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HEAVY ION SPECTROMETER AT THE SUPERHILAC

Joachim M. Nitschke

May 1976

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HEAVY ION SPECTROMETER AT THE SUPERHILAC

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May 1976

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This report was done with support from the United States Energy Research and Development Administration.

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I. SUMMARY

A spectrometer for the SuperHILAC would have the following principal features:

(1) Physical separation between the primary beam and the recoil products if these differ in one or more of the following parameters: velocity (v), energy to charge ratio (E/q), or mass to charge ratio (m/q). The suppression of unwanted particles will depend on the extent to which they differ from the desired particles in these three quantities.

(2) Mass determination up to the superheavy element region with unit mass resolution.

(3) Physical separation of masses according to their m/q values for further study of decay modes.

(4) Z-identification. The Z-resolution will depend on the details of the reaction and the construction of the spectrometer. In favorable cases unit Z-resolution up to Z = 100 can be expected.

(5) The full angular range from 0° to approximately 160° can be studied.

(6) All particles which can be accelerated by the SuperHILAC can be analyzed. This includes 2 GeV uranium.

II. THE BASIC CONCEPT

Limitations imposed by target thickness and uniformity, scattering and straggling, beam quality and beam intensity, high coulomb barriers, kinematic broadening, etc. make it advisable to consider - as the first spectrometer for the SuperHILAC - an instrument with moderate energy resolution but great flexibility as a kinematic tool.

The basic concept is therefore a velocity filter coupled with a magnetic spectrometer. (Fig. 1) The whole instrument is dispersionless in energy and constitutes a recoil mass spectrometer. Moderate energy information will however be obtained from the focal-plane detector and/or time of flight measurements.

The following is a brief description of the principle of the spectrometer. The electrostatic deflection in the velocity filter can be expressed as

$$F\rho = \frac{mv^2}{q}$$

the magnetic deflection as

$$B\rho = \frac{mv}{q}$$

F is the electric field, all other letters have the usual meaning.

The principal components of the spectrometer consist of one electrostatic followed by two magnetic deflectors.

A variation in the electric rigidity can be expressed to first order as:

$$\frac{\Delta(F\rho)}{F} = K_{el}\left(\frac{\Delta m}{m} + \frac{2\Delta v}{v}\right)$$

K is the dispersion constant. This is followed by a magnetic field. Its variation in rigidity is expressed as:

$$\frac{\Delta(B\rho)}{B} = K_{mag}\left(\frac{\Delta m}{m} + \frac{\Delta v}{v}\right)$$

If the magnetic is opposite and equal to the electric dispersion $K_{el}=-K_{mag}$ one obtains a pure velocity spectrum (the $\Delta m/m$ - terms cancels). The second magnetic dipole is identical to the first one and compensates the remaining velocity dispersion so that a pure mass spectrum results. Schematically this can be written as:

$$\frac{\Delta(F\rho)}{F} - \frac{\Delta(B\rho)}{B_1}_1 - \frac{\Delta(B\rho)}{B_2}_2 = - \frac{\Delta m}{m}$$

All mass lines in the focal plane will however be split into "multiplets" according to their ionic charge. In some cases these lines will overlap. To remove this charge ambiguity a time-of-flight system forms an integral part of the spectrometer. Start detectors can be located behind the E/q-slit and/or the velocity slit. The focal-plane detector acts as a stop-detector. In addition the focal-plane detector allows a coarse energy measurement. This coarse energy measurement ($\tilde{E}$) and the velocity measurement from TOF result in a coarse mass determination ($\tilde{m}$) which allows to resolve the m/q ambiguities. Schematically:

$$\tilde{E} + v\ (TOF) = \tilde{m}$$

$$\tilde{m} + m/q \rightarrow m$$

The "exact" energy of the particle can then be obtained from

$$m + v\ (TOF) = \rightarrow E$$

Two modes of operation of the spectrometer are anticipated. For compound nucleus reactions and other reactions near zero degrees a beam inflection system will be

used which scans a moderate range of -5° to $+ 30^{o}$. For studies at angles larger than 30° the first part of the spectrometer (the electrostatic deflector) will be bypassed and the second part used as an "ordinary" magnetic analyzing system. The angle over which this magnetic part of the spectrometer can turn will be as large as practical: -10° to approximately $+160^{o}$. The idea here is that for large angles the beam separation afforded by the electrostatic deflector is not necessary because the intensity of the scattered beam falls sharply with increasing angle.

