Caldwell

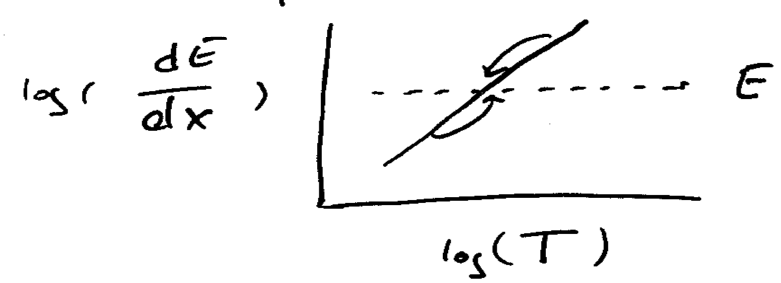
Basic idea: cool muons by working in regime where $\frac{dE}{dx} \propto \beta$

for $\beta_\mu \leq \beta_{e^-}$, ionization no longer possible. Energy loss dominated by

- nuclear recoil
- excitation
- charge exchange (for μ^+) $\mu^+ \to M_\mu \to \mu^+ \ldots$

In regime where $\frac{dE}{dx} \propto \beta$, can imagine applying an E·field which compensates $\frac{dE}{dx}$

$\Longrightarrow$ equilibrium kinetic energy



→ cooling

23.2. Ionization energy loss by heavy particles [4–1]

Moderately relativistic charged particles other than electrons lose energy in matter primarily by ionization. The mean rate of energy loss (or stopping power) is given by the Bethe-Bloch equation,

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right] . \tag{23.1}$$

Here $T_{\max}$ is the maximum kinetic energy which can be imparted to a free electron in a single collision, and the other variables are defined in Table 23.1. The units are chosen so that dx is measured in mass per unit area, *e.g.*, in g cm^{-2}.

In this form, the Bethe-Bloch equation describes the energy loss of pions in a material such as copper to about 1% accuracy for energies between about 6 MeV and 6 GeV (momenta between about 40 MeV/c and 6 GeV/c). At lower energies "C/Z" corrections

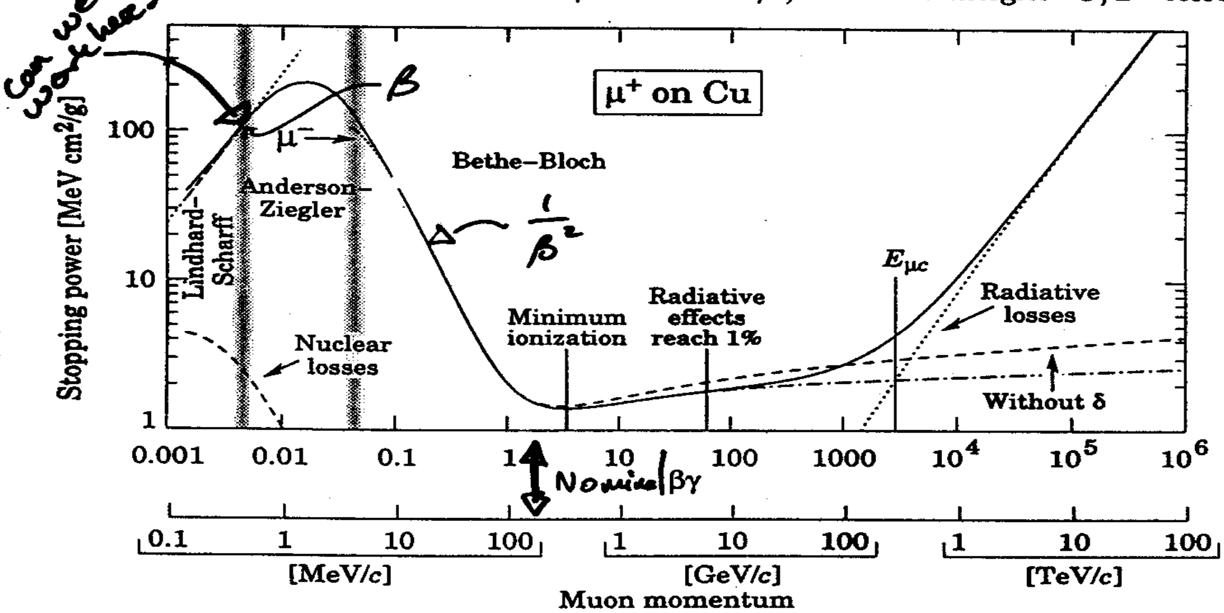


Fig. 23.1: Stopping power ($= \langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy) [1]. Solid curves indicate the total stopping power. Data below the break at $\beta\gamma \approx 0.1$ are taken from ICRU 49 [2], and data at higher energies are from Ref. 1. Vertical bands indicate boundaries between different approximations discussed in the text. The short dotted lines labeled "μ^-" illustrate the "Barkas effect," the dependence of stopping power on projectile charge at very low energies [3].

