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CONSIDERATIONS OF BEAM QUALITY REQUIREMENTS FOR
EXPERIMENTS WITH VERY HEAVY IONS *

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Introduction

The object of this paper is to examine factors that limit the attainable resolution in certain heavy-ion experiments. It has been argued that beam quality from accelerators such as the SuperHILAC will often prove to be a very serious limitation. It will be shown that other, purely experimental factors are likely to impose considerably more severe limitations. The emphasis of this paper has been placed on particle spectroscopy experiments because of the tremendous popularity and success of this technique in recent years, and because such experiments probably place the most severe requirements on beam quality. However, future experiments in heavy-ion physics may well be based mainly on differently techniques, with less severe beam quality requirements. Part I of this paper discusses some beam properties of existing heavy-ion accelerators at LBL, and Part II details some of the experimental problems which must be considered.

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Part I

Accelerator Beam Quality

1. Definition of Beam Quality

The "quality" of an accelerator beam involves three of its properties:

- (a) The energy width, ΔE , is usually defined as the full energy width at half maximum intensity (FWHM). It is generally quoted as a percentage of the total energy, or $(\Delta E/E) \times 100\%$.
- (b) The horizontal emittance is an area in a special phase space that is a measure of how well the beam can be focussed in the horizontal direction. It is proportional to the product of the horizontal width (x-width, where z is the beam direction) times the angular spread (dx/dz) at that point along the beam where the x-width has a local minimum. The vertical emittance is similarly defined in terms of the y-width. Thus a perfectly parallel beam has zero x- and y- emittance since $dy/dz = dx/dz = 0$, and a beam focussed to a y-line has zero x-emittance because its x-width is zero. Emittance is given in units of millimeters-milliradians (mm-mrad). A beam of poor emittance can be improved by collimation, only at the expense of beam intensity.

Another important criterion is the intensity distribution of the beam across the phase space area. If most of the beam intensity can be concentrated in a small central area, one can often reduce the emittance by collimation without substantially decreasing the quantity of beam that gets through. The brightness is the beam intensity that remains in this remanent area of emittance. This slightly reduced quantity of beam can be used in experiments that require a high beam quality (low emittance). Beam outside the central bright area is a bonus that can be used for the large number of experiments where total intensity is important but emittance is not.

- (c) The duty cycle, is the fraction of time during which there is a beam. The duty cycle is often divided into a microscopic and a macroscopic component. The microscopic duty cycle is correlated with the accelerating frequency of the machine and is represented by the time duration of the beam pulse, usually less than 10^{-6} seconds, divided by the time between beam pulses. The macroscopic duty cycle is due to external limiting factors such as power limitations, heat dissipation problems, or magnet cycling, that require the beam pulsing to be

terminated for a certain periodic fraction of the time. Thus the macroscopic beam structure consists of groups of sharp beam pulses (the microstructure) separated by the macroscopic duty time. In practice a low macroscopic duty cycle on a time scale equal to or longer than the time resolution of the particle detectors in an experiment is undesirable since it represents time during which nothing is happening. A high microscopic duty cycle is helpful in coincidence experiments (i.e. simultaneous detection of two separate particles or gamma rays), but its importance is often overestimated for the reasons discussed in Section 2-C. For some experiments, such as time-of-flight measurements, microstructure is desirable since sharp beam pulses provide good timing references. With some linear accelerators, such as the SuperHILAC, it is possible to wash out the microstructure by suitable "debunching", which can have the added advantage of enhancing the energy resolution.¹

2. Performance of Different Accelerators

A. Energy Resolution

Van de Graaff beams of very light ions can have energy widths of less than 1 keV ($\Delta E/E \sim .01\%$ FWHM). Most cyclotron beams (e.g. the LBL 88-inch) have 0.2-0.3% FWHM.² The SuperHILAC beam has 0.2-0.5% FWHM.^{3,4}

In many experiments, beam energy widths are of no consequence - for example in isotope production and in most experiments in which gamma-rays are detected. However, a small energy width is essential for the study of sharp resonances, or whenever the results of the experiment vary rapidly with beam energy. Such work is being done with present day cyclotrons, using beams that have been energy-analyzed by means of carefully designed magnets. Of course there is a loss of beam intensity, but a good cyclotron produces so much beam that even after analysis the intensity and energy width is about the same as a Van de Graaff beam. A much more intense beam is still available for the many experiments that do not require a small energy width. Figure 1 shows the sharp resonance in elastic scattering of 14.2 MeV protons from ^{12}C measured with an analyzed beam from the LBL 88-inch cyclotron.⁵ The beam energy width is about 0.012%.

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Sharp resonances have been observed in the interaction of ^{12}C and ^{16}O ions with light nuclei, using Van de Graaff beams.⁶ Such work could be done with equal accuracy at the 88-inch cyclotron or at the SuperHILAC with the use of an analyzing magnet.

