Z, A)}{kT} \right]$$

where η_n is the neutron number density; $n(Z, A)$ is the relative abundance of isotope A with atomic number Z ; $G(Z, A)$ is the partition function for the nucleus A_Z ; T is the r-process temperature, and $B_n(Z, A)$ is the neutron binding energy for the nucleus A_Z .

A second important influence of nuclear masses on an r -process calculation arises when one attempts to determine the values of Z and A where neutron-induced fission begins to dominate neutron capture. This is the point at which the build up of heavier elements in the r -process ceases.

We have used three different compilations of nuclear masses. Empirical estimates of the binding energies of r -process nuclei have been derived by Viola *et al.*² on the basis of α - and β -decay energy systematics.

The Seeger and Howard mass formula³ involves the usual separation into a smooth macroscopic liquid drop term and microscopic corrections. The expression for the macroscopic energy includes a shape-dependent Coulomb term corrected for a diffuse nuclear surface. The microscopic corrections employ the Strutinsky renormalisation procedure and BCS pairing theory. The parameters of the formula are adjusted to give, simultaneously, self-consistent nuclear masses and fission barriers. The fission barriers are calculated assuming the idealised liquid drop saddle point shapes of Cohen and Swiatecki.⁴

The third formulation of nuclear masses is the droplet model formula of Myers and Swiatecki⁵. In addition to containing many of the features of the liquid drop approach, the droplet model allows the neutron and proton densities to vary independently, and includes higher order terms in $(N-Z)$ which are important for the neutron-excess r -process nuclei. The new droplet model parameters are determined from a fit to experimental masses and fission barriers.

In general the masses derived from empirical systematics predict increased stability for neutron-deficient isotopes and decreased stability for neutron-excess isotopes compared with the predictions of the mass formulae.

To compare the different sets of nuclear masses we have performed a static r-process calculation, for each mass table separately. The r-process temperature and density (or equivalently the r-process cycle time) were then adjusted to reproduce the centroid of the experimentally observed $A=195$ abundance peak. β -decay rates were estimated using the formulation of Senbetu⁶ for calculation of f and assuming an average $\log ft$ value of 6.5

The abundances before decay-back of the r-process paths which best fit the $A=195$ peak for each mass table are shown in Fig. 1. Also shown for comparison are the abundances calculated with the Myers and Swiatecki liquid-drop formula⁷. 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 difficulty in reaching the super-heavy nuclei in our calculation is the increased magnitude of the surface asymmetry term in the newer mass formulae. This increase in the magnitude of the surface asymmetry term results in lower fission barriers along the r-process path and, hence, neutron-induced fission becomes important at lower values of Z and A . A secondary reason for the decrease in the maximum

mass number achievable is that the newer 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 the predictions based on the energy-density mass formula of Brueckner *et al.*⁹. 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 formulae, one would still encounter difficulty in obtaining mass numbers of $A > 290$ needed to form the superheavy nuclei.

Hence, it seems that the most recent nuclear mass compilations make the possibility of the formation of superheavy nuclei during most of the r-process quite difficult. Although in a dynamic calculation one might expect to form a small amount of superheavy nuclei during 'freeze out', the bulk of the r-process period (responsible for the $A=195$ abundance peak) seems not to produce superheavy nuclei, according to the most recent predictions of nuclear stability.

- 1) Burbidge, E.M., Burbidge, G.R., Fowler, W.A., and Hoyle, F., *Rev. Mod. Phys.*, 29, 547 (1957).
- 2) Viola, V.E., Swant, J.A., and Graber, J., *At. Data Nucl. Data Tables*, 13, 35 (1974).
- 3) Seeger, P.A., and Howard, W.M., *Nucl. Phys.* A238, 491 (1975).
- 4) Cohen, S., and Swiatecki, W.J., *Ann. Phys.* 19, 67 (1962).
- 5) W.D. Myers, *Atomic and Nuclear Data Table* (1976).
- 6) Senbetu, L., *Phys. Rev. C*, 7, 1254 (1973).
- 7) Myers, W.D. and Swiatecki, W.J., *Ann. Phys.*, 55, 395 (1969); 84, 786 (1974).