III. SCIENTIFIC JUSTIFICATION

As outlined in the previous section the proposed spectrometer will be able to separate particles according to their energy (E/q), velocity(v), and mass(m/q). These properties have different importance for the large variety of possible heavy ion reactions.

Following a treatment by W. J. Swiatecki and C. F. Tsang heavy ion reactions can be classified by an increasing mixing of nuclear matter as shown schematically in Fig. 2. The spectrum of reactions for which a spectrometer can make significant contributions reaches from grazing collisions where nuclear densities barely touch and only few nucleons are exchanged to compound systems where target and projectile have lost their identity completely.

1. Grazing collisions:

One of the dominating features of grazing collisions is the transfer of one or more nucleons between target and projectile. The other is the excitation of rotational levels by coulomb interaction. With very heavy projectiles the interesting situation occurs, that the target may be coulomb excited to higher states before transfer occurs. By studying transfer reactions on excited rotational states one should be able to learn something about the super fluid properties of these states. For studies of this kind it is however necessary that an instrument with single mass resolution be available. For very heavy ions this can only be achieved with a spectrometer.

2. Composite systems

As the overlap of nuclear densities increases larger amounts of nuclear matter are exchanged. This is however not only a function of overlap but also of contact time and is therefore seen by L. G. Moretto as a form of nuclear diffusion process. Part of the experimental evidence is, that target and projectile maintain some of their initial identity in the reaction exit channel. For light projectiles successful studies of this reaction mechanism has been possible with (gas-ΔE)-E detector systems, giving however only Z-identification. Since masses are not determined the transformation from laboratory to center of mass system is uncertain and thus the reaction kinematics. Also neither Z nor A can be determined with sufficient resolution for the heavy partner and it is not known how much particle evaporation occurs. A coincidence arrangement between the (gas-ΔE)-E telescope and a spectrometer could alleviate some of these uncertainties. In the optical model picture (R. Vandenbosch) it is thought that surface transparency is responsible for the sharply peaked angular distributions seen for instance in the deep inelastic scattering of Kr on Pb. This phenomenon might be enhanced where target and projectile are of comparable mass. In this case the large separating power between beam and reaction products of the spectrometer becomes important. This is based on the observation that a rapid relaxation of the entrance channel kinematic energy into the internal degrees of freedom occurs. And since the spectrometer operates predominantly on energy and velocity differences it would be well suited for the study of this type of reaction mechanism.

All of these highly inelastic processes show a broad distribution in charge and mass as well as in energy, and the spectrometer has to be optimized so as to accept as large a "bite" of these parameters as practical. For the investigation of high angular momentum fission - be it of the fusion-fission or the quasi-fusion type - the zero degree properties of the spectrometer become important. Since the angular distribution is forward peaked the highest yield for the study of these fragments is obtained at zero degrees.

3. Quasi symmetric reactions and inverse fission. According to J. R. Nix one of the best ways to obtain experimental information about the nuclear potential energy of deformation, the nuclear inertia, and nuclear viscosity is to measure the cross-section for compound nucleus formation in the collision of two nearly symmetric moderately heavy nuclei, because a necessary condition for forming a compound nucleus is that the dynamic trajectory for the fusing system pass inside the fission saddle point (in a multi-dimensional space). An example of a proposed reaction is $^{110}Pd + ^{110}Pd \rightarrow ^{220}U$. The spectrometer would provide sufficient background suppression to make the observation of such a compound system possible. If the α-halflife of ^{220}U is too short (estimate ∿3ns) $^{124}Sn + ^{124} \rightarrow ^{248}Fm^*$ could be studied.