In studies of nuclear reactions such as $^{16}\text{O} + ^{208}\text{Pb} \rightarrow ^{15}\text{N} + ^{209}\text{Bi}$, the ^{15}N ions must be detected with an energy resolution smaller than the energy separation between the levels of the final nucleus (^{209}Bi). Thus even though the physics of the reaction changes only slowly with the ^{16}O beam energy, it is sometimes necessary to use an ^{16}O beam that has a small energy width. However, the well-established technique of dispersion matching in a magnetic spectrometer permits the use of a beam with a broad energy spread.⁷ The method is illustrated in Fig. 2. The beam is passed through one or more magnets which bend the trajectories of the particles of lower energy more than those of high energy. A monoenergetic beam would be obtained by placing an analyzing slit in the dispersed beam so that only one momentum component passes on to the target. If the analyzing slit is opened wide, all momentum components arrive at the target but they are separated in space across the target surface. In Fig. 2 the quadrupole lens is used to invert the beam energy profile on the target, so that the lower energy portion of the beam strikes the left side of the target (as seen by the beam) while the higher energies traverse the right side of the target. After scattering through a fixed angle θ , particles entering the spectrometer magnet are bent according to their total kinetic energy, thus following different orbits. If the parameters of the beam transport system are adjusted properly, these particle orbit variations and the spreading out of the beam on the target will combine to produce a sharp focus on the detector surface. Therefore all particles which undergo the same type of scattering event will arrive at the same point on the focal plane. This is demonstrated by the dotted lines at the focal plane in Fig. 2, where all particles elastically scattered arrive on the right side of the focal surface regardless of the initial beam energy dispersion, while particles resulting from various inelastic phenomena are all focussed at the left side of the plane. Thus the energy resolution in the focal plane is independent of the energy resolution of the beam on the target.

For experiments with exotic beams that cannot be made in sufficient intensity to permit the losses that occur during beam energy analysis, this technique is enormously valuable. It is in use at the 88-inch cyclotron in light- and heavy-ion experiments.^{8,9} About 30% of the total cyclotron beam can

be used instead of the 2% that survives analysis to Van de Graaff energy quality. Note that dispersion matching cannot be used when the reaction product particle is measured with particle counters; a spectrometer is essential. (A magnetic spectrometer has many other advantages for heavy-ion experiments. For a general discussion of spectrometers, see Ref. 7.)

The intrinsic energy resolution of linear accelerator systems is dependent on the synchronous phase angle, ϕ_s , used in the acceleration process. This parameter can be adjusted by means of the electric gradients in the linac cavities. For the SuperHILAC, with $\phi_s = 20^\circ$, an energy resolution of 0.5% has been measured for 7.2 MeV/A argon ions⁴, and 0.25% has been measured for 7.2 MeV/A carbon ions³. It is expected that SuperHILAC beams can be magnetically analyzed using existing equipment to decrease the energy spread to about 2×10^{-4} with approximately an 8% transmission. Duplication of the 88-inch cyclotron spectrometer would decrease this figure to about 1.3×10^{-4} with a transmission theoretically approaching 50% to 80%.

It should be emphasized that no experiment yet proposed for ultra heavy ions requires this high order of energy resolution. Should the need arise, however, simple straight-forward techniques can be applied to provide the necessary high quality beams. Part II of this paper analyzes some of the problems encountered in doing such high resolution experiments with heavy ions. It is seen that it is very difficult to achieve a resolution of better than 10^{-3} in an experiment for reasons that have absolutely nothing to do with the accelerator.

B. Beam Emittance

Production of a beam that can be simultaneously focussed into a small spot and still remain nearly parallel is of capital importance in some experiments and of little in others. For isotope production experiments, the beam intensity is important but its optical quality is not.

Beam emittance is very important in high resolution counter experiments, especially with heavy-ion beams. In a reaction such as $^{20}\text{Ne} + ^{27}\text{Al} \rightarrow ^{19}\text{F} + ^{28}\text{Si}$, the kinetic energy of the outgoing ^{19}F ions varies very rapidly as a function of their angle with respect to the incident ^{20}Ne beam particles. This is referred to as a kinematic shift. For ^{20}Ne ions of 150 MeV, the ^{19}F energy changes by 1.2 MeV per degree in the neighborhood of 20° . Thus, if the horizontal angle of the beam cone at the target is only 0.1° ,

the energy of ^{19}F ions emitted at 20° will vary from the mean value by ± 60 keV. The rate of variation depends sensitively upon the ratio of the beam particle mass to the target nucleus mass and is much greater for heavy ions than for light ions with the same target.

Although the full horizontal emittance of the 88-inch cyclotron beam² (50 mm-mrad) is too large to permit it to be focussed to a sufficiently parallel beam of a small enough size to perform the experiment described above, the beam intensities at least up to ^{20}Ne are so great that even after collimation to about 5 mm-mrad enough beam is still available to carry out such experiments with counters.

This reduction of emittance is not required for spectrometer experiments, as a relocation of the beam focus can compensate for large beam emittances.⁷

The emittance of the SuperHILAC has been measured with a 7.2 MeV/A carbon beam of 1.1×10^{13} pps to be 28 mm-mrad.¹⁰ Since this emittance is mainly a function of the ion source characteristics, it is not expected to become larger for other beams; in fact it may even decrease for heavier beams.