Issues/comments:

- $\frac{dE}{dx}$ very large in this region
  $\Rightarrow$ need to work with gas

- Lifetime of $\mu^\pm$
  $$v\tau_\mu = 0.1\sqrt{T(eV)}\ m \quad \Big\}\ T \ll mc^2$$
  $\Rightarrow$ cannot stay at low T for very big distances

- Cannot have $\vec{E} \parallel \vec{P}$ or we never get below dE/dx peak
  $\Rightarrow$ will apply $\vec{E} \perp \vec{B}$

- $\vec{E}$ field only works if have μ^+, not $M\mu$
  $\Rightarrow$ Helium only sol^n

- For μ^-, need to keep T as large as possible to minimize capture

CONTENTS

INTRODUCTION

Charge transfer in collisions of atomic particles with gaseous atoms and molecules is one of the important processes in plasma physics, radiation physics, astrophysics, and other areas. Especially, knowledge of the total cross sections for charge transfer of hydrogen ions and atoms is necessary for thermonuclear fusion research, because this process is crucial to the containment time for plasmas, particle recycling, plasma diagnostics, and surface effects.[1] Several theoretical approaches have been developed to calculate the cross sections (see, for example, the recent review article by Morgan et al.[2]). These approaches, however, require time-consuming computations. For rapid evaluation of the cross sections, therefore, it is useful to have analytic formulas fitted to experimental data.

In the present work, analytic formulas† have been constructed for the total cross sections of the following charge transfer processes:

(1) σ_{10} for single-electron capture of H^+.

(2) σ_{0-1} for single-electron capture of H.

(3) σ_{1-1} for double-electron capture of H^+.

(4) σ_{01} for single-electron loss of H.

(5) σ_{-10} for single-electron loss of H^-.

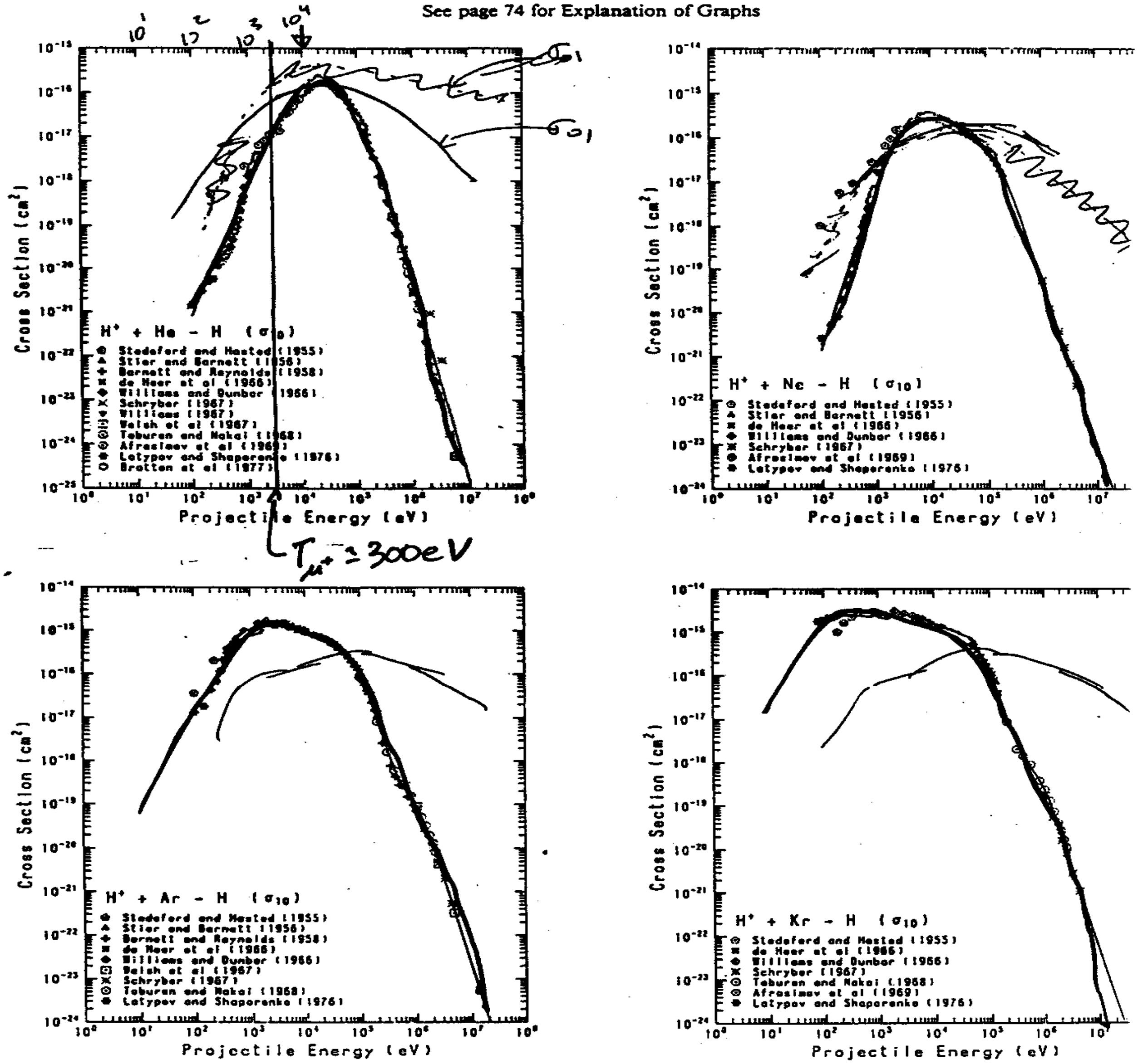
(6) σ_{-11} for double-electron loss of H^-.