Fig. 6. r-Process abundances before decay-back predicted for the best fit to the $A=195$ abundance peak for each mass formula....., r-Process abundances; _____, Myers⁷; ————ref.³; ————, ref.²; ————, ref.⁵.

- B. The $\alpha+\alpha$ Reaction and the Origin of ${}^7\text{Li}$ (C.H. King, H.H. Rossner, S.M. Austin, W.S. Chien, G.J. Mathews, V.E. Viola and R.G. Clark; Phys. Rev. Lett. 35, 988 (1975)).

The problem of the origin of ${}^7\text{Li}$ may prove to have significant implications for models of cosmic evolution. Traditional stellar nucleosynthesis seems to be inadequate to account for ${}^7\text{Li}$. Detailed calculations have indicated that this nuclide is under-produced in cosmic-ray spallation processes, and, in particular, have predicted a ${}^7\text{Li}/{}^6\text{Li}$ abundance ratio which is smaller than the observed ratio by nearly an order of magnitude. This result would seem to imply that an additional production mechanism is required for ${}^7\text{Li}$.

However, the spallation calculations depend on accurate measurements of the cross sections for the nuclear reactions involved. For ${}^7\text{Li}$, a principal spallation source is the $\alpha+\alpha$ reaction, and prior to this work a direct measurement of the cross section for ${}^7\text{Li}$ production in this reaction had been made at only two energies (38.5 and 42 MeV). Since ${}^7\text{Be}$ decays to ${}^7\text{Li}$ by electron capture, the cross sections for ${}^7\text{Be}$ formation must also be known, and no successful measurement of this cross section had been made. In an attempt to improve this situation, we performed a direct measurement of the cross sections for both ${}^7\text{Li}$ formation and ${}^7\text{Be}$ formation in the $\alpha+\alpha$ reaction.

We determined the cross sections for $\alpha+\alpha \rightarrow {}^7\text{Li} + p$ by measuring the angular distributions of the protons in the center-of-mass forward quadrant. The differential cross sections were

then integrated to obtain the total cross sections, using the fact that the angular distributions are symmetric about 90° in the center-of-mass system. These measurements were made at eleven energies between the reaction threshold (34.7 MeV for $\alpha + \alpha \rightarrow {}^7\text{Li} + p$ and 38.0 MeV for $\alpha + \alpha \rightarrow {}^7\text{Be} + n$) and 50 MeV using α particles from the Michigan State University sector-focused cyclotron. The ${}^7\text{Li}$ -production cross sections were also measured at 60.2, 92.4, and 140.0 MeV using α particles from the University of Maryland cyclotron. In these latter runs, the proton angular distributions were measured with a Si-NaI ΔE - E counter telescope. The summed cross sections are shown in Fig. 1 for the higher energies.

The ${}^7\text{Be}$ -formation cross sections were obtained by directly collecting the ${}^7\text{Be}$ recoils. Since these particles are confined to a narrow forward-angle cone (ranging from 3° maximum laboratory angle at 39 MeV to 18° at 140 MeV), they can all be collected in aluminum absorbers placed downstream from the target. We determined the number of ${}^7\text{Be}$ nuclei captured in the foils by measuring the 478-keV γ rays resulting from the 10.3% branch of the decay to the first excited state of ${}^7\text{Li}$, using a Ge(Li) detector whose absolute efficiency had been calibrated.