A reaction quite different from the above but requiring the same detection apparatus can be explored with deformed nuclei. In the collision of such nuclei with deformed targets at the lowest energy at which the nuclear reaction will occur, the contributing collisions will be of the tip-to-tip type - termed by J. O. Rasmussen: inverse fission. Other orientations

will not contribute to the reactions because the surfaces are not close enough together.

4. Reverse reactions and secondary reactions. Two somewhat exotic reaction mechanisms which could benefit from a spectrometer will be discussed briefly. A classical compound nucleus reaction is for example $^{208}Pb(^{48}Ca,3n)^{253}No$. Having a lead-beam available however the inverse reaction $^{48}Ca(^{208}Pb,3n)^{253}No$ can be studied. Because of the much higher forward momentum of the product, thicker targets can be used and a lead-beam might be less expensive than ^{48}Ca. The recoil energy in the "normal" reaction is 170 KeV, in the reverse reaction it is 3.1 MeV. The ratio of the recoil energies for a given reaction goes as the square of the ratio between target and projectile masses, which in the Ca-Pb example is 18.7. The higher recoil energy greatly inproves the energy resolution in a focal-plane-stop detector and makes Z-identification up to Z = 100 possible. In some cases even radioactive targets could be used with the reverse reaction mechanism while it would be highly impractical to produce radioactive beams for the "normal" reactions. To take full advantage of this method however particles of similar mass (in the above case mass 208 and 253) have to be separated efficiently which can only be done with a spectrometer.

The second exotic mode of operation is based on the following idea. Since the spectrometer consists essentially of two idependent sections - a velocity separator and a magnetic analyzer, it is possible to produce secondary beams of proton or neutron rich projectiles which could react with a second target.

For example one could think of passing a ^{48}Ca beam through a ^{238}U foil to produce ^{50}Ca. The ^{50}Ca is separated from the ^{48}Ca beam by the velocity filter and impinges on a ^{244}Pu target. The analyzing magnet then separates the compound nucleus $^{294}114$. This nucleus would be within 4 neutrons of the predicted doubly magic nucleus $^{298}114$. Other applications of secondary beams can be foreseen.

5. Compound nucleus reactions. The strong points of the proposed spectrometer become particularly apparent when the study of compound nucleus reactions is considered.

The reaction products are sharply forward peaked and have a velocity which is drastically different from the beam. This allows for large separation factors and the study of small cross-sections. Because of competing charged particle emission either in the compound-or precompound state as well as transfer reactions which will occur with high cross-sections, mass determinations in the heavy element region is vital. Furthermore the actual physical mass separation allows the study of decay mechanisms in the focal plane.

In the region of lighter elements the exploration of the onset of general nuclear instability is of great interest, for instance in nuclei whose ground states are proton radioactive. According to J. Cerny mass analysis is essential in these studies due to the prolific yield of beta delayed proton emitters nearer stability, which constitute an overwhelming "background". The advantage of the spectrometer over the existing RAMA system would be the higher efficiency (factor 10) and the short separation time of approximately 1μs (factor 10^5).

6. Superheavy elements. The predicted center of the island of stability is at N = 184, Z=114. If such a nucleus could be formed it would - without a spectrometer - be difficult to determine its mass or nuclear charge. If the halflife were sufficiently long chemical studies could lead to a Z identification. A study of the decay properties would then reveal its identify (fast α-decay, high α-energies, large fission energy, α-f-sequence, large neutron multiplicity, K,L-X-ray measurements). For a timescale down to approximately 100ms a He-jet system could be used relying again on decay properties for identification. With the spectrometer however the mass of the superheavy element could be determined to within one mass and in addition its decay modes could be studied. The background due to scattering will determine the lower limit of the cross-sections which can be measured.