Here the subscripts represent the initial and the final charge state of the hydrogen. For each of the six processes,

† Brief accounts of the formulas were given in T. Tabata, R. Ito, Y. Nakai, A. Kikuchi, and T. Shirai, Preprints of Autumn Meeting of the Physical Society of Japan, Okayama, October 1983, p. 194; Annu. Rep. Radiat. Center Osaka Prefect. 24, 55 (1983).

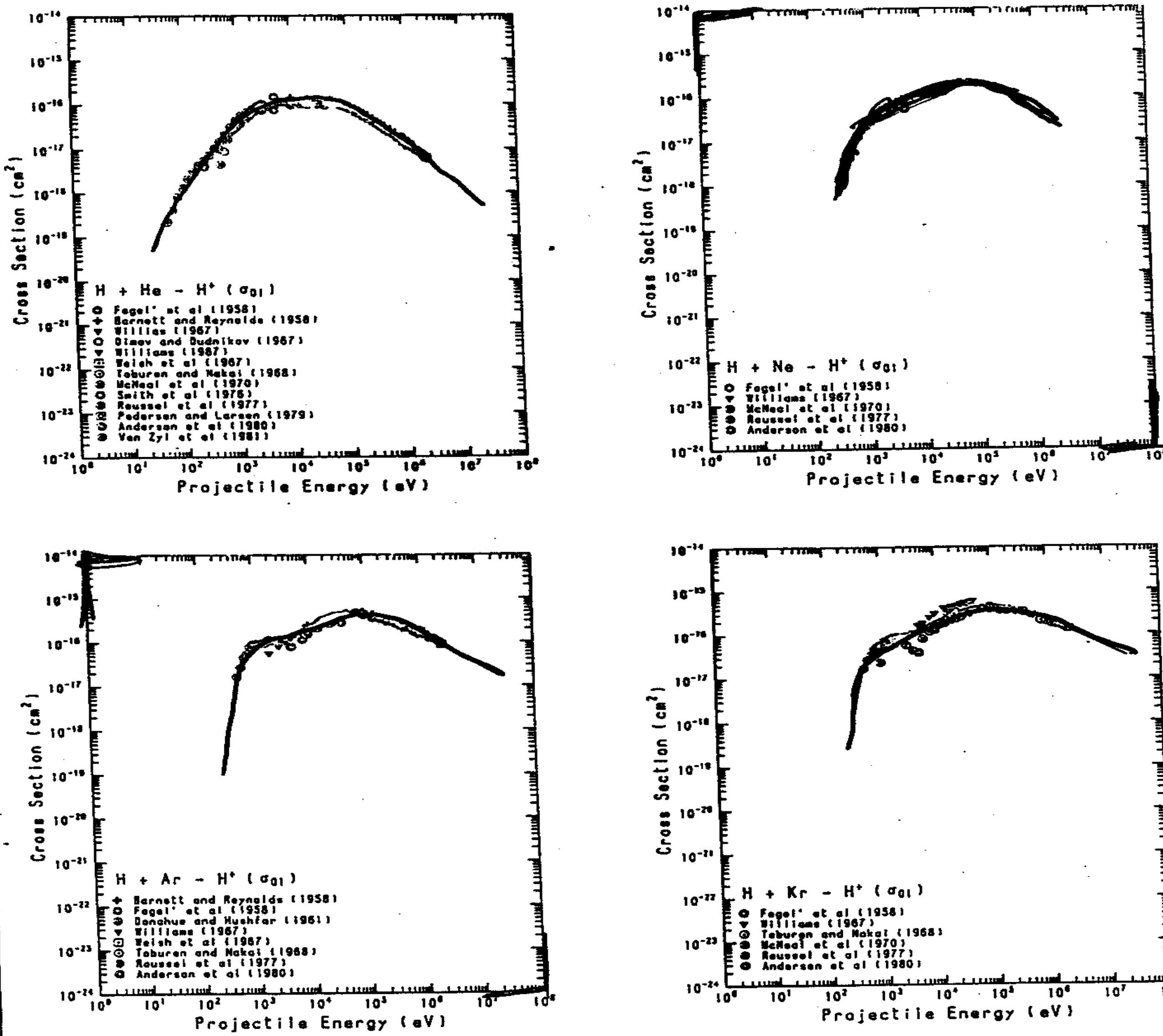
GRAPH I. Cross Section vs Energy. σ_{10} of H^+ in He, Ne, Ar, and Kr