Comparisons between our measurements and the cross sections assumed by Mitler¹ in his calculations of ${}^7\text{Li}$ production in $\alpha + \alpha$ spallation are also indicated in Figure 1. Calculations of Meneguzzi, Audouze, and Reeves² utilized a similar excitation function. In general the ${}^7\text{Li}$ production cross sections have been overestimated at the low energies, and have been

overestimated for the most part at the higher energies as well. On the other hand, our measurements indicate that the ${}^7\text{Be}$ cross sections are essentially equal to those for ${}^7\text{Li}$, the only marked difference occurring at the lowest energies where threshold effects reduce the ${}^7\text{Be}$ cross section.

In view of these uncertainties, an appealingly simple alternative for the explanation of ${}^7\text{Li}$ abundance is that the majority of the present ${}^7\text{Li}$ was created during the big bang, and it is suggestive that standard models of this event yield substantial ${}^7\text{Li}$ production. Moreover, the mean baryon density required to generate the observed ${}^7\text{Li}$ abundance during the big bang³ is reasonably close to that required to generate deuterium, and both of these production processes are quite sensitive to variations in the baryon density. Thus, the universal abundance of ${}^7\text{Li}$ may become, as in the case of deuterium, a means of inferring the nature of the primordial universe.

- 1) H.E. Mitler, *Astrophys. Space Sci.* 17, 186 (1972).
- 2) M. Meneguzzi, J. Audouze and H. Reeves, *Astron. Astrophys.* 15, 337 (1971).
- 3) R.V. Wagoner, W.A. Fowler, and F. Hoyle, *Astrophys. J.* 148, 3 (1967); R.V. Wagoner, *Astrophys. J.* 179, 343 (1973); J.R. Gott, J.E. Gunn, D.N. Schramm, and B.M. Tinsley, *Astrophys. J.* 194, 543 (1974).

Fig. 1.a. Cross sections (sum of ground-state and first-excited-state transitions) for the formation of ${}^7\text{Li}$ and ${}^7\text{Be}$ in the $\alpha + \alpha$ reaction above 50 MeV. The dashed curve represents the cross sections (assumed equal for the two reactions) used by Mittler in his spallation calculations. The solid line is to guide the eye.

C. Li, Be and B Nucleosynthesis: Cross Sections for the
 $p + {}^{16}\text{O}$ Reaction from 50-90 MeV (B.G. Glagola, R.A. Moyle,
G.J. Mathews and V.E. Viola).

The excitation functions for the production of mass 6-11 isobars have been measured at incident proton energies of 50, 55, 65, 75, and 90 MeV on an oxygen gas target and 75 and 90 MeV on a nitrogen gas target. For the oxygen target the mass 6-11 excitation functions reach their maxima in this energy range, whereas for the nitrogen target the points measured are after the maxima where the cross section is flattening out. At all energies time-of-flight and reaction product kinetic energies were measured. The kinetic energy of the products was measured with a 75 μm silicon detector at all energies except 90 MeV. At 90 MeV a ΔE - E telescope was used with 15 μm and 700 μm silicon detectors, which also enabled the collection of particle identification data.

The reaction product TOF was measured using a thin foil, microchannel plate fast timing device, CPFTD, and a 75 μm silicon detector. This system achieves an experimental time resolution typically in the range of 250-300 ps. For the 90 MeV data, the particle TOF was measured relative to the cyclotron radio frequency oscillator, which gives a ΔT of ~ 1 ns. The use of a CPFTD has given approximately a factor of four increase in time resolution. This has allowed the use of a much shorter flight path and hence a greater solid angle. The average flight path used was 21 cm. From the time and energy obtained,

the mass (which is proportional to ET^2) was computed for each reaction product. A typical mass vs. energy spectrum displaying well separated mass lines is shown in fig. 1. Differential cross-sections were determined for lab angles in the range $15-140^\circ$. The excitation functions for mass 6-11 are shown in fig. 2.