Another method of superheavy production is the collision of two heavy nuclei like U + U. The idea is that there is a finite probability that among the fission fragments a sufficiently "cold" nucleus with low angular momentum will survive secondary fission. To study this effect the yield of "intermediate" heavy nuclei like ^{259}Fm has to be studied. Since many of these nuclei are short-lived, off-line techniques cannot be used, a He-jet system or a spectrometer are required.

IV. SPECIFICATIONS

The spectrometer should be capable of analyzing all particles at the maximum energy the SuperHILAC can deliver, including Uranium at 8.5 Mev/A. The magnetic and electric rigidities are then determined under the assumption that the beam is always stripped by the target. The cost of the instrument is largely determined by the desired acceptance angle, in particular when good isochronism and small aberrations in the magnetic analyzer are of importance. Dispersion, energy acceptance, and magnification are linked in the following way:

The position resolution of focal-plane detectors is approximately 1mm. In order not to limit the resolution of the instrument by the resolution of the detector a mass-line separation of 3mm is required. To achieve a mass resolution of $m/\Delta m = 300$ the dispersion has to be 1cm/%. It then follows that the magnification has to be 1 for a target size of 3mm.

As indicated before the mass dispersion equals the velocity dispersion which then becomes also 1cm/%.

The energy dispersion is twice the velocity dispersion viz. 2cm/%.

Considering ion optical aberrations, the size of the quadrupole apertures, and the vacuum chamber, the maximum excursion of the beam at the E/q - focus has to be limited to approximately 20cm. This results in an energy acceptance of 10%.

The maximum necessary inflection angle for the velocity filter is determined by Rutherford scattering Considering the worst case: Uranium on Uranium near the coulomb barrier, it can be calculated that at 30° the contribution from coulomb-scattering and multiple scattering becomes so small that it can be discriminated against with the spectrometer.

The angular range of the magnetic analyzing system will be made as large as practical.

The energy resolution is largely determined by the quality of the time of flight measurement.

Summary of the Specifications:

Mode I = velocity separator and magnetic analyzer

Mode II = magnetic analyzer only

		Mode I	Mode II
1)	Solid angle	$\geq$ 1msr	$\geq$ 2msr
2)	Energy acceptance $\frac{\Delta E}{E}$	10%	$\geq$ 10%
3)	Maximum magnetic rigidity	1.6 Tm	1.6 Tm
4)	Maximum electric rigidity	63 MV	63 MV
5)	Dispersion (D)		
	Energy	$\geq$ 2 cm/%	$\geq$ 2 cm/%
	Mass	$\geq$ 1 cm/%	---
	Velocity	$\geq$ 1 cm/%	---
6)	Magnification (M)	1	1
7)	D/M	1 m	1 m
8)	Inflection angle	-5° to $+30^{o}$	-10° to $+160^{o}$
9)	Radii		
	electrostatic	10 m	---
	magnetic	1 m	1 m
10)	Bending angles		
	electrostatic	2×10°	---
	magnetic	$2 \times 10^{o} + 2 \times 90^{o}$	2×90°
11)	Energy resolution	approx. 1%	approx. 1000