The table below gives the measured and expected intensities of various SuperHILAC beams. (These values have been measured during the debugging stage of the machine development and do not represent the maximum beam intensities that the final machine will be able to deliver.)

Table I
SuperHILAC Beams
(Integrated particle currents)

Beam	Measured	Expected
C	10^{13} pps (1.6 pua)	5×10^{11} pps (80 pua)
Ar	2×10^{12} (320 pna)	5×10^{13} pps (8 pua)
Kr	6×10^{10} (10 pna)	5×10^{12} pps (800 pna)
Xe	-----	10^{12} pps (160 pna)
U	-----	10^{11} pps (16 pna)

It will be noted that even after energy analysis and collimation to Van de Graaff quality, the remaining intensities will be greater than Van de Graaff intensities.

C. Duty Cycle

In experiments of nearly all types, a low macroscopic duty cycle is a disadvantage since it represents time during which the experiment could use a beam that is not in fact available. For the 88-inch cyclotron and Van de Graaffs, the macroscopic duty cycle is close to 100% in normal operation. For the Super-HILAC it varies between 30 and 80%.¹¹

In both the 88-inch cyclotron and the SuperHILAC, there is a microscopic beam time-structure. Particles arrive in bunches at the frequency of the accelerating radio frequency (5-15 MHz for the 88-inch, 70 MHz for the Super-HILAC). Between these beam bunches, there is no beam.

The disadvantage of a low microscopic duty cycle only becomes apparent in coincidence experiments in which two outgoing particles from the same nuclear event are to be detected. The degree of disadvantage depends on the resolving time of the detector system τ_c between beam pulses and the time width τ_w of each pulse. One measure of the problem is the ratio of true coincidences to chance coincidences. (Chance coincidences are due to detection within the time τ_f of two particles arising from different nuclear events.) If R is the true-to-chance coincidence ratio for the pulsed beam divided by the true-to-chance ratio for a truly continuous beam then

$$\text{when } \tau_f \geq 1/2 \tau_c, \quad R = 1 \quad (1)$$

$$\tau_f \leq 1/2 \tau_c, \quad R = 2 \tau_f / \tau_c \quad (2)$$

$$\tau_f \leq 1/2 \tau_w, \quad R = 2 \tau_w / \tau_c = 2 \times \text{duty cycle}. \quad (3)$$

For the 88-inch cyclotron, in a recent experiment,¹² τ_c was 140ns, τ_w was 6ns and τ_f about 20ns. Condition 2 therefore applies, and $R \approx 0.3$. In many experiments with modern electronics, condition 3 would apply, with $R \approx 0.1$.

Thus it appears that truly continuous (Van de Graaff) beams are always 3-10 times better than pulsed beams for coincidence experiments, and this conclusion is often quoted. However it is not really correct for the following reason.

In practice, true-to-chance ratios are nearly always so large - both for

Van de Graaff and cyclotron beams - that factors other than R determine the accuracy of the experiment and the time required to do it. For example in a current (α , 2α) coincidence experiment at the 88-inch cyclotron,¹² the true-to-chance ratio is 100. The rate of data accumulation is limited by the need to preserve good energy resolution in the two α -detectors by limiting the count rate. A continuous beam would be of negligible advantage since the time between counts must be held to intervals much greater than the microscopic beam structure anyway.

The SuperHILAC poststripper linac consists of six independently excited cavities, used to provide variable energy beams, with the maximum energy of 8.5 MeV/A. The majority of experiments will require energies from 2-6 MeV/A, in which case some cavities may not be required for acceleration. Calculations and preliminary experiments indicate that operation of one of these cavities in a de-bunching mode can spread the beam in phase, to eliminate the microstructure, and at the same time substantially decrease the spread in energy.¹ Thus for partial energy beams, microstructure can be tailored to fit the experiment from pulses as sharp as 1 nanosecond, to completely continuous beams.

Part II

High Resolution Heavy Ion Experiments

Many heavy-ion particle experiments require as high an energy resolution as possible; for example, inelastic scattering, resonance, and accurate Q value measurements. However, there are factors peculiar to heavy ions which limit the amount of beam resolution that can be used, and these factors are independent of the capabilities of the accelerator. We shall attempt to describe some of these limitations and where possible give some representative numbers for practical experiments.

1. Problems Involving High Coulomb Barriers

Interactions via the nuclear forces are observed only when the center-of-mass energy of the incident particle is above the Coulomb barrier. Therefore the greater the atomic number of particle and target, the higher is the required minimum beam energy. This means that in order to investigate nuclear phenomena such as narrow resonances of width ΔE , the resolution $\Delta E/E$ of the experiment must get smaller and smaller as the projectile mass increases. It is instructive to consider the difficulties involved in such an experiment, taking into account that the particle beam must be monoenergetic to at least the width ΔE of the resonance.

Table II lists the resolution necessary to perform such an experiment on a hypothetical resonance of width 10 keV, using beams and targets of increasing mass. The beam energy is 5 MeV/A, which is slightly above the Coulomb barrier for all the cases considered.

