21
- 11-76
25 up to NTLS

UCID- 17201

Lawrence Livermore Laboratory

ON THE INTERACTION OF INTENSE HEAVY
ION BEAMS WITH VARIOUS TARGETS

Carol Alonso

July 22, 1976

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Recently it has been proposed that heavy ion beams could be accelerated with sufficient power and focus to generate shock heating and create hot plasmas in targets of various materials.^{1,2} This preliminary study addresses two aspects of this process: first, the energy deposition by the primary beam, and second, the problem of energy deposition by secondary nuclear reaction particles. For the purpose of discussion we will assume here that beams of 600 MeV/amu uranium (143 GeV total) are focussed on various targets of thickness 1-10 mm. We wish to explore energy deposition within such targets by the primary and secondary particles.

1. Energy Deposition by the Primary Beam

The range-energy characteristics of 600 MeV/amu heavy ion beams as heavy as Ar have been measured in targets at room temperature at the Bevalac at LBL. A typical Bragg curve (stopping power dE/dx versus penetration depth x) from the biomedical group at the Bevalac is shown in Figure 1.³ These data do not include energy deposited by secondary neutrons in the target material. The energy deposited up to and slightly beyond the Bragg peak could be considered as useful energy to be deposited into a high-Z absorbing material whose thickness is of the order of the range of the primary beam. The long tail extending far beyond the Bragg peak is a potential contributor of energy to materials lying behind the absorber,

since many of the particles which generate this tail could penetrate several mm of almost any material.

Turning our attention in this section to the primary energy deposition, we note that at room temperature the heavy ion, upon penetrating the target, undergoes many small-angle Coulomb collisions with the bound electrons of the target atoms. The stopping power at room temperature is described by the Bethe-Bloch equation⁴

$$-\frac{dE}{dx} = \frac{4 Z}{m_e v^2} n_t Z_t \left[\ln \left(2 \frac{m_e v^2}{I} \right) - \ln (1-\beta^2) - \beta^2 - \frac{C_k}{Z} \right]$$

where Z is the effective charge of the heavy ion, m_e is the electron mass, v is the heavy ion velocity, Z_t is the target atomic charge, n_t is the number of target atoms per unit volume, $\beta = v/c$, and I is the mean ionization potential of the bound electron. It is a good approximation to use

$$I \approx 11.5 Z \text{ eV}$$

The last term, $-C_k/Z$, in the Bethe-Bloch stopping power is a correction for non-participation of bound K electrons in the slowing-down process.

As the heavy ion slows down in a target at room temperature, it begins to pick up or lose electrons and thus change

its effective charge Z . The heavy ion is usually fully stripped upon entering the target. In the vicinity of the Bragg peak it slows down to a velocity at which it begins to pick up electrons. As the heavy ion slows down its energy deposition rate is increased in a manner that is strongly dependent on its changing effective charge. These charge exchange processes, as well as nuclear scattering at low velocities, affect the Bragg peak at the end of the range. The Bragg peak provides a means of depositing a great deal of energy into a highly localized region. For a beam of 500 MeV/amu Ar in water the width of the Bragg peak is about 3 mm.

At present there is no available uranium beam in the energy range of 600 MeV/amu. (The GSI accelerator at Darmstadt succeeded a few weeks ago in producing the first uranium beam of any kind at approximately 6.5 MeV/amu.)⁵ The only accelerator that can produce relativistic heavy ions even as heavy as Ar is the Bevalac at Berkeley. Therefore we are forced to use extrapolation and scaling as well as the Bethe-Bloch equation to predict the room temperature range-energy relation for 600 MeV U in a heavy material such as Au. We have constructed such a prediction in Figure 2.

The curve in Figure 2 was constructed in the following manner. An extrapolation of the theoretical stopping power

(dE/dx) curves of Northcliffe and Schilling⁶ for high energy U beams in Au is shown in Figure 3. The range of a particle of energy E_0 is defined by

$$R \equiv \int_0^{E_0} \left(\frac{dE}{dx} \right)^{-1} dE .$$

This integration has been performed graphically to create the dE/dx vs. range graph in Figure 4. Note that after about 100 MeV/amu the rate of energy deposition is not as efficient per mass of target as it is at the lower energies. The range of 600 MeV/amu is predicted to be about 4 gm/cm² in Au.

Several empirical computer programs exist which calculate the range of heavy ions in various materials, among them the popular Northcliffe code⁶ as well as the Steward code⁷ in use by the Heckman group at LBL. Predictions for low energy ions (below 10 MeV/amu) have been verified many times by the experimental data, which have in fact been fed back into the Northcliffe tables. But stopping power predictions for most of the high energy heavy ions of mass past Ar have not been checked experimentally and we do not know how well the known data extrapolate to uranium beams.

