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Reactions of Complex Nuclei with Pions in the Hundred GeV Range

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Summary

The objective of this experiment is to obtain information on the details of pion-complex nucleus interactions at hundreds of GeV by measuring the yields of residual nuclei and comparing them with the yields of the same products when protons of similar energy are used. The yields are to be determined by radiochemical techniques.

Previous studies have established that: a) the total pion cross section is smaller than the proton cross section on the same nuclei. Presumably this is a result of the free pion-nucleon cross section being smaller than the free nucleon-nucleon cross section. b) the full hadronic shower to be expected from free hadron-nucleon collisions is not fully developed inside nuclear matter.

Although the patterns of yields from proton bombardment of complex nuclei have been surveyed up to 400 GeV (with only small changes established above 12 GeV), there are no such data for pions above a few GeV. If the intra-nuclear cascade induced by pions is characterized throughout by a smaller hadron-nucleon cross section, significantly lower yields of products requiring many collisions in the nucleus should result than when protons are the incident particles. In any case, identification of the products whose yields must go down will add to the information on this problem.

100 hours of irradiation of copper foils, in six 8-hour batches (stage I) and two 24-hour batches (stage II) each with intensities greater than 4×10^6 m^{-1} of π^- are requested. Since the beams should be as free as possible of secondaries and other hadronic particles, the m-2 beam operating on π^- appears appropriate. The targets would be less than 5 g/cm^2 and no heavy equipment would be needed. The experiment could thus be interleaved with other, longer-running experiments. Recovery of the targets by access in less than 15 min after the end of the irradiation would be required.

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I. Science Objectives

Detailed studies of the disintegration of complex nuclei with pions in the GeV energy range have both theoretical and practical interest. On the fundamental side, more detailed data than we have at present can provide information on the interaction of pions inside nuclear matter. On the practical side it may be remembered that the shielding of most FNAL beams involves a cascade, important early steps of which are the interaction of multi GeV pions with complex nuclei.

In the past, studies of high energy pion interactions with complex nuclei have concentrated on the particles emitted in the interaction. The present experiment proposes to obtain information on these interactions through studies of the yields of residual nuclei left over after the nuclear process has been completed. Comparisons of the yields of radioactive products produced with hundred GeV pions will be made with those produced by hundred GeV protons, leading to information about some of the details of what went on inside the nucleus.

Present knowledge about the interactions of high energy pions with complex nuclei is confined to average quantities such as total cross sections, numbers and rapidity distribution of fast prongs and some information about average excitation energy left behind in the nucleus as evidenced (e.g.) by numbers of evaporation prongs in emulsion or bubble chamber pictures.

On the other hand, the gross data available on both proton and pion interactions with complex nuclei suggest that the nucleus is an interesting laboratory in which to study the properties of matter. For example, the multiplicities of pions produced in complex nuclei at hundreds of GeV suggest that the multiplicities observed in free hadron hadron collisions are not effectively achieved in the space-time between collisions inside nuclear matter.[1]

It is also pertinent that at these energies the pion nucleon total cross section is about two-thirds of the nucleon nucleon cross section. Presumably this is the basic explanation for the total cross section of complex nuclei for pions being smaller than the cross sections for protons.[2] For example, the total inelastic cross section of copper is 800 mb for protons at 60 GeV and 650 mb for π^+ at 50 GeV. This experiment proposes to establish which yields of residual nuclei are affected by these differences in total inelastic cross sections. The mass change from that of the target nucleus can be expected to reflect the number of nucleons in the nucleus that participated in the intranuclear cascade. Table I presents the results of a simple calculation comparing the probabilities for n collisions in copper when the incident particle is a pion with the probability for the same number of collisions when the incident particle is a proton. In this calculation it was assumed that the number of nucleons struck on a straight line path through the nucleus is determined by the original free hadron-nucleon cross section. Thus, if this is the mechanism, the results of this calculation suggest that products with masses far removed from the target nucleus (e.g. ^{24}Na from ^{63,65}Cu) will have significantly lower yields as a result of pion interactions with copper than if protons are the bombarding particle. Products with small mass change (e.g. ^{61}Cu) may actually increase slightly in yield.

On the experimental side the gross yield patterns from 400 GeV proton interactions with selected complex nuclei have been studied. They show little change from the results at 10-20 GeV. For example, figure 1 shows, for cobalt irradiated with protons, the ratio of the yields at 300 GeV to those at 11.5 GeV as a function of mass number.[3] Similar results have been obtained from gold.[4] On the other hand, there are no published data on pion spallation yields above a few GeV. Thus, at the very least, this experiment should fill a gap in our empirical data on the products of high energy hadron interactions with complex nuclei.