Table II
Beam Energy Resolution Required to Scan a Resonance of
Width 10 keV

Beam	Target	$\Delta E/E$
C	C	7×10^{-4}
Ar	Ar	2×10^{-4}
Kr	Kr	9×10^{-5}
Xe	Xe	6×10^{-5}
U	U	3×10^{-5}

Resolutions of this order are in principle obtainable for the C and Ar systems with a magnetically analyzed beam, but it is expected that fractional resolutions for heavier beams will be at best of the same order as lighter beams, and thus we must conclude that it will be increasingly more difficult to study fine structure of nuclear levels with heavier ions.

It is possible that experimental techniques can be used to analyze and compensate for the energy spread in the beam, such as careful time of flight measurements on the reaction products, but energy spreading due to target effects which will be discussed below will complicate the application of such techniques and make such experiments with very heavy ions quite difficult.

2. Problems involving Kinematic Broadening

Momentum conservation dictates that a target nucleus must recoil after undergoing a collision with a projectile, and the exact energy of the scattered particle depends on the laboratory scattering angle. If an experiment is performed with a detector which has a finite opening angle, $\Delta\theta$, the detector will measure particles scattered over a range of angles $\theta \pm \Delta\theta/2$. Thus the energy detected will show a distribution about the mean value corresponding to the kinematic energy shift associated with the angular opening $\Delta\theta$. The magnitude of this kinematic spreading goes approximately as the ratio of projectile mass to target mass, M_B/M_T , so that the energy spread becomes progressively worse as the projectile mass is increased, or as the target mass is decreased. Table III summarizes the spread $\Delta E/E$ for various monochromatic beams on gold and rhodium targets, counting at $\theta_{lab} = 10^\circ$ with an angular aperture of 0.1° (corresponding to a circular aperture of 17 mils at 10 inches). Note that the severity of the problem increases by one or two orders of magnitude on going from light to heavy beams.

Kinematic broadening is not important in some types of resonance experiments, because the measured quantity is the scattering probability (cross-section) as a function of beam energy. It is usually not necessary to detect scattered particles with high resolution. (The resonance shown in Figure 1 was detected with counters whose energy resolution was 20-40 times poorer than the width of the resonance.) The beam emittance is no longer important, but for such experiments its energy spread must be equal to or less than the width of the resonance to be studied.

However in experiments that require a careful measurement of the actual energy of the scattered particles, kinematic broadening must be taken into account. In counter telescope experiments the detectors must either have a very restricted angular acceptance with the corresponding decrease in counting efficiency, or a position sensitive counter must be employed. In spectrometer experiments, a displacement of the focal surface is all that is required for a first-order compensation of kinematic shifts.

Thus it appears that kinematic broadening can be controlled experimentally. This is true as long as the uncertainty is small in the scattering angle of the primary event. It will be demonstrated below that multiple scattering of very heavy ions in even the thinnest targets introduces enough uncertainty in this scattering angle to make high resolution extremely difficult to achieve, with counters or spectrometers.

Table III
Kinematic Energy Shifts for Scattering at $\theta = 10^\circ$,
with $\Delta\theta = 0.1^\circ$ and $E = 5 \text{ MeV/A}$

<u>Beam</u>	Kinematic shift ΔE	<u>Targets</u>		
		<u>^{197}Au</u>	<u>^{103}Ru</u>	
		$\Delta E/E$	Kinematic shift ΔE	$\Delta E/E$
C	1.8 keV	3.0×10^{-5}	4.1 keV	6.9×10^{-5}
Ar	24 keV	1.2×10^{-4}	48 keV	2.4×10^{-4}
Kr	112 keV	2.6×10^{-4}	210 keV	2.9×10^{-4}
Xe	285 keV	4.2×10^{-4}	540 keV	7.9×10^{-4}
U	870 keV	7.3×10^{-4}	1760 keV	14.8×10^{-4}

3. Problems Involving Target Thickness

The most serious problems to be encountered in high resolution heavy-ion experiments are associated with the target. Difficulties due to the target are discussed in this section.

(a) Target uniformity. It is very difficult to obtain and maintain better than a few percent overall target thickness variation for thin targets.

- (b) **Energy straggling.** A monoenergetic beam loses energy in passing through matter, and in doing so ends up with a distribution of energies centered around the average final value. For very thin targets this distribution can approach 60% to 80% of the average energy loss in the target.
- (c) **Multiple scattering.** This leads to energy dispersion through kinematic broadening.
- (d) **Reaction site.** The total energy loss depends on the point in the target where the reaction actually occurs, especially in transfer reactions, which change the stopping power for the projectile.
- (e) **Beam heating.** For heavy ion beams, the total energy lost in the target is sufficiently high that beam currents must be kept to low levels to prevent target melting. This limits the rate at which data can be collected, and ultimately the sensitivity of an experiment.

These points will be discussed briefly, with numbers relevant to a hypothetical experiment in which a gold target is bombarded with various heavy ion beams from carbon to uranium at an energy of 5 MeV/A. Carbon is selected as a calibration point as considerable data are available from high resolution experiments with carbon beams.