See page 74 for Explanation of Graphs



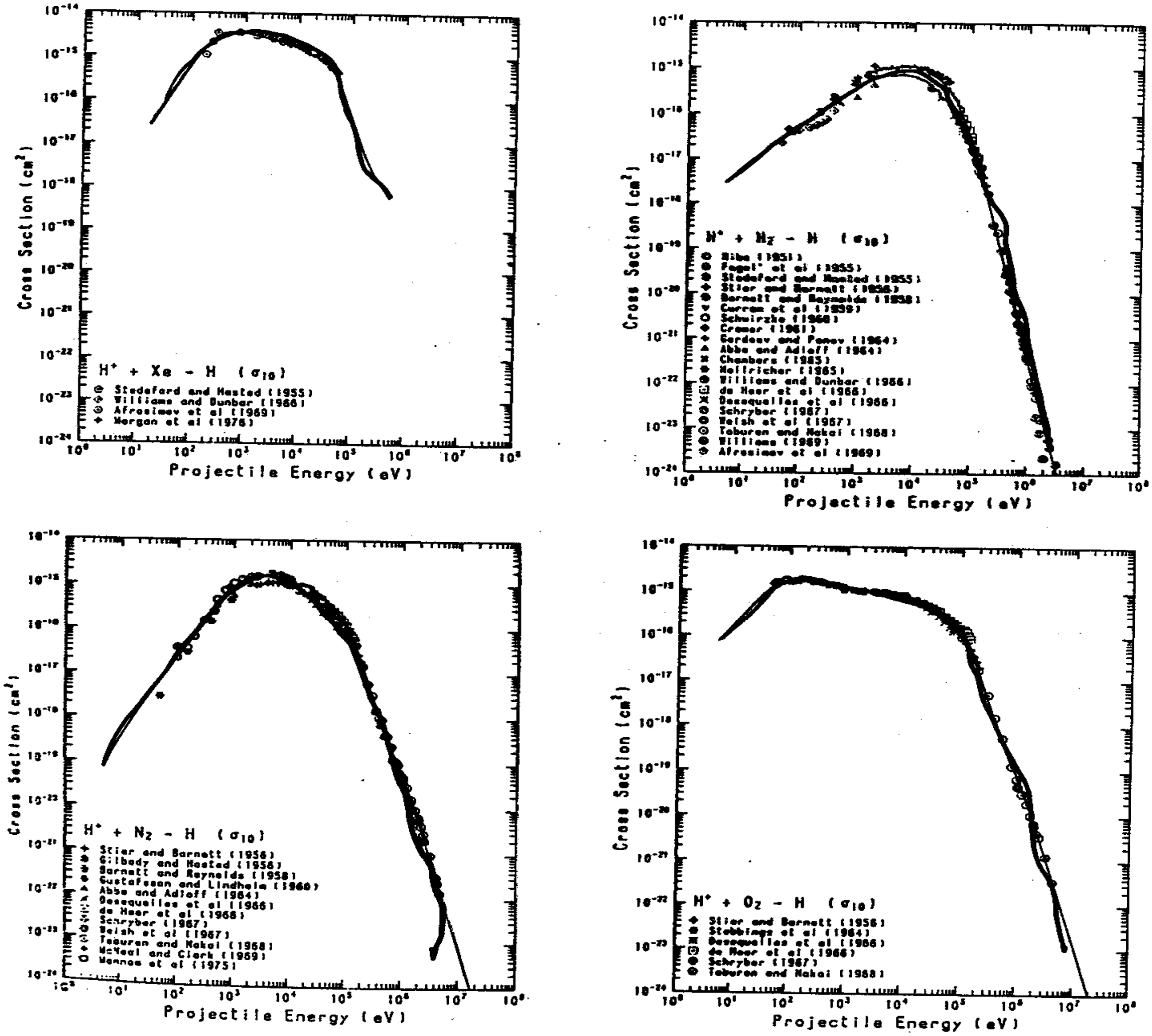
GRAPH IV. Cross Section vs Energy. σ_{01} of H in He, Ne, Ar, and Kr