The principal experimental problems will be the low intensities of the pion beams, their purity from other hadronic particles, and finally, undesirable effects of secondary particles born inside the target materials themselves. These considerations suggest that these experiments be performed in the m-2 beam with π^- particles and with relatively thin targets as far away as possible from materials producing secondaries. The comparison runs, with ~300 GeV protons on copper, can be performed, on a non-interfering basis, in the Nuclear Chemistry Train Targeting Station (Expt. 81a), upstream of the meson production target (m-1 service area).

II. Experimental Details

A. Target Materials and Arrangements

It is proposed to use copper as a target and π^- and proton beams as irradiating particles. Copper has been chosen because, although no spallation studies have been done with protons in the 100 GeV range, it has been extensively studied at lower energies (e.g. at 24 GeV by Rudstam et al.[5]). In addition, the highest energy pion spallation studies (2-3 GeV π^+ and π^-) on any complex nucleus are on copper.[6] Copper is available in high purity and in very thin foils and wires that may be needed to cut down on secondary effects. Although not mono-isotopic, copper has convenient radioactive spallation product nuclides that cover the mass range from A = 7 to 61 and 64 (see Table II), thus providing a sample of products reflecting both small and large nuclear damage effects. For example, the yields of ^{57}Co, ^{58}Co, ^{57}Ni, ^{61}Cu and possibly ^{64}Cu should reflect nuclear interactions involving small numbers of primary hadron-nucleon collisions, whereas the yields of nuclides such as ^{24}Na, ^{43}K, ^{43}Sc, ^{47}Sc may well reflect more extensive intra-nuclear cascades.

The total inelastic cross section of copper for 60 GeV protons is 800 mb;[2] that for 50 GeV π^+ is 650 mb.[2] In order to pick up the indicated ~20% differences in yields, comparative measurements on the same nuclides (using the same measurement techniques) produced by protons and pions will be made. In order to avoid the errors in absolute measurements of incident particle fluxes, the ratios of production yields as a function of mass number will be determined. With careful work, comparative ratios should be determinable to about 10% or better.

The relatively low pion beam intensities available ($\sim 10^6$ m^{-1}) would ordinarily suggest the use of thick targets in order to form products in adequate amounts to measure their radioactivity accurately. However, at multi-GeV energies, 10-20 fast secondaries are produced per nuclear interaction. These are very forward directed, and although mostly pions themselves, their reactions in the target should be minimized since they are of lower energy than the primary beam. In addition, there are similar numbers of nuclear cascade and evaporation particles (neutrons, protons, alphas, etc.) produced. Most of these are relatively isotropically emitted. In order to avoid dilution of the effects of the primary interactions by secondary effects produced by both types of particles, thin targets must be used. A possible compromise is an arrangement of fifteen ½ cm diameter copper discs, each 200 mg/cm^2, spaced about 13 cm apart, giving a total length of about two meters for the target arrangement. Since the m-2 pion beam has dimensions of only a few mm near the focal points, such an arrangement appears feasible to line up in the beam line.

In order to check that the intensities to be available from an irradiation of 3 $g\ cm^{-2}$ Cu by $10^6\ \pi^-/m$ for 6.5 hrs (an integrated intensity of $>1.2 \times 10^9\ \pi^- \times gm$), an irradiation of 0.1 mg/cm^2 Cu was carried out in the proton beam upstream of the meson producing area (nuclear chemistry train station) with 3×10^{13} protons, thus giving about twice the numbers of interactions being planned for the short irradiation of this experiment. Table 2 lists, in column 3, the observed counting rates (without chemical separation) measured in a GeLi gamma ray spectrometer. With chemical separation and appropriate, more efficient, measurement techniques, the yields of most of these nuclides should be measurable to better than 5% in pion irradiations relative to the yields in a proton irradiation.

Table 2 lists, in addition, other radioactive species for which data may be obtained depending on the intensities available and further considerations of the sensitivities of various measurement techniques.

B. Irradiation Conditions

It is proposed to use the m-2 beam at FNAL for the 200 MeV π^- irradiations. Any convenient energy between 100 and 300 MeV π^- would be suitable, with the momentum range not being critical. This is because the effects being studied are not expected to be energy sensitive. (Proton induced spallation yields are relatively energy independent between 30 and 300 GeV.) Much more important is total intensity and purity of the beam from other hadrons. A minimum intensity of 4×10^6 π^- per min would be needed.