A. Target Uniformity

A beam traversing a non-uniform target experiences an additional spread in energy roughly equal to the integral of (dE/dx) over the thickness uncertainty, Δx . The best thin targets are usually produced by vacuum evaporation, and are subject to non-uniformities on both a macroscopic and a microscopic scale. Macroscopic variations can be controlled by very careful experimental arrangement; proper substrate orientation, large distances between substrate and oven, etc. Overall variations can be controlled to about 1 or 2 percent. However, microscopic variations in the target due, for example, to clustering effects on the surface, are not so easily controlled. Such microscopic variations are probably of no consequence for targets thicker than a few hundred micrograms per square centimeter, but a variation of a few tens of atomic layers represents a large uncertainty in the thickness of a $50 \mu\text{g}/\text{cm}^2$ thick film of gold. Table IV shows the energy spreading generated for various beams through a $50 \mu\text{g}/\text{cm}^2$ gold target assuming a microscopic surface irregularity of 20 atoms ($\sim 10 \mu\text{g}/\text{cm}^2$).

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It is apparent that such irregularities can contribute in large measure to experimental energy uncertainties, and should be controlled as carefully as possible.

Table IV
Effect of Target Thickness Variations on Energy Spreading of 5 MeV/A Beams
for a $50 \mu\text{g}/\text{cm}^2$ gold target

Beam	Microscopic Irregularities $\Delta x = 20 \text{ atoms}$ ($10 \mu\text{g}/\text{cm}^2$) $\Delta E/E$
C	1.7×10^{-4}
Ar	3.0×10^{-4}
Kr	3.7×10^{-4}
Xe	3.8×10^{-4}
U	4.5×10^{-4}

B. Energy Straggling

As it traverses the target material a projectile normally undergoes many collisions with electrons in the target. Each collision slightly changes the projectile energy. The statistical nature of the collision process results in a distribution function for energy loss in the target. Energy straggling is defined to be the full width at half maximum of this distribution function, which is itself a function of the total amount of energy lost in the target. The diagram below demonstrates how for low energy losses the distribution is asymmetric (Landau distribution), but as more energy is lost a symmetric Gaussian shape develops. For intermediate energy losses, Vavilov¹³ has given a solution for the distribution functions, tables of which have been compiled by Seltzer and Berger.¹⁴

Estimates of the energy straggling for various beams through gold targets have been made from the full width at half maximum of these Vavilov distributions. (See Appendix A)

Figure 3 shows these estimates for energy straggling in terms of $\Delta E/E$ of 5 MeV/A beams as a function of gold thickness. Normally, targets thinner than $50 \mu\text{g}/\text{cm}^2$ are not self-supporting, so the dotted lines show the combined effect of straggling through gold deposited on a $10 \mu\text{g}/\text{cm}^2$ carbon backing. Figure 3 appears to imply that the heavier ions are less affected by energy straggling, but in terms of actual energy dispersion in keV, heavier ions in fact suffer considerably greater energy spreading. This ΔE , however, is a smaller fraction of the total incident energy and therefore $\Delta E/E$ decreases. It is observed in Fig. 3 that resolutions better than 0.01% are not achievable for a solid target experiment but that straggling effects can be controlled for physically realizable targets if one relaxes the resolution requirement to 0.03%.

Column 1 of Table V summarizes the maximum thickness of target possible to keep the resolution to 0.03%. For the carbon and argon experiments, the targets are assumed to be mounted on a carbon backing.

C. Multiple Scattering

A beam passing through a target experiences angular spreading due to many small angle Rutherford scattering events. If one large angle scattering event occurs within the target the angle of scattering will be uncertain by the contribution of multiple scattering before and after the event of interest. As the energy loss of the projectile to the recoiling target nucleus (kinematic shift) is a sensitive function of scattering angle, the angular uncertainty caused by multiple scattering will limit the accuracy possible in an experiment. Column 2 of Table V gives the maximum target thickness that keeps kinematic broadening due to multiple scattering to less than 3×10^{-4} of the incident energy. The total mean scattering angle varies relatively slowly for different beams, from .1 mrad/ $(\mu\text{g}/\text{cm}^2)^{1/2}$ for a carbon beam to around .2 mrad/ $(\mu\text{g}/\text{cm}^2)^{1/2}$ for a uranium beam; but it will be recalled from Table III that kinematic shifts are much more important for heavier beams. These mean scattering angles are estimated using the formula derived by Jackson.¹⁵ This formula is not the most accurate available, but it can be applied for the target thicknesses we are

considering, where the more general Moliere theory cannot.¹⁶ Indications are that the Jackson formula underestimates the mean scattering angle, so that the numbers quoted are probably conservative estimates.

Kinematic shifts due to finite acceptance angle can be compensated for by properly designed spectrometers, because of the correlation between the total scattering angle and the energy of the particle. Multiple scattering, however, washes out this correlation, so that resolution can only be maintained by reducing the amount of target material. Notice that the gold targets necessary for the Kr, Xe and U experiments are too thin to be self-supporting, and the necessary carbon backing introduces more multiple scattering problems. Column 3 of Table V shows the maximum amount of gold which can be placed on a $10 \mu\text{g}/\text{cm}^2$ backing to keep the 3×10^{-4} resolution figure, including the total scattering in target and backing. Note that the scattering for the uranium beam is so great that the desired resolution of 3×10^{-4} is unattainable.