V. COST ESTIMATE FOR THE SPECTROMETER

1)	Beam Transport System		$ 92,750
	Magnets - 2 dipoles	$35,000	
	Magnet dipole PS:10^{-4} reg.	16,500	
	Quadrupoles 4 QD, QS	14,500	
	Quad PS	11,250	
	Steering Magnets (4 sets)	2,000	
	Steering Magnet PS	1,500	
	Vacuum System	5,000	
	Instrumentation	5,000	
	Wiring & Utilities	2,000	
2)	Target Chamber Apparatus		147,500
	2 inflection magnets	30,000	
	2 inflection magnet PS	15,000	
	1 target chamber w. sliding seal	45,000	
	Sliding seal & vac for switch magnet	25,000	
	Pad & drive mechanism	25,000	
	Electronic installation	7,500	
3)	Velocity Filter & Spectrometer		428,750
	3 electric dipoles	30,000	
	± 300 kV, 1 mA, PS:10^{-4} reg.	75,000	
	± 100 kV, 1 mA, PS:10^{-4} reg.	11,250	
	5 singlet quads	20,000	
	Quad PS	15,000	
	2 spectrometer magnets	60,000	
	2 spectrometer magnet PS: 10^{-5} reg.	30,000	
	Vac equipment	15,000	
	Instrumentation	15,000	
	Wiring & interlock	7,500	
	Spectrometer drive	30,000	
	Focal plane detector	75,000	
	Target chamber w. sliding seal	45,000	

4)	Control System		$ 46,100
	1 cluster	$18,000	
	"4-knob" TV terminal	5,000	
	Aydin terminal	5,000	
	Decwriter & interface	3,100	
	Misc. controllers & interfaces	10,000	
	Installation	3,000	
	Documentation	2,000	
			715,100
	EDI & A on 1-4 (25%)		178,800
	Contingency 1-4 (25%)		223,500
5)	Shielding for Spectrometer		100,000
	Walls	40,000	
	Roof	60,000	
	EDI & A (20%) on 5		20,000
	Contingencies (20%) on 5		24,000
	Total cost ('75 dollars)		$1,261,400
	General Plant		180,000

July 2, 1976

ACKNOWLEDGMENT

The author wishes to thank Professor Harald Enge, MIT, for the excellent cooperation during the development of this project. It is he who proposed the velocity matching between the Wien-filter and the magnetic dipole as well as the ion optical calculations.