A gas cell designed by Laumer¹ was used to contain the oxygen and nitrogen targets. The cell is specially designed to minimize flight path errors by looking at a point source rather than a line source and also to minimize energy loss by reaction products in moving through the target. This cell, along with using a thin carbon foil ($30\mu\text{g}/\text{cm}^2$) on the CPFTD, gives a measured low energy cutoff of $\sim 0.75-1.0$ MeV. Reaction yields were extrapolated from the low energy cutoff to zero particle energy. In the worst cases this adds $\sim 30\%$ error to the experiment. Typically the energy extrapolation contributes 10-15% error to the measurements.

Table 1 lists the cross sections measured. The 90 MeV O_2 and N_2 data are still to be analyzed.

All models for light-element nucleosynthesis begin with the rate equation,

$$N_L = \sum_{i,j} N_i \int_{E_{\text{threshold}}}^{\infty} \sigma_{ijL}(E) \phi_j(E) dE, \quad (1)$$

which is the sum of the rate of light-element production from all possible combinations of targets, i , and projectiles, j , with incident fluxes, ϕ_j . σ_{ijL} is the cross section for

the production of light element, L, from projectile j incident on target i. If one inserts the observed target cross sections and particle fluxes into this equation, one then generates the present production rate for the given element.

For reactions on stellar surfaces (i.e. induced by flare activity) one generally assumes a power law in kinetic energy per nucleon,

$$\phi(E) \propto E^{-\gamma}$$

where $\gamma \cong 1.5-5$. Numerous analytical and numerical spectral shapes have been suggested for the interstellar galactic cosmic ray flux. The various functional forms include a power law in total energy,

$$\phi(E) = kW^{-2.6} ,$$

where W is the sum of the particle rest energy and kinetic energy,

$$W = m_0 c^2 + E ,$$

(A value of $k = 12.5$ fits the observed high-energy cosmic-ray proton flux), and a power law in magnetic rigidity,

$$\phi(E) = kR^{-M(R)} ,$$

where R is the magnetic rigidity defined,

$$R = \frac{pc}{Ze} ,$$

p = particle momentum and Z = atomic number and the exponent, M(R), varies so that the spectrum flattens at lower energies.

When all available cross section data, including those contained in this report, are used in Eq. (1) for various assumed particle fluxes, the abundance ratios shown in Table II

are obtained. It is observed that in general the calculated ratios for the cosmic ray flux and for $\gamma < 3$ are in reasonable agreement with experiment. However, the ${}^7\text{Li}/{}^6\text{Li}$ ratio is anomalous, giving support to the need for a low energy mechanism, such as the big bang, for producing additional ${}^7\text{Li}$.

- 1) H.W. Laumer, Michigan State University Ph.D. Thesis (1971).

TABLE 1 $p + {}^{16}\text{O}$ Cross Sections (mb).

Ep(MeV)				
Mass	50	55	65	75
6	17.59	22.98	28.53	9.39
7	26.88	42.73	54.75	30.10
9	3.61	7.92	10.04	6.39
10	19.65	33.76	34.28	27.32
11	73.40	86.92	71.95	51.93

Table II. Calculated and Experimental Abundance Ratios.

	${}^7\text{Li}/{}^6\text{Li}$	${}^{11}\text{B}/{}^{10}\text{B}$	${}^6\text{Li}/\text{Be}$	$\text{B}/{}^6\text{Li}$
Exp	12.5	4.1	4.5	2.7-95.
$W^{-2.6}$	1.6	2.0	4.4	3.1
$R^{-M(R)}$	1.8	2.2	4.8	3.0
$E^{-1.5}$	2.8	2.9	5.9	3.1
$E^{-2.6}$	4.6	5.1	9.8	3.4
$E^{-4.5}$	6.1	9.4	14.6	7.9

Fig. 1. Typical Mass versus energy spectrum for products from $P + {}^{16}\text{O}$ reaction with CPFTD time-of-flight.

Fig. 2. Excitation functions for $A=6, 7, 9, 10$ and 11 isobars from $P + {}^{16}\text{O}$ reaction.