See page 74 for Explanation of Graphs



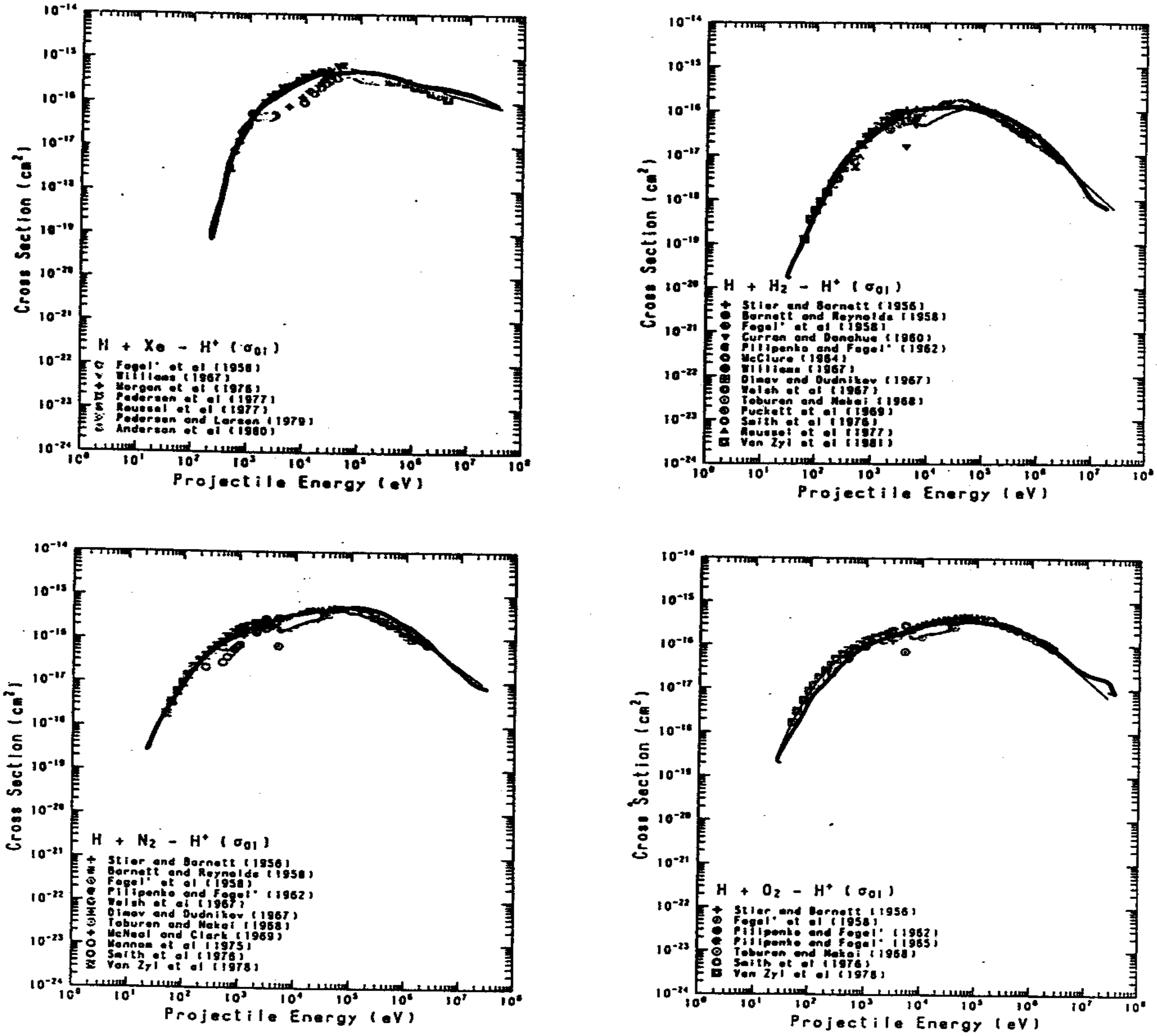
GRAPH I. Cross Section vs Energy. σ_{10} of H^+ in Xe, H_2, N_2, and O_2

See page 74 for Explanation of Graphs



GRAPH IV. Cross Section vs Energy. σ_{01} of H in Xe, H_2, N_2, and O_2

See page 74 for Explanation of Graphs



$\sigma_{capture} \leq \frac{(2\ell+1)\lambda^2}{4\pi}$ Theoretical limit for capture into state of given n

A.H. de Borde, Proc. Phys. Soc., London 67 (1954) 57.

capture dominantly in n_{μ^-} such that $v_{\mu^-} = v_{e^-}$ $n_{\mu^-} = \sqrt{\frac{m_\mu}{m_e}} \simeq 15$

$$\lambda^2 \sim \frac{1}{p^2} \sim \frac{1}{T}$$

$$\sigma_{cap} \leq (2\ell+1)\, 2\pi \, \frac{10^{-18}\,cm^2}{T(eV)} \sim \frac{2\;10^{-16}\,cm^2}{T\,(eV)}$$