The stopping power curves predicted by all the existent codes have sharp Bragg peaks rather than the sloped peak with a high-energy tail that is observed in the experimental data as typified by Figure 1. This high energy tail is produced by secondary reaction products which consist of many species

of light ions. We have attempted a calculation of this tail for U in Au and the results are shown in Figure 2. Details of this calculation are given in the next section on secondary energy deposition. The primary beam undergoes nuclear reactions with the target nuclei with an essentially geometric cross section; this has been verified many times over in Bevalac experiments. For 600 MeV/amu U in Au we therefore estimate that 8% of the primary beam undergoes nuclear reactions during the primary range. The mean free path for such reactions is 2.6 cm of Au (50 gm/cm²). Therefore a substantial portion of the primary beam is converted to longer-range secondary particles in the absorbing target material. The angular distribution of these secondary particles will be discussed in the next section.

So far the discussion has been limited to range-energy relations in room-temperature targets. Since a target would be raised to very high temperatures during most of the duration of the proposed nanosecond beam pulse, we must inquire how much the room-temperature range-energy relations can be expected to change at elevated temperatures of the order of a kilovolt. The target at these temperatures is a fully ionized plasma. Therefore the incoming beam will scatter off Maxwellian distributions of unshielded ions and electrons instead of scattering off bound electrons.

During most of its range the relativistic heavy ion beam has much greater velocities (600 MeV/amu U has $\beta = .8$) than the non-relativistic electrons or ions of the plasma. (For Au at a temperature of 1 keV, $\beta_e = .06$.) Therefore one expects that the stopping power of the beam is probably relatively insensitive to the temperature of the target material until the first term of the Bethe-Bloch equation becomes relatively important. This view is reinforced by the observed geometric cross section for nuclear reactions; the relativistic beam plows through the electron clouds of room-temperature ions with barely a change in trajectory. If the projectile hits any part of the ion nucleus both the nucleus and the projectile explode in a rather violent manner. The beam cannot distinguish a bound electron from an unbound electron until it slows down to a velocity comparable to the electron velocity.

When the heavy ion projectile has slowed down to relative velocities of the order of the Coulomb barrier (about 5 MeV/amu for U in Au), Coulomb scattering off the unshielded target ions should replace the nuclear reactions. This type of scattering does not exist in comparable amounts in targets at room temperature because the nuclei at room temperature are shielded by electron clouds. It is not clear at this point what total effect this additional ion scattering has on the shape of the Bragg curve, but we would probably expect

it to smear out the Bragg peak. Since the energy loss to ions goes inversely as the square of the ion mass the contribution may not be too significant.

When the heavy ion beam slows down to velocities comparable to the plasma electron velocities there should be a significant change in the range-energy curve. For U in Au at a temperature of 1 keV this occurs when the U ion has slowed down to 11 MeV total kinetic energy. This occurs at the very end of the range. Therefore for essentially the entire range of the heavy ion beam the range-energy relations at elevated temperatures can be expected to be fairly similar to the room temperature relations, taking into account the appropriate changes of density of the target material with temperature.

At the very end of the range at high temperatures the theory of Sigmar and Joyce applies for projectile velocities intermediate between the plasma electron and ion velocities. The Sigmar-Joyce⁸ energy deposition rate is given by

$$\frac{1}{Z^2} \frac{dE}{dt} = aE + \frac{b}{\sqrt{E}}$$

where the first term represents scattering against plasma electrons and the second term represents scattering against plasma ions. At projectile velocities comparable to the plasma electron velocity the scattering against ions predominates; at lower projectile velocities the scattering against electrons is more important. The temperature dependence of the stopping power becomes

$$\frac{dE}{dx} = \alpha \frac{\sqrt{E}}{\theta^{3/2}} + \beta \frac{1}{E}$$

where α and β are functions of temperature T and $\theta = kT$. Figure 5 shows a calculation we have made of the stopping power of 3.5 MeV alpha particles in compressed Au ($\rho / \rho_0 = 10^4$) compared to the Northcliffe stopping power at room temperature in uncompressed Au. These numbers were scaled up from the dE/dt values calculated by Sigmar and Joyce for 3.5 MeV alphas in a tenuous plasma.

We conclude from these range estimates that the effects of temperature on energy deposition of the primary beam during

most of its range will probably not be severe because of the high velocity of the heavy ion relative to the plasma velocities. However the shape of the Bragg peak can be expected to change because of the great difference in charge exchange and scattering in the plasma at high densities and temperatures at the end of the range when the ion has slowed down.