- D. Li, Be and B Production in Reactions of 45-100 MeV Protons with ^{12}C : Astrophysical Implications (C.T. Roche, R.G. Clark, G.J. Mathews and V.E. Viola; Phys. Rev. 14C, 410 (1976)).

Cross sections for the production of mass 6 to 11 isobars from proton spallation of carbon targets have been measured at six bombarding energies from 45-100 MeV at the Maryland Cyclotron. Time-of-flight mass measurements using rf timing were employed in these measurements. Isotopic cross sections for Li and Be have also been measured at 100 MeV. The cross sections for these reactions are tabulated in Table I and the excitation functions, including lower energy data taken at Michigan State University are shown in Fig. 1. The excitation functions for these reactions have been used to test theories of Li, Be and B nucleosynthesis, and have been described in more detail in the previous report (III. C.)

The measured abundance ratios for $^{11}\text{B}/^{10}\text{B}$ and B/Be can be reproduced using the experimental cross sections and astrophysical models which propose LiBeB synthesis in nuclear reactions well above the threshold energy. In order to obtain the natural $^7\text{Li}/^6\text{Li}$, Li/Be, and Li/B abundance ratios, however, it is concluded that a substantial amount of ^7Li must be synthesized via some lower energy mechanism.

TABLE I Total production cross sections in mb for $^{12}\text{C}(p, \text{HI})$ reaction.

(MeV) Energy	HI (Mass number)				
	A=6	A=7	A=9	A=10	A=11
45.0	13.3±2.7	39.9±7.4	...	28.6±6.6	104.6± 2.4
55.0	13.4±2.5	35.6±6.4	2.3±0.6	23.8±5.7	81.5±20.9
60.0	14.9±2.8	34.1±6.5	...	34.5±8.0	75.9±22.1
65.0	17.6±3.5	36.2±7.1	...	36.3±8.1	80.0±18.9
75.0	13.6±2.5	29.4±5.6	2.6±0.6	27.8±5.4	76.7±14.3
100.0	10.9±1.1	21.1±2.1	2.8±0.4	22.0±2.8	67.5± 7.9
		11.5±2.6(^7Be)		0.5±0.4(^{10}Be)	
		9.6±2.4(^7Li)

Excitation functions for $E_p \leq 100$ MeV for production of $A=6, 7, 9, 10$, and 11 isobars in reactions between protons and carbon. Open points are this work and solid points are data from MSU.

Excitation functions for $E_p \geq 100$ MeV for production of $A=6, 7, 9, 10$, and 11 isobars in reactions between protons and carbon. Data at 100 MeV are from this work, and higher energy data from Raisbeck and Yiou.

IV. Nuclear Structure

A. A Unifying Theory for Odd-A Nuclei

(G. J. Mathews and J. D. Immelet†)

The equations-of-motion method is applied to solve the pairing problem for an odd-A nucleus which is undergoing arbitrary static or dynamic deformation. This theory introduces an important new step in that it completes the generalization of the particle-core coupling picture necessary to describe transitional nuclei. In Fig. 1 the results for solution of the equations of motion for an $h_{11/2}$ quasi-particle coupled to an asymmetric ($\gamma = 30^\circ$) rotating core are plotted as a function of the Fermi energy λ . The parameterization is based on the work of Meyer-ter-Vehn¹ and only the lowest state for spins $3/2 - 11/2$ are shown. These results are identical to those obtained from a complete triaxial-rotor-plus-particle calculation; which demonstrates the generality of the method.

†Lawrence Livermore Laboratory

1. J. Meyer-ter-Vehn, Nucl. Phys. A249, 111 (1973).

Fig. 1. Solutions to the equations of motion for an $h_{11/12}$ quasi-particle coupled to an asymmetric ($\gamma=30^\circ$) rotating core as a function of the Fermi energy, λ .