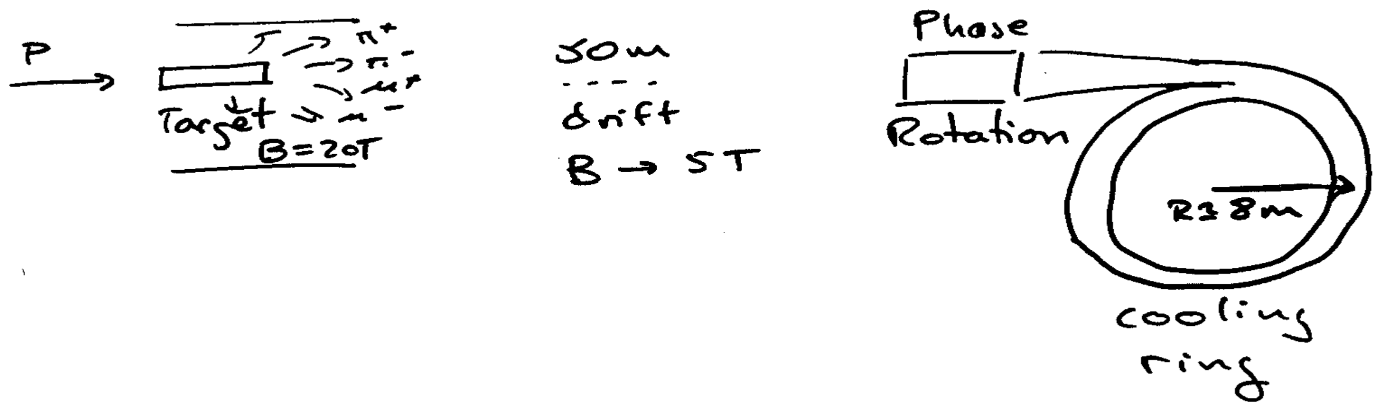
for $\rho = 10^{-4}$ g/cm³ He, T = 300 eV

mean free path ~ 0.1 cm

This is too short, but it is an lower limit. Can also lower ρ, but this will lower efficiency of cooling.

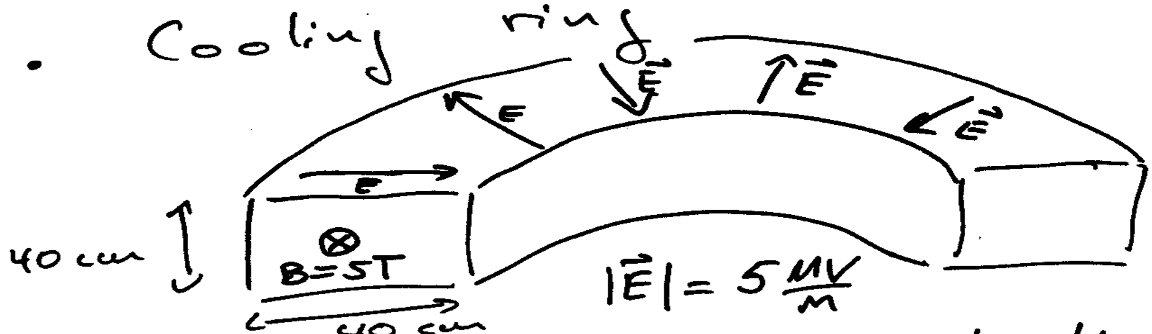
For now, proceed, but will eventually need to measure this cross section.

Scheme:



- Phase rotation is used to slow down $\mu^\pm$

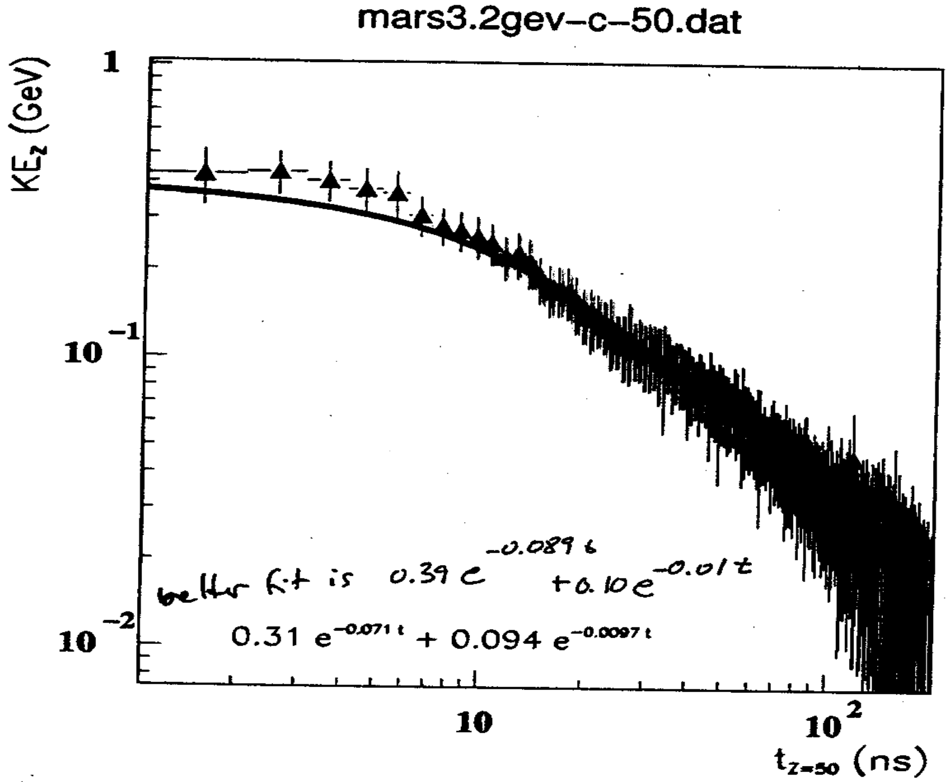
- Cooling ring



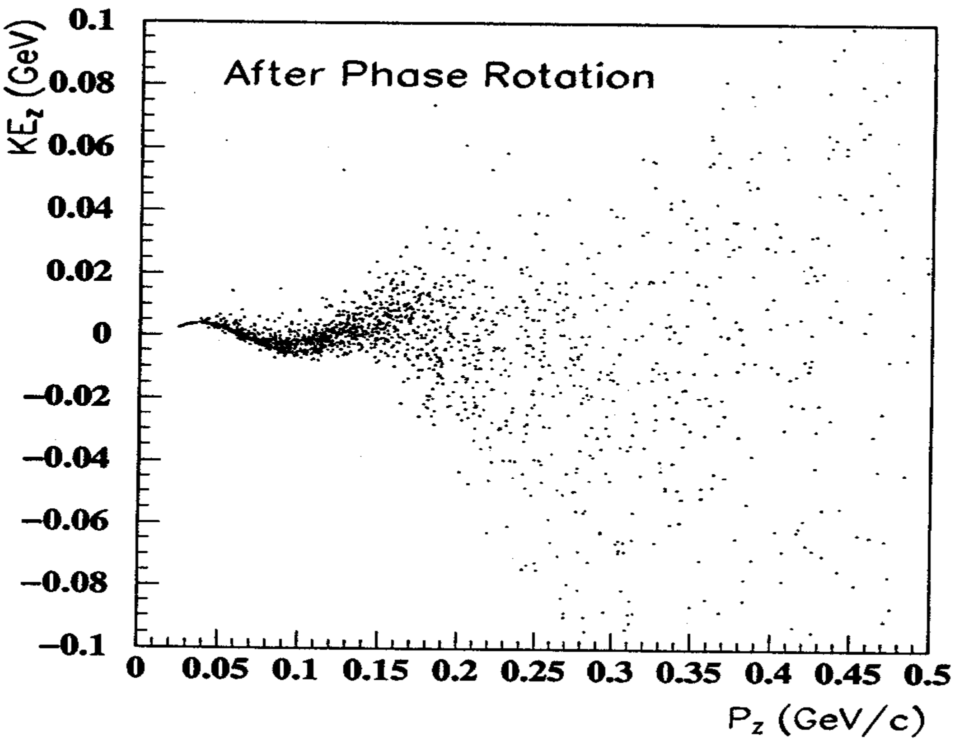
$\vec{E}$ alternates (consistently with Maxwell eq.) so no net drift. Swap dist ~1m