II. Energy deposition from Secondary Reaction Products

We turn now to estimates of energy deposition from the various nuclear reaction products created during the energy deposition of the primary beam. Since these particles are usually lighter than the primary beam their range is often much greater than the range of the primary beam, a fact which can generate undesired heating of materials in the vicinity of the absorbing target.

First let us estimate the extent of the secondary energy deposition problem for 600 MeV/amu U beams bombarding a slab of Au in front of H gas. The various types of reaction products that we expect to observe from this reaction are shown in Figure 7 as a function of product mass.⁹ By designing the Au target to be about 50 microns thicker than the range of the primary beam, most of the heavy fission products and spallation residues can be stopped in the Au target before they reach the H gas. These heavier products

would preheat the inner edges of the target somewhat, and such an effect should probably be included in target studies. Batzel¹⁰ has pointed out that these high energy fissions are preceded by an evaporation of many nucleons which in this case might also contribute to secondary energy deposition.

Speaking broadly, the reaction products are composed of a forward cone containing the fragments from the projectile and a relatively isotropic distribution of fragments from the target nucleus. Greiner has shown that the projectile at large impact parameters breaks up into a Gaussian distribution of mostly light particles (p , n , α) with very little momentum transfer to the target nucleus.¹¹ Poskanzer shows that the angular distribution of products from the target is roughly isotropic.¹² Bevalac experiments have shown that energy/nucleon is the important quantity in relativistic heavy ion reactions and not total energy; the projectile nucleons arrive in a bunch but act more or less independently of each other. The cross sections for reaction products from the target at 90° to the beam for 5.5 GeV protons on U have been measured by Poskanzer and are shown in Figure 8. Each of these distributions represents a roughly Maxwellian evaporation spectrum from the compound nucleus. The slanted line roughly indicates to its right those particles that would contribute to secondary energy deposition by penetrating 0.5 mm of Au. The major contribution is from high energy protons.

Not measured here are the even higher fluxes of high energy neutrons.

The tail on the Bragg peak for U in Au can be extrapolated in the forward direction with the help of the experimental data shown in Figure 1. This has been done by assuming a geometric cross section

$$\sigma = \pi (r_1 + r_2)^2 = 1.5\pi (A_1^{1/3} + A_2^{1/3})^2 .$$

The mean free path or interaction length at normal density is

$$\ell = \frac{1}{n\sigma} = 50 \text{ gm/cm}^2 = 2.6 \text{ cm Au} .$$

Assuming that primary beam survivals go as $e^{-x/\ell}$ where x is the penetration depth into the target material, we can calculate the secondary contribution to dE/dx at each point along the residual range curve of Figure 4. The secondary spectrum is then assumed to be symmetric about the Bragg peak as shown in Figure 9. The resulting Bragg curve, which is to be considered only as a very rough estimate, is shown in Figure 2. This estimated curve does not include any contribution from the considerable neutron flux generated by the primary beam.

The vertical line in Figure 2 represents the slice of the tail which might contribute secondary heating to the H gas

behind the target. The density of H gas at one atmosphere is .09 mg/cm³. From the graph of Figure 2 this implies that about .03 MeV are deposited per mm of the H gas by each primary beam particle. Since the primary beam particle energy is 1.41×10^5 MeV, each beam particle deposits roughly 10^{-7} of its energy into each mm of gas behind the target via secondary reaction products in the forward direction. Therefore a beam pulse consisting of 5×10^{14} primary particles deposits about 2 joules in each mm of H gas following the target.

If we assume that this energy goes into the internal energy U of an ideal gas,

$$kT = \frac{2}{3} \frac{k}{R} \frac{U}{n} = 7 \times 10^{-6} \frac{U(\text{joules})}{n(\text{gm moles})} \text{ eV}$$

where n is the number of moles (for a volume of 5 mm³ the number of moles is 2.3×10^{-7} for one atmosphere of H gas), the resulting estimated temperature in 5 mm³ of H gas behind the target, corresponding to linear gas dimensions of the order of 1 mm, is 66 eV. Since we have not included the effects of the considerable secondary neutron flux, these estimates should be considered as lower limits.