- B. Gamma-Gamma Angular Correlations in ^{105}Rh Following the Decay of 4.4-h ^{105}Ru (E. W. Schneider, G. J. Mathews, S. V. Jackson, P. W. Gallagher and W. B. Walters; Phys. Rev. C13, 1624 (1976)).

Gamma-gamma angular correlations have been measured for 349-149, 575-149, 393-262, 414-262, 350-326 and 316-469 keV cascades in ^{105}Rh following the decay of 4.4-h ^{105}Ru . Samples were prepared by thermal neutron irradiation of ^{104}Rh at the National Bureau of Standards reactor and the University of Maryland reactor. Samples were counted with two coaxial Ge(Li) detectors with active volumes $>55 \text{ cm}^3$ and coincidence data were recorded with a buffer-tape system. A $3/2^+$ spin and parity assignment is established for the 806-keV level and $1/2^+$ or $5/2^-$ values are found consistent for the 786-keV level, with $1/2^+$ favored. For the 149-keV transition a δ value of 0.4 ± 0.1 is deduced.

V. Equipment Development

A. Channel-Plate Fast Timing Device (B.G. Glagola, and R.A. Moyle)

In order to perform fragment mass identification for reaction products produced at the LBL SuperHILAC and low energy Li, Be, and B ions from the Maryland Cyclotron, a channel-plate fast timing device has been developed.

A schematic diagram of the CPFTD is shown in Figure.1. The particles to be detected are incident on a thin carbon foil, which is placed 30° to the detector axis. The carbon foil is kept thin ($30 \mu\text{g}/\text{cm}^2$) to minimize the velocity degradation of the detected particles. On passing through the carbon, the particle knocks a packet of secondary electrons from the foil which are detected by the CPFTD. The CPFTD generates a fast timing signal which can be used as a start or stop signal for a TAC. The other signal for the TAC is generated by a silicon detector or a second CPFTD.

The secondary electrons are emitted from the carbon foil with a large angular spread and energies of only a few electron volts. The angular spread is minimized by accelerating the electrons to $\sim 1.5 \text{ keV}$. The grid used for acceleration is a 97% transmission electroformed copper mesh. The accelerated electrons travel through a field-free region to a pair of cascaded microchannel plates. Each channel plate gives an electron multiplication of approximately 1000 per incident electron. The electrons from the second microchannel plate are collected by an anode cone which delivers a very fast rise-time ($\sim 300\text{ps}$) negative signal to the electronics shown in

Fig. 2.

Detection efficiency of the CPFTD varies with the charge of the detected particle. This is due to the number of secondary electrons emitted from the carbon foil. On the average ~3.5 secondary electrons are emitted per alpha particle, whereas heavy ions give ~3000 secondary electrons per particle. For heavy ions ($Z > 3$) 100% detection efficiency is achieved. The detection efficiency for low energy alpha-particles (primarily from a ^{228}Th source) is shown in Figure 3.

The improved time resolution with the use of a CPFTD has allowed the use of much shorter flight paths. Figure 4 shows a timing spectrum obtained for alpha-particles from an ^{241}Am source and a thick ^{148}Gd source. This spectrum shows a FWHM of 172 ps for the ^{241}Am alpha-particles. The ^{148}Gd alpha-particle peak is broadened due to the thickness of the source which smears out the alpha-particle velocity. In experimental measurements of the $p + ^{16}\text{O}$ reaction a time resolution of 275-300 ps has been achieved. All measurements were made using commercially available electronics which normally accept 1 ns rise time pulses. Electronics especially matched to the CPFTD fast rise time signals improve the time resolution¹. A mass spectrum from the $p + ^{16}\text{O}$ system using a 21 cm flight path is shown in Sec.III. C. Well-separated peaks for mass 6-11 are shown, with even the higher masses ($A=12-16$) clearly visible.

One of the biggest problems with the CPFTD has been the breakage rate of the microchannel plates due to mechanical strain

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and vacuum failures. A new mounting system for the channel plates is under design to relieve mechanical strain and prevent breakage of the micro-channel plates.