The suggested irradiation layout in the m-2 beam is shown in fig. 2. Minimum mass upstream of the target is required in order to cut down the secondaries in the beam.

In the first stage of the experiment, six 8-hour shifts are asked for, separated by at least a week. In each shift, one hour will be adequate for set-up, provided no heavy apparatus has to be moved from the area of fig. 2. At the end of an ~6.5 hr irradiation, immediate access for ~½ hr will be needed to retrieve the irradiated targets. Since many of the radioactive species are short-lived, this access cannot be postponed.

In a later stage, two 24-hour periods separated by at least two weeks, will be needed to get data on some longer lived radioactive species.

Concurrently, irradiations of thin copper foils with 200-400 GeV protons will be performed at the Nuclear Chemistry train targeting station. These will be treated chemically and measured in the same way as the meson targets, in order to be able to compare the yields of the same products as accurately as possible.

III. Summary of Irradiation Requirements

A. Beam Characteristics

100-400 GeV/c π^-

Absolute Energy and homogeneity not critical.

Purity: <10% other hadrons. Electron contamination acceptable.

Intensity: at least 4×10^6 π^- per min.

Beam size: as small as possible ~6 mm diameter acceptable.

B. Time and Access

~100 hrs total, in beam area, after beam has been tuned, focussed and mapped.

Phase 1: Six shifts of eight hours each, to be spaced at least one week apart.

~1 hr for set up - access required.

6½ hrs irradiation.

½ hr for dismantling - access required immediately after end of irradiation.

Phase 2: Two periods of 24 hrs each, to be spaced at least two weeks apart.

1 hr for set up - access required.

22½ hrs irradiation.

½ hr for dismantling - access required.

C. Beam Area Requirements (see figure 2 for sample arrangement in m-2 beam)

~4 meter length at least several meters away from any significant shower producing material.

D. Radiation Hazards

a. During irradiations, up to 5 g/cm^2 will be irradiated with $\geq 4 \times 10^6$ particles/min, producing consequent spray particles down stream.

b. The meson irradiated targets will be barely measurable and no hazard healthwise.

IV. Time and Effort Commitments

Anthony Turkevich:	Spokesman, supervisor, and participant at ~10% level of his time during the period of the experiment.
Dale E. Boyce:	This work is expected to be the doctoral thesis of Mr. Boyce. He will give essentially full time to the experiment.
John Warren:	~30% of his time would be spent on this experiment until end of sabbatical year in June.
Sheldon Kaufman:	Participation as necessary in the irradiations, chemistry, measurements and analyses.

Other members of Turkevich, University of Chicago, group (T. Economou, J. LaRosa and J. Cadieux) will be available to help during critical times.

V. Support Requirements

Aside from the support connected with beam tuning, focussing, mapping and monitoring (see III, above), the only requirements would be use of some measuring equipment at the Nuclear Chemistry Counting Facility in the Village at Fermilab. Most of the chemistry and measurements of the radioactivity will be performed either at the Fermi Institute, University of Chicago, or at the Argonne National Laboratory.

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4. S. B. Kaufman, et al., Phys. Rev. <u>C14</u>, 1121-1132 (1976).
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TABLE I.

Calculated Cross Sections for n Collisions Of Pions and Protons in a Copper Nucleus

n =	1	2	3	4	≥5
σ_π (mb)	282	167	109	64	53
σ_p (mb)	255	154	120	95	184

TABLE II

Nuclides Detectable in Meson Irradiation of Copper

Nuclide	Half Life	Observed γ-ray Activity*	Prospects for Meson Irradiation**
Be7	53.28 d		
Na22	2.6 y		
Na24	15.02 h	0.43 ± 0.03	✓
Mg28	21.8 h		
S38	2.84 h		
Cl38	37.2 m		
K42	12.36 h		
K43	22.2 h	0.17 ± 0.03	✓
Sc43	3.89 h		
Sc44m	58.6 h		
Sc46	83.8 d	0.008 ± 0.006	
Sc47	3.41 d	0.44 ± 0.05	✓
Sc48	43.7 h		
V48	15.97 d	0.06 ± 0.04	✓
Cr48	22.96 h	0.07 ± 0.05	✓
Cr49	42 m		
Cr51	27.71 d	0.09 ± 0.03	✓
Mn51	46 m		
Mn52	5.63 d		
Mn54	312.5 d		
Mn56	2.58 h	0.63 ± 0.09	✓
Fe52	8.3 h		
Fe59	44.6 d		
Co55	17.9 h		
Co56	78.5 d	0.010 ± 0.006	✓
Co57	271 d		
Co58	71.3 d	0.06 ± 0.02	✓
Ni57	36 h		
Cu61	3.37 h	0.47 ± 0.09	✓
Cu64	12.74 h		✓

*Counting rate (counts min^{-1}) after a sample irradiation of 0.1 mg/cm^2 of Cu by 3×10^{13} protons. Rates are without chemical separations.