D. Reaction Site

If the target is perpendicular to the beam, a particle scattered at an angle θ traverses different amounts of target material depending on where in the target the scattering event occurs. In addition, the recoil energy loss changes the (dE/dx) value of the particle, so that the rate of energy loss through the remaining target material is affected. If the particle is modified by transfer, the rate of energy loss is also different. All of these effects can be corrected for by a proper orientation of the target relative to the beam and scattering angles.¹⁷ However it should be noted that in many cases the correct orientation angle is quite large, magnifying the target uniformity and flatness requirements.

E. Beam Heating

Because of the higher (dE/dx) values for heavier ions, target heating can be a serious problem. It is important to keep targets at temperatures well below the melting point, since the vapor pressure for most materials becomes substantial at this point and considerable target evaporation can occur. Also, thermal expansion causes sagging and wrinkling, leading to non-uniformities. For the experiments with gold, the temperature should be kept at less than 500°C to preserve an adequate margin of safety. For thick targets conduction cooling is more important than radiation cooling in this temperature range. However

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for gold targets thinner than $100 \mu\text{g}/\text{cm}^2$, the cross-sectional area available to conduct away the heat is so small that surface radiation is the dominant mode of target cooling.

A useful computer program has been written by J. O. Liljenzin¹⁸ to evaluate the equilibrium temperature at any point of an arbitrarily shaped target for any beam distribution and duty cycle. We have utilized this program to determine the maximum beam current which can be passed through a target to maintain the temperature at 500°C . For these calculations, it is assumed that the target is 0.5 cm diameter with water cooled edges, the beam is uniformly spread out over the target, and the macroscopic duty cycle is 100%. If the duty cycle is less than 100%, the beam currents calculated correspond approximately to the maximum peak currents allowed, as the thermal relaxation time is generally shorter than the macroscopic beam pulse length, and thermal equilibrium is attained during the beam pulse.

The calculated beam currents are summarized in Table VI for target thicknesses corresponding to experiments performed at resolutions from 0.015% to 0.07%. Since the radiating surface area is a constant, targets can radiate a constant amount of power and thus for very thin targets, where the total energy loss per beam particle is small, very large beams can be used for the experiment.

As the target thickness is increased, though, the beam currents must be reduced to keep down the total power deposited in the target. Pure gold is a very poor radiator, having only 3% of the theoretical black body efficiency, whereas the efficiency of amorphous carbon approaches 90% of that of a pure black body. Thus for targets deposited on a carbon backing, almost all of the heat is dissipated through the backing. Also, for thicker gold targets which do not require a carbon backing for support, the total beam which the target can handle is considerably reduced if the carbon is not present (see Table VI). Thus it is worthwhile even for very thick targets to place a thin layer of carbon on the surface to serve as a heat dissipator. The calculations summarized in Table VI assume that only one surface is carbon. Greater beam strengths could be used if the other surface were also coated. Note that if the target must be inclined at an angle θ to the beam, to compensate for reaction site effects, the beam pathlength, and thus the energy deposited in the target, increases as $1/\sin \theta$, while the cooling capacity does not change. Thus these estimates for

maximum beam currents are upper limits, corresponding to a target perpendicular to the beam.

If we examine the numbers in Table VI, we see that the sensitivity of an experiment is limited not only by the thickness of the target which can be employed, but also by the thermal effects of the beam in the target. In particular, as the projectile mass increases, the maximum allowable beam intensity drops drastically, by a factor of about 20 between carbon and the heavier ions.

4. Experimental Sensitivity.

Combining the maximum beam currents and greatest target thicknesses, estimates can be made for counting rates in a realistic experiment. These estimates are shown in Fig. 4 for an experiment utilizing the spectrometer at the 88-inch cyclotron (opening angle ~ 2 milliradians), assuming the cross-section of the desired event to be 1 millibarn/steradian. It is seen that experiments become progressively more difficult for the heavier beam. Under the best conditions, experiments with uranium beams will have counting rates about 200 times below the corresponding experiments with carbon beams.

If a magnetic spectrometer is utilized, yet another factor can decrease the sensitivity of an experiment, namely the multiplicity of charge states for heavy ions. Ions lighter than carbon at 5 MeV/A are fully stripped of atomic electrons on traversing the target, so that all projectiles emerging from the target at a given energy have the same charge to mass ratio, and so the same radius of curvature through the spectrometer. However, as the ion mass is increased, the inner electrons are more tightly bound, and are in general not stripped from the projectile. Under such conditions the beam emerging from the target has a distribution of charge states centered around the most probable ionization state.¹⁹ Ions in each charge state follow a different orbit in the spectrometer, so that the total reaction strength is divided between the total number of charge states allowed. As simultaneous collection on the focal surface of all charge states is impossible, many events of interest are not recorded. This decreases the sensitivity of the experiment. Since the number of charge states (width of the distribution function) increases as one goes to heavier nuclei, the loss in intensity becomes more serious. It is possible to recover a good portion of the intensity by filling the spectrometer with a low pressure (around 0.1 torr) gas.^{20,21} The ions when undergo many charge

exchange collisions with the gas atoms, and follow the trajectory of the average charge state for the ion. However, the multiple scattering caused by the gas adversely affects the resolution on the detector surface in a very serious manner.