FIGURE CAPTIONS

Fig. 1 - Schematic layout of the proposed Hilac spectrometer

Fig. 2 - Classification of heavy ion reactions

Fig. 3 - Location of the proposed heavy ion spectrometer

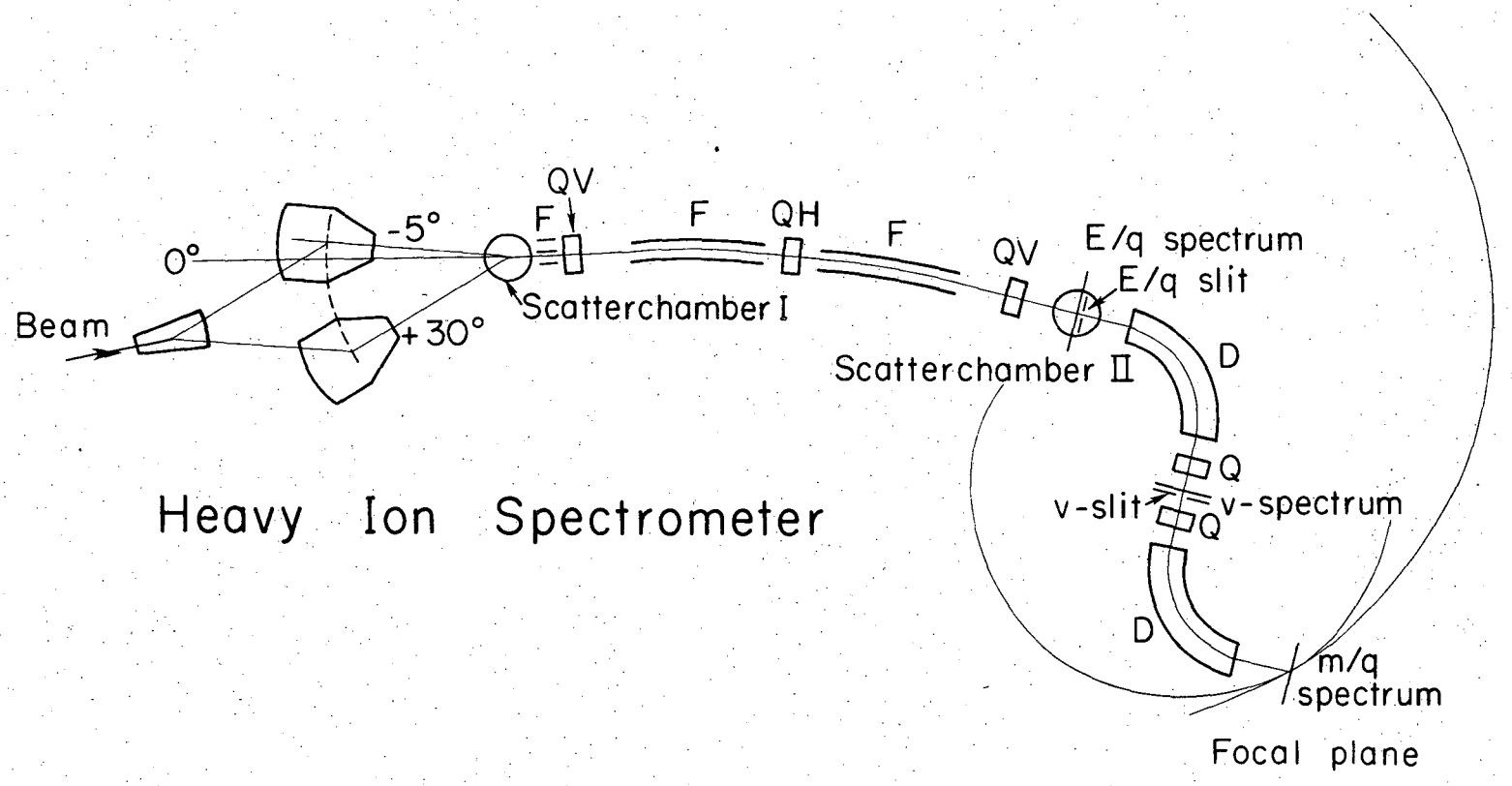