The above estimates refer to the forward direction of the beam which includes the forward cone of projectile fragmentation. If a cylindrical type of target is designed to avoid the secondary heating from this forward cone, there still remain the reaction products from the target fragmentation, which are distributed roughly isotropically in the lab, as is shown in the data of Figure 10¹¹ and Figure 11¹⁵. For the higher projectile masses the angular distribution is isotropic to within a factor of 10, the isotropy diminishing slowly as the projectile mass increases. For the time being we shall neglect the neutron flux from the reactions, which can be expected to be even greater than the proton flux. We also neglect pion production, which will be low since the threshold for pion production is around 300 MeV. The cross sections of Figure 8 can be integrated roughly to give a total cross section for various products at 90° from 5.5 GeV p on U.

From the p, D, T, and α spectra in Figure 8 one obtains a total cross section for secondary heating of about 0.7 barn/steradian by assuming an exponential form for $d\sigma/dE$ and integrating from the slanted line to infinity. This represents the reaction products emitted into one steradian at 90° by the breakup of U target nuclei bombarded with 5.5 GeV protons. Since excitation functions for these reactions flatten at about

300 MeV/amu, we can roughly assume that the same cross section is valid for 600 MeV/amu protons on U. Preliminary experiments at LBL by Gutbrod and Poskanzer¹³ have indicated that the cross sections scale roughly as $A^{2/3}$ where A is the projectile mass. Scaling the beam mass up by $238^{2/3}$ and the target mass down by $197/238$, we arrive at a cross section of 22 barns/steradian for emitting light products in the 90° direction from Au targets bombarded by U projectiles. Although these particles are emitted in a Maxwellian spectrum, let us estimate the secondary heating assuming they were all 30 MeV protons. We stress that this estimate and succeeding calculations are only very rough extrapolations and the true value might be ten times greater or smaller.

A cross section of 22 barns/steradian for 30 MeV protons emitted from a Au target with thickness equal to the primary range of 4 gm/cm² yields, for 5×10^{14} primary particles, a total of 10^{14} protons/steradian in the 90° direction (about 3 protons/steradian boiled off per reaction). The stopping power of 30 MeV protons in H gas at 1 atmosphere is about .04 MeV/mg/cm². So for a 1 mm path length in H gas we estimate roughly that 4×10^{10} MeV/steradian (.006 joule/steradian) gets deposited in the gas. That is, the secondary heating from target breakup in the 90° direction may be down a factor of approximately 100 from the heating in the forward

direction along the beam. This would indicate secondary heating temperatures of about 1 eV for a gas volume of 5 mm^3 corresponding roughly to a linear dimension of the order of 1 mm.

An estimate of the additional heating from neutron collisions with H gas can be made by assuming 40 neutrons are boiled off in each reaction with an average energy of 8 MeV. Then about 10^{14} neutrons/steradian are emitted per pulse in the 90° direction. In a collision with protons a neutron loses half its energy on the average. The cross section for the interaction of 8 MeV neutrons with protons is about 1 barn.¹⁴ Therefore the energy deposited at 90° into .01 mg/cm of H gas (about 1 mm) is about 10^9 MeV/steradian or .0002 joules/steradian compared to .006 joules/steradian from the protons. Thus we estimate that 50 times as much heat is deposited in the gas by protons as is deposited by neutrons in the 90° direction. The implication for target heating is that these neutrons cannot be stopped appreciably by an absorbing material whose thickness is of the order of millimeters.

The general conclusion is that in the case of direct 0° irradiation of targets the secondary heating problem can be serious since the preceding estimates are rather conservative. Absorbing layers to minimize this problem might be of the order in thickness of

the target itself, and this should be considered in target design. Cylindrical targets that avoid heating from the forward cone can reduce the secondary heating problem by about a factor of 100. If a target is designed with appropriately large dimensions and appropriate absorbers the secondary heating can probably be brought to below an electron volt. We do feel that these calculations indicate that more detailed reaction data from relativistic heavy ion beams would be a very useful input in the design of various target systems.

These secondary heating estimates are to be regarded as conservative, especially since we have no direct measurement of the multiplicity of light particles produced by a relativistic U beam. The secondary heating could easily be a factor of ten greater than is indicated by these estimates, and so there is the possibility that secondary heating could be a serious problem for certain classes of experiments. One way to cut down reaction products is to drop the beam energy below the threshold of the excitation function, for the emission of light particles. Another way to decrease heating, besides making the target larger, is to use a low-Z absorber such as carbon. All of these methods sacrifice some efficiency in energy absorption.