The target thickness problem can be reduced by the introduction of differentially pumped gas or vapor targets. In this case the straggling and multiple scattering associated with the carbon backing are eliminated. The last column of Table V gives the thickest gas target which could be used ($\Delta E/E \approx .03\%$) assuming that uniformity were not a problem. Although there is an improvement, it is not large. By far the greatest advantage of a gas target is that there are no target heating problems, so that the full available beam strength can be used. If 50% of the expected SuperHILAC beam can be passed through a dispersion matched spectrometer, Table VII gives a comparison between counting times to accumulate 1000 counts with solid and vapor targets. It is seen that about a factor of 20 improvement is possible for light beams, but that for xenon and uranium beam experiments solid targets are capable of absorbing most of the available SuperHILAC beam so that there is relatively little to be gained from using a vapor target.

Note that it is relatively straightforward to produce a sufficiently dense stream of a naturally gaseous element to generate targets in the hundreds of micrograms/cm² range, but a target from a vaporized metal is not so easy to produce. A quick calculation shows that to generate a gold target 45 $\mu\text{g}/\text{cm}^2$ thick requires the vaporization of 2 grams of gold per second.

Conclusion

In Part I we have shown that the existing heavy-ion accelerators at LBL are capable of delivering high quality beams. In fact these beams have sufficient intensity that they can be magnetically analyzed to the highest quality available in any other machine and still have beam intensities comparable to the other machines. However in Part II we have attempted to show that in many cases these qualities may be irrelevant because target thickness effects very definitely limit the resolution achievable in many experiments.

For light beams energy straggling is the predominant effect, whereas for heavier beams ($Z \gtrsim 36$) multiple scattering is the chief cause of energy dispersion. For example the finest resolution obtainable for ^{12}C on gold is limited to around 2×10^{-4} due to energy straggling while for a ^{238}U beam on a gold target multiple scattering limits the resolution to 5×10^{-4} . It has been seen that these effects, which limit the target thickness, and heating of the target, which limits the maximum beam current, combine to make high resolution solid target experiments extremely difficult to perform. Moreover the beam heating leads to increasingly longer running times for heavier ion experiments because the intensity must be progressively lowered (e.g. by a factor of 20 between C on Au and U on Au) to keep from melting or vaporizing the target. Use of a gas or vapor target improves the situation, but at the present state of development of these targets only a very limited number of elements can be used as target materials.

We have concluded from the above estimates that at this point in the development of heavy-ion physics the limiting factors in high resolution particle experiments do not lie in the accelerator itself but rather in the manner in which heavy-ion beams must interact with the usual target materials. It would appear therefore that more effort should be expended on solving the target problems, and, more generally in feeling out what types of heavy-ion experiments can be most successfully performed under these limitations. It is quite possible that new techniques which might be developed will require accelerator qualities that are entirely different from those that are at present considered important.

We have purposely focussed the discussion on one of the areas of heavy-ion physics (high resolution particle spectroscopy) which requires the highest beam qualities and most stringent target requirements. Our rather pessimistic conclusions about the inherent limitations in this area do not apply to most other areas that do not require high resolution beams. Examples of fields with less restrictive beam resolution requirements are the many types of beam-foil spectroscopy and x-ray studies that are becoming possible with heavy-ion beams, all forms of gamma-ray, gamma-gamma and particle-gamma coincidence studies (such as Coulomb excitation and $(HI, xn \gamma p \gamma)$ reactions), perturbed angular distribution studies for magnetic and electric moments, particle-induced fission studies, isomer and spontaneously fissioning isomer studies, radiochemical and track detector studies, the many types of reaction mechanism studies, and of course isotope production (including super-heavy elements). The fact that high resolution particle spectroscopy will be more difficult with heavier ions has always been clear and means only that less emphasis will be placed on this area than has been the case in light-ion physics. Thus from a general viewpoint the rather sobering conclusions reached in this report do not significantly diminish the excitement and promise of heavy-ion physics.

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Table V

Maximum Gold Target Thickness ($\mu\text{g}/\text{cm}^2$) to Keep Energy Dispersive Effects
to within 0.03%

(The numbers in columns A and B give the contributions only from the effect named
at the top of the column.)

Beam	A Straggling	B Multiple Scattering at $\theta_{\text{lab}} = 20^\circ$		Greatest possible thickness, considering both A and B	
		Au	Au + Backing	Solid Target	Gaseous Target
C	22	3800	3800	22	28
Ar	35	340	340	35	45
Kr	80	63	55	30	40
Xe	125	21	15	10	21
U	170	4	--*	--	4

* Best possible resolution for solid target is 5×10^{-4} , for zero gold thickness
(caused entirely by scattering in carbon backing).

Table VI

Gold Target Thicknesses and Corresponding Maximum Beam Currents for Experiments with
Best Attainable Resolutions from 0.015% to 0.07%

(Note that unless otherwise specified the targets are mounted on a $10 \mu\text{g}/\text{cm}^2$ carbon backing).