**Nuclides for which the short meson irradiations being proposed are expected to lead to at least 10% accuracy in the ratios of production cross sections.

Figure I (ref. 3)

300 GeV and 11.5 GeV protons on Cobalt-59
Ratios of Spallation Cross Sections

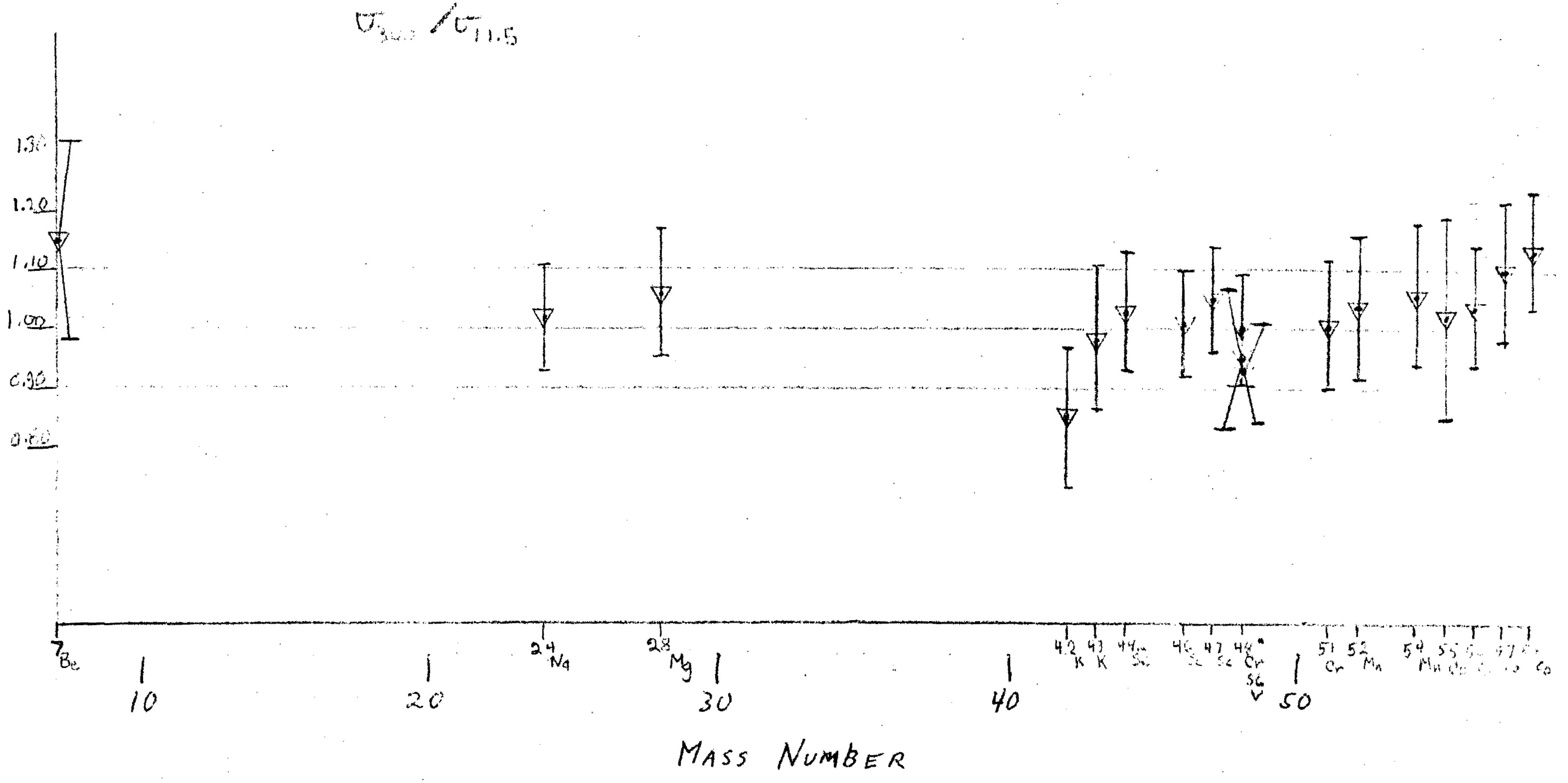