- 1) G. Gabor, W. Schimmerling, D. Greiner, F. Bieser and P. Lindstrom, LBL-Report - 3833 (1975).

CHANNELPLATE FAST TIMING DEVICE SCHEMATIC DIAGRAM

FIG 1

ELECTRONICS BLOCK DIAGRAM

FIG 2

Fig. 3. CPFTD efficiency as a function of energy for alpha particles.

Fig. 4. Time spectrum for 3.18 MeV ^{148}Gd and 5.49 MeV ^{241}Am alpha particles.

VI. Personnel

Faculty

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

Research Associates

R. A. Moyle*

W. G. Meyer**

G. J. Mathews

Graduate Students

W. G. Myer, Ph.D., 1975

P. A. Schuster

E. W. Frick, M.S., 1975

G. J. Mathews, Ph.D., 1977

B. G. Glagola

Undergraduate Students

S. Eagleson

J. Pierce

*Present address: BDM Corporation, Reston, Virginia

**Present address: Nuclear Sciences Division, Lawrence Berkeley
Laboratory, Berkeley, California

VIII. Theses and Publications

A. Theses

1. E.W. Frick, "Total Kinetic Energy and Mass Distributions from 140-MeV ^4He -Ion-Induced Fission of ^{238}U , ^{209}Bi and ^{197}Au ." M.S., 1974
2. W.G. Meyer, "Reaction Mechanism Studies with ^4He Ions and Heavy Target Nuclei" Ph.D., 1975
3. G.J. Mathews,* "Reflections and Research on:
 - I) Nucleosynthesis of Light and Heavy Nuclei;
 - II) A Unifying Theory of Odd-A Nuclei, and
 - III) Three Heavy-Ion Systems

* Research Excellence Award, Sigma Xi, 1976 AWU Fellowship, 1976.

B. Publications

- 1) A. M. Zebelman, A. M. Poskanzer, J. D. Bowman, R. G. Sextro and V. E. Viola, Jr., "Fragments from Uranium Irradiated by 2.1 GeV/Nucleon Deuterons and Alpha Particles", Phys. Rev., C11, 1280-1286 (1975).
- 2) R. G. Clark, C. T. Roche, G. J. Mathews and V. E. Viola, Jr., "Li, Be and B Production in Proton-Induced Reactions: Implications for Astrophysics and Space Radiation Effects", to be published in Proc. Conf. on Nuclear Cross Sections and Technology (American Physical Society, 1975).
- 3) R. G. Clark, W. G. Meyer, M. M. Minor, C. T. Roche and V. E. Viola, Jr., "Fragment Angular Distributions from Fission of ^{238}U , ^{209}Bi and ^{197}Au by 140-MeV ^4He Ions", Zeit. Phys., A274, 131 (1975).
- 4) V. E. Viola, Jr., K. L. Wolf, J. P. Unik, J. R. Huizenga, J. Birkelund and H. Freiesleben, "Strongly Damped Collisions in the $^{84}\text{Kr} + ^{209}\text{Bi}$ Reaction", Proc. Second Int. Conf. on Clustering Phenomena in Nuclei, (IUPAP, 1975) in press.

- 5) C. H. King, H. H. Rossner, S. M. Austin, W. S. Chien, G. J. Mathews, V. E. Viola, Jr. and R. G. Clark, "The $\alpha + \alpha$ Reaction and the Origin of ${}^7\text{Li}$ ", Phys. Rev. Letters 35, 988 (1975).
- 6) J. Birkelund, J. Huizenga, K. L. Wolf, J. P. Unik, V. E. Viola, Jr. and H. Freiesleben, "Elastic Scattering of ${}^{40}\text{Ar}$ and ${}^{84}\text{Kr}$ Ions from ${}^{209}\text{Bi}$ and ${}^{238}\text{U}$ ", Physical Review C13, 133 (1976).
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