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Figure 1

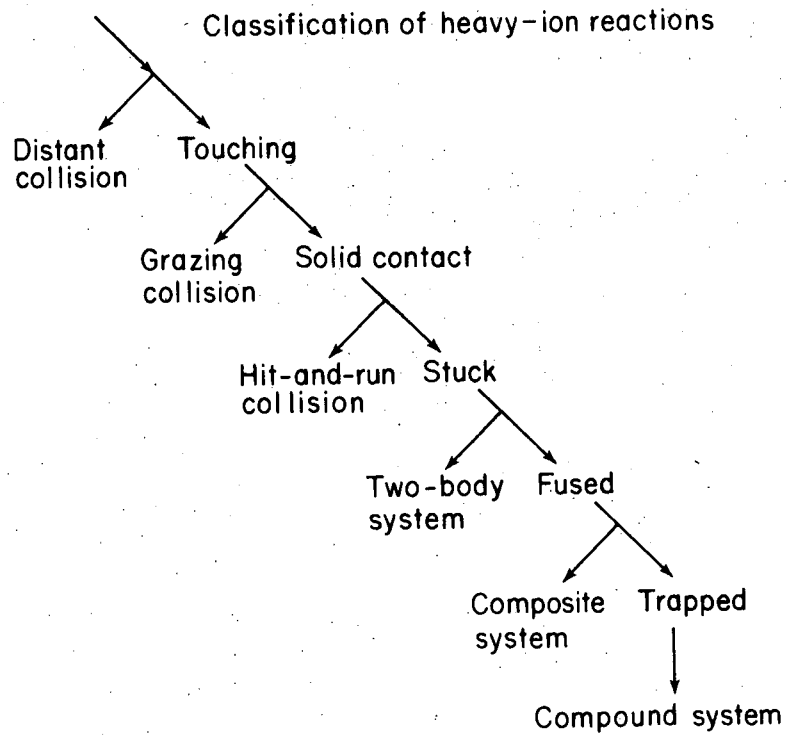

Figure 2

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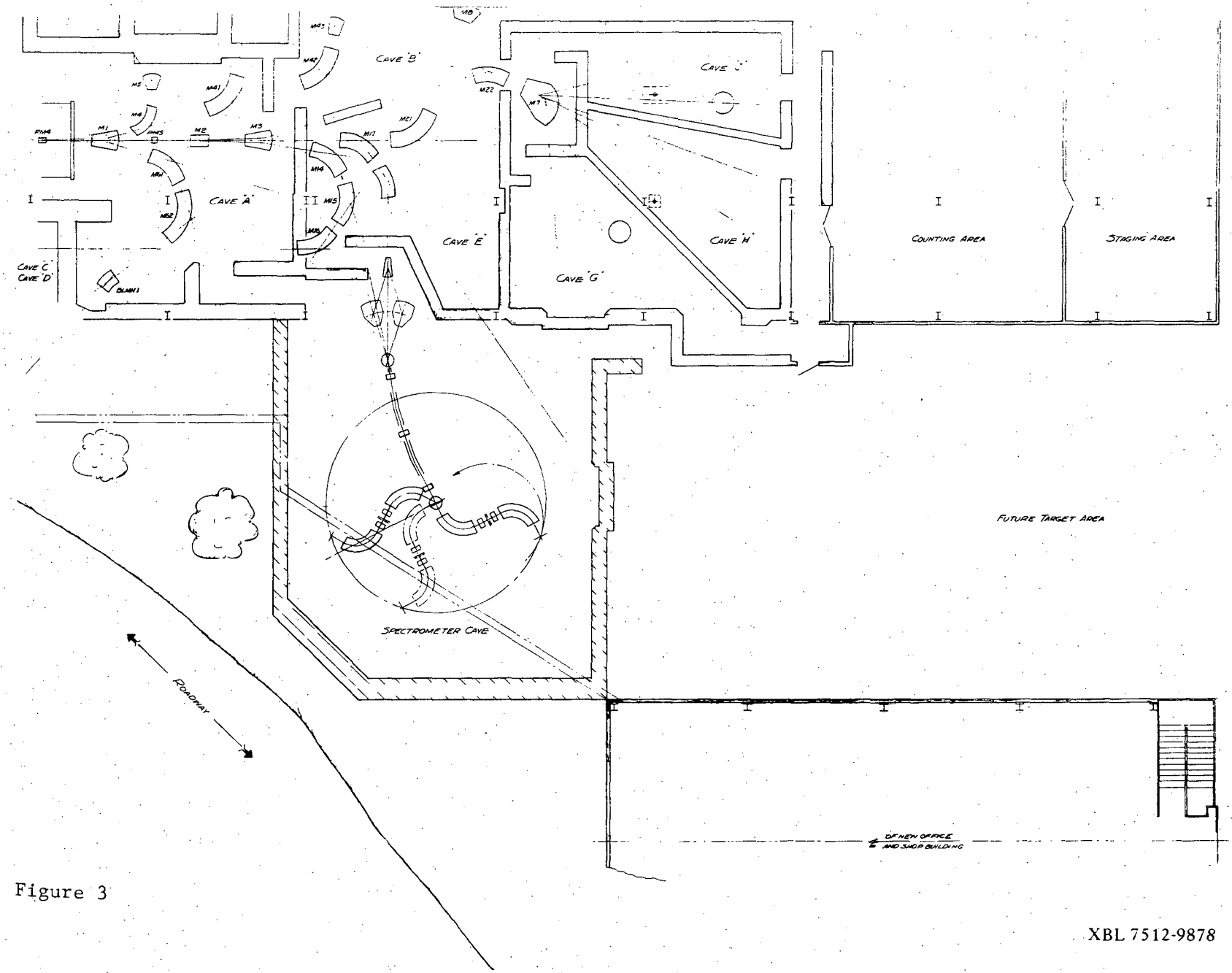

Figure 3

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