REFERENCES

1. A. W. Maschke, "Relativistic Heavy Ions for Fusion Applications", IEEE Transactions on Nuclear Science, Vol. NS-22, No. 3, p. 1825, (June 1975).
2. R. L. Martin, "The Ion Beam Compressor for Pellet Fusion", IEEE Transactions on Nuclear Science, Vol. NS-22, No. 3, p. 1763, (June 1975).
3. J. Lyman and J. Howard, private communication, (February 1976).
4. See, for example, Marmier and Sheldon, Physics of Nuclei and Particles, Vol. I, p. 156, Academic Press, (1969).
5. G. Hermann, private communication.
6. L. C. Northcliffe and R. F. Schilling, "Range and Stopping-Power Tables for Heavy Ions", Nuclear Data Tables, Vol. 7, p. 233, (January 1970).
7. P. Steward, UCRL 18127.
8. D. J. Sigmar and G. Joyce, Nuclear Fusion II, p. 447 (1971).
9. H. Heckman and A. Poskanzer, private communication.
10. R. E. Batzel, as discussed by Hicks and Gilbert, Phys. Rev. 100, 1286, (1955).
11. D. E. Greiner, et al, PRL 35, 152, (1975).
12. A. M. Poskanzer, G. W. Butler, and E. K. Hyde, "Fragment Production in the Interaction of 5.5 GeV Protons with Uranium", Phys. Rev. 3C, 882, (1971).
13. A. Poskanzer, private communication.
14. R. K. Adair, Rev. Mod. Phys. 22, 249, (1950).
15. A. Poskanzer, R. G. Sextro, A. M. Zebelman, H. H. Gutbrod, A. Sandoval, and R. Stock, "Search for Fragment Emission From Nuclear Shock Waves", LBL-4309.

900 $\frac{\text{MeV}}{\text{amu}}$ ^{40}Ar in H_2O

Experimental Data
(J. Lyman, J. Howard Bevalac)

0°

Figure 1

Estimated $600 \frac{\text{MeV}}{\text{amu}}$ ^{235}U in Au (J. Lyman and J. Howard, Bevatron)

Figure 2

Figure 3

Figure 4

Figure 5

A

Figure 7

From A. Piskunov et al. Phys Rev 30, 882, (1971)

Figure 8

Laboratory energy spectra at 90° to the beam. The curves for each element have been multiplied by a different factor which is indicated in the upper right part of the figure. The broken curves are for the most neutron-deficient isotope of each element. All the curves should be raised by the factor 1.10.

Theoretic | Bragg Peak + Secondary Contribution = Experimental Curve

Figure 9

Figure 10

From A. Poskanzer et al., Phys. Rev. 3C, 882, (1971)

XBL758-3794

Figure 11

From A. Poskanzer et al., Preprint LBL-4309

Distribution:

Lawrence Livermore Laboratory

Carol T. Alonso, L-32
 Roger O. Bangerter, L-545
 Patrick W. Crowley, L-81
 Byron C. Groseclose, L-33
 John D. Immele, L-32
 William A. Lokke, L-33
 Donald J. Meeker, L-545
 John H. Nuckolls, L-545
 James W. Shearer, L-387
 Roy D. Woodruff, L-32
 TID File, L-9 (15)

Lawrence Berkeley Laboratory

Albert Ghiorso, 71-275
 Douglas E. Greiner, 50-248A
 Hermann A. Grunder, 50-152
 Bernard G. Harvey, 70A-3317B
 Bradford K. Heckman, 50B-3209E
 Glen R. Lambertson, 47-103
 Edward J. Lofgren, 50-157
 Arthur M. Poskanzer, 70A-4447
 Andrew M. Sessler, 50A-5111
 Lloyd Smith, 50A-3115
 Glenn T. Seaborg, 70A-3307A
 David L. Judd, 50A-3115

Oak Ridge, Tennessee

TIC(27) Oak Ridge, Tennessee

Printed in the United States of America
 Available from
 National Technical Information Service
 U.S. Department of Commerce
 5285 Port Royal Road
 Springfield, VA 22161
 Price: Printed Copy \$; Microfiche \$2.25

Page Range	Domestic Price	Page Range	Domestic Price
001-025	\$ 3.50	326-350	10.00
026-050	4.00	351-375	10.50
051-075	4.50	376-400	10.75
076-100	5.00	401-425	11.00
101-125	5.25	426-450	11.75
126-150	5.50	451-475	12.00
151-175	6.00	476-500	12.50
176-200	7.50	501-525	12.75
201-225	7.75	526-550	13.00
226-250	8.00	551-575	13.50
251-275	9.00	576-600	13.75
276-300	9.25	601-up	*
301-325	9.75		

*Add \$2.50 for each additional 100 page increment from 601 to 1,000 pages; add \$4.50 for each additional 100 page increment over 1,000 pages.

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."

Technical Information Department

LAWRENCE LIVERMORE LABORATORY

University of California | Livermore, California | 94550