Beam	0.015%		0.03%		0.05%		0.07%	
	Thickness ($\mu\text{g}/\text{cm}^2$)	Max. Beam (pna)*	Thickness ($\mu\text{g}/\text{cm}^2$)	Max. Beam (pna)	Thickness ($\mu\text{g}/\text{cm}^2$)	Max. Beam (pna)	Thickness ($\mu\text{g}/\text{cm}^2$)	Max. Beam (pna)
C	.4	7000	22	4000	65	2400 (1000)†	150	1650 (420)†
Ar	1.1	1000	35	600	100	320 (100)†	220	230 (50)†
Kr	1.0	430	30	230	100	130	220	90
Xe	---	----	10	220	45	130	100	75
U	---	----	--	----	6.4**	115**	12	100

* Particle nanoamperes.

† Beam corresponding to targets without carbon backings. (Note that carbon serves as an efficient radiator when it is not required for target support.)

** Figures represent 0.06% resolution for uranium.

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Table VII

Comparison of Counting Times for Experiments with Solid and Vapor Targets
 (Beam time necessary to accumulate 1000 counts, i.e. 3% statistics)

Beam	$\Delta E/E = 0.03\%$		$\Delta E/E = 0.07\%$	
	Solid Target	Vapor Target	Solid Target	Vapor Target
C	5.2 min	25 sec	1.8 min	5 sec
Ar	22 min	2.6 min	8.8 min	30 sec
Kr	60 min	26 min	22 min	5 min
Xe	12 hours*	5.6 hours	57 min	54 min
U	-----	230 hours	77 hours*	40 hours

* Limited by expected beam intensities.

Appendix A - Energy Straggling Calculations

The expressions given by Seltzer and Berger¹⁴ to evaluate κ and ξ , the quantities in which the Vavilov distributions are parametrized, are valid for singly charged particles (protons or mesons). However, by scaling their formulas by z^2 , where z is the projectile charge, the expressions become valid for all projectiles with energies sufficiently high that they are fully stripped of atomic electrons while traversing the target. As these conditions are not met for heavier ions, it is necessary to extend the theory. Noticing the direct correlation between ξ and the mean energy loss $\bar{\Delta}$ (Seltzer and Berger's equations 2 and 3), it was decided to calculate ξ using energy loss values given in the Northcliffe and Schilling tables.²² As these tables calculate the most probable energy loss, the assumption is most accurate where this quantity is close to the mean energy loss $\bar{\Delta}$. In the range where the Vavilov distribution is Gaussian, the case for most very heavy ions through reasonable targets, this is in fact the case. For asymmetric distributions, $\Delta_{\text{most probable}} \neq \bar{\Delta}$, but these cases are most often encountered for light ions, where it is more likely that the projectile will be fully stripped, and so the original equations can be utilized.

A recent experiment at the 88-inch cyclotron has afforded an opportunity for checking calculated numbers.²³ A system resolution of 60 keV (0.08%) was measured for inelastically scattered 78 MeV carbon ions from a 75 $\mu\text{g}/\text{cm}^2$ ¹⁵²Sm target on a 10 $\mu\text{g}/\text{cm}^2$ carbon backing. Instrumentation, mainly spectrometer resolution, detector spatial resolution and electronics, contributed 40 ± 10 keV to the 60 keV total figure. The value of 33 keV calculated from the above theory for energy straggling in the target accounts very well for the remaining contribution to the total resolution. Note that the multiple scattering contribution is expected to be minimal for carbon beams, so that energy straggling is the primary mechanism for energy broadening in the target.

It is expected that for the wide range of ions considered the energy straggling numbers calculated from this theory are probably accurate to no better than about 20%, but in any event the conclusion that energy straggling is a problem for high precision experiments with heavy ions will still hold.

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Figure Captions

- Fig. 1 Resonance in elastic scattering of 14.2 MeV protons from ^{12}C measured at 165° (lab).⁵
- Fig. 2 Principle of dispersion matching in a beam analysis and spectrometer system.
- Fig. 3 Energy straggling of heavy ion beams at 5.0 MeV/A energy through gold targets. Straggling is given in terms of the spread in energy as a percentage of the total incident energy. Dotted lines correspond to thin gold targets mounted on a carbon backing $10 \mu\text{g}/\text{cm}^2$ thick.
- Fig. 4 Sensitivity for heavy ion experiments, as a function of experimental resolution, given as the counts per second recorded in a spectrometer with a 2 milliradian opening angle ($\frac{d\sigma}{d\Omega} \approx 1 \text{ mb/sr}$). The count rates are proportional to the product of the beam currents and target thicknesses given in Table VI. All targets are assumed to be mounted on a carbon backing. Count rates for carbon and argon experiments with thick targets without carbon backings are also shown. It is seen that carbon acts as a good heat radiator so that greater beam intensities can be used.

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XBL687-3260

Fig. 1

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XBL734-2743

Fig. 2

XBL733-2449

Fig. 3

XBL 734 - 2727

Fig. 4