Figure II

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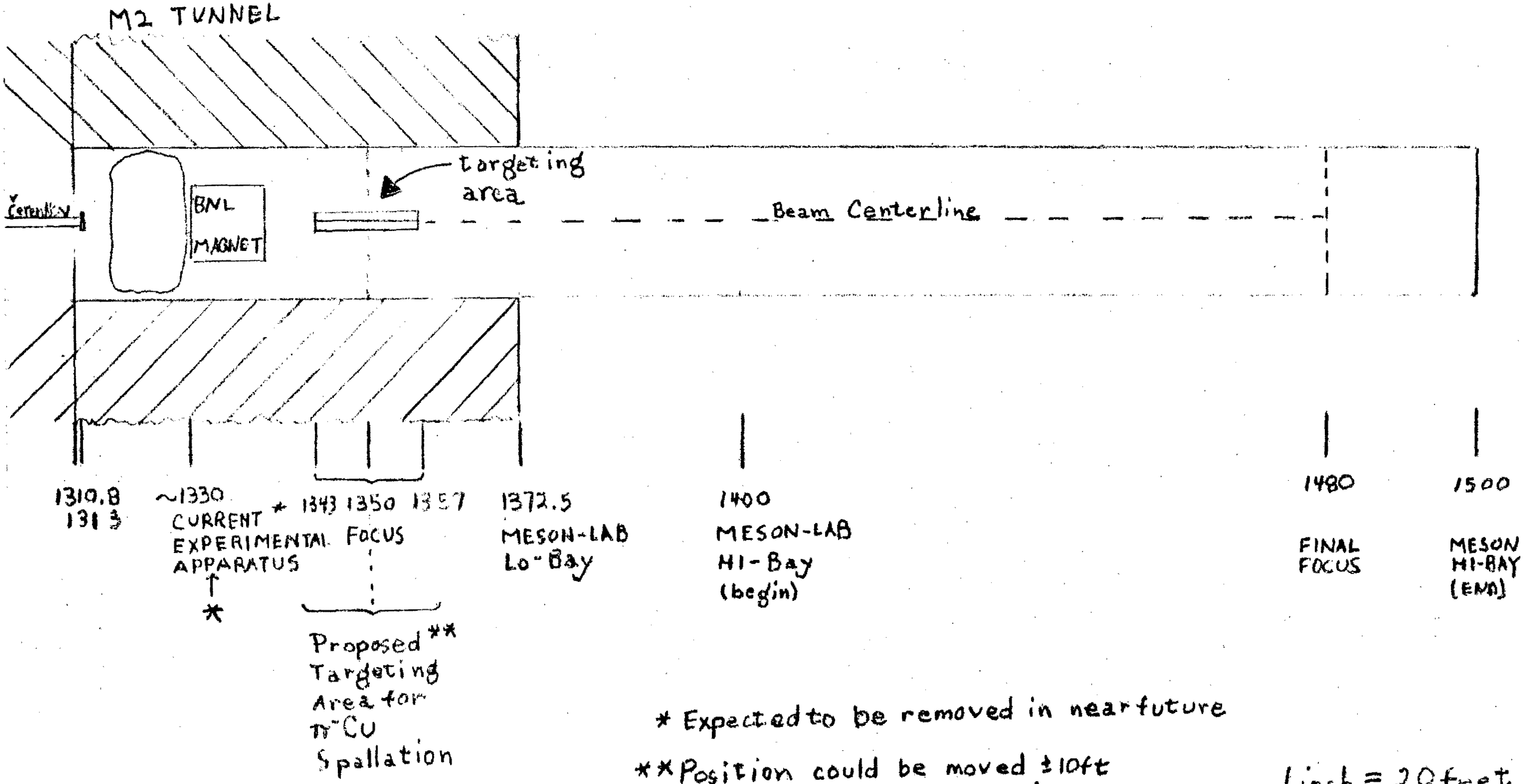
M2 Beamline Layout
for π⁻Cu spallation experiment



* Expected to be removed in near future

** Position could be moved ±10ft depending on presence or absence of other apparatus*

1 inch = 20 feet