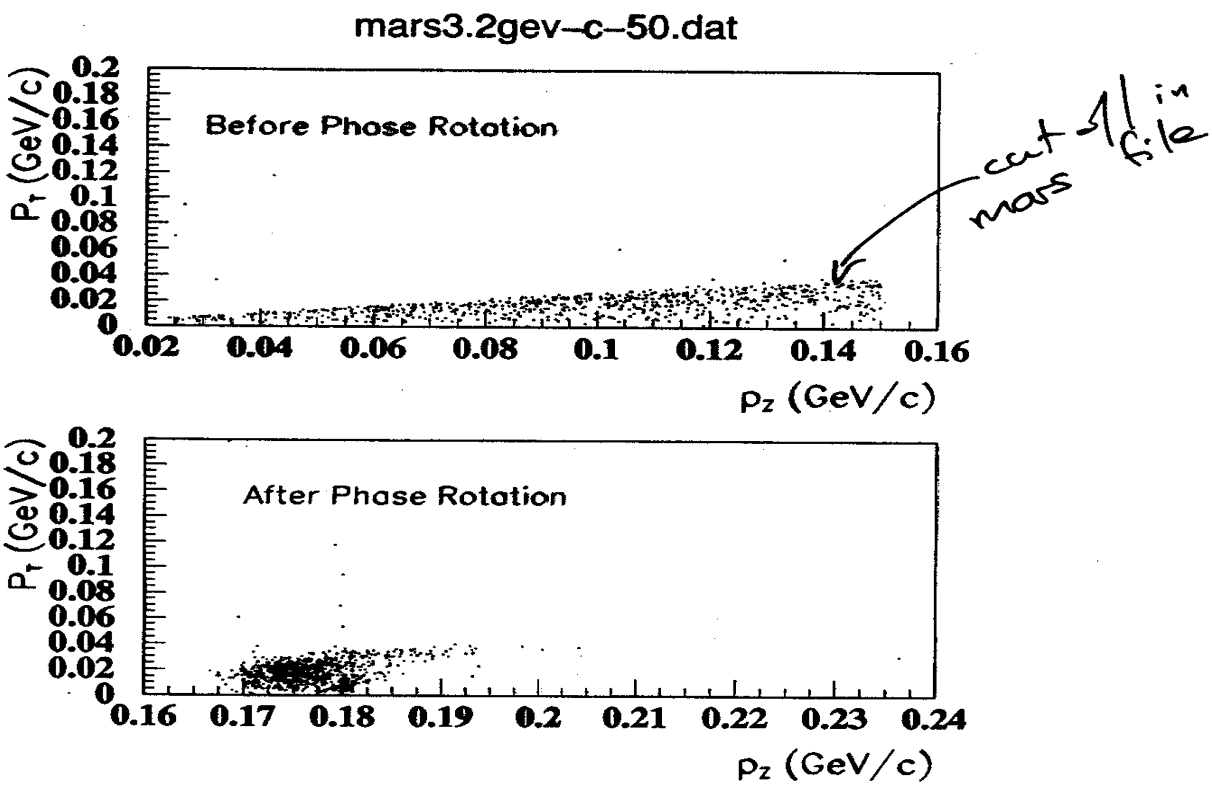
Note: cannot be DC field → He breakdown

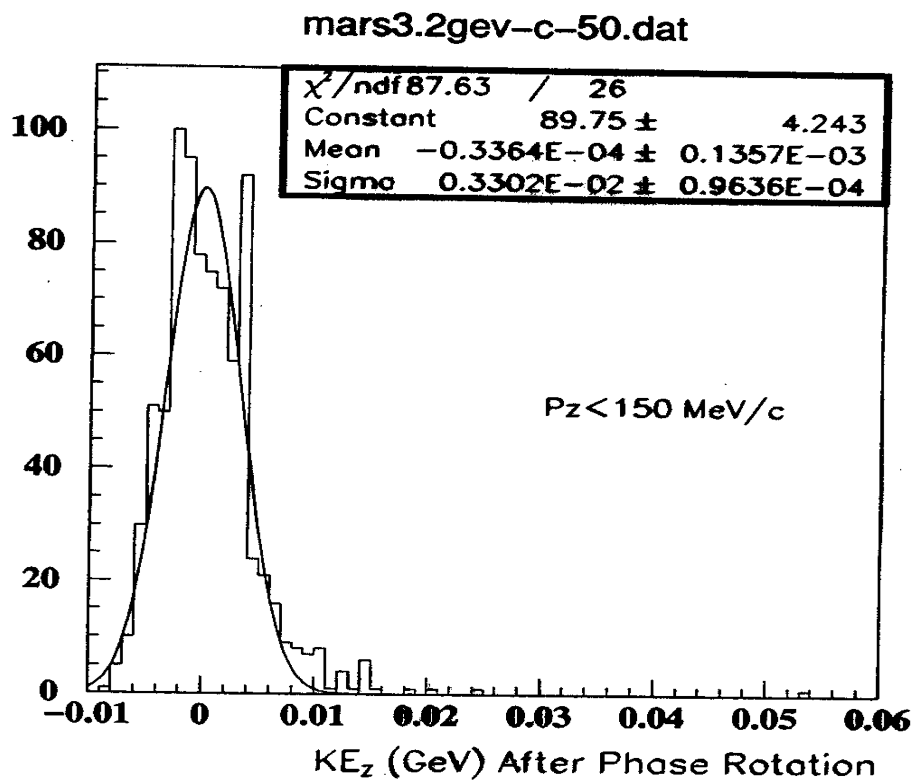
$\rho_{He} = 10^{-4}\ g/cm^3$



Phase rotation is just a parametrization of KE vs t mars3.2gev–c–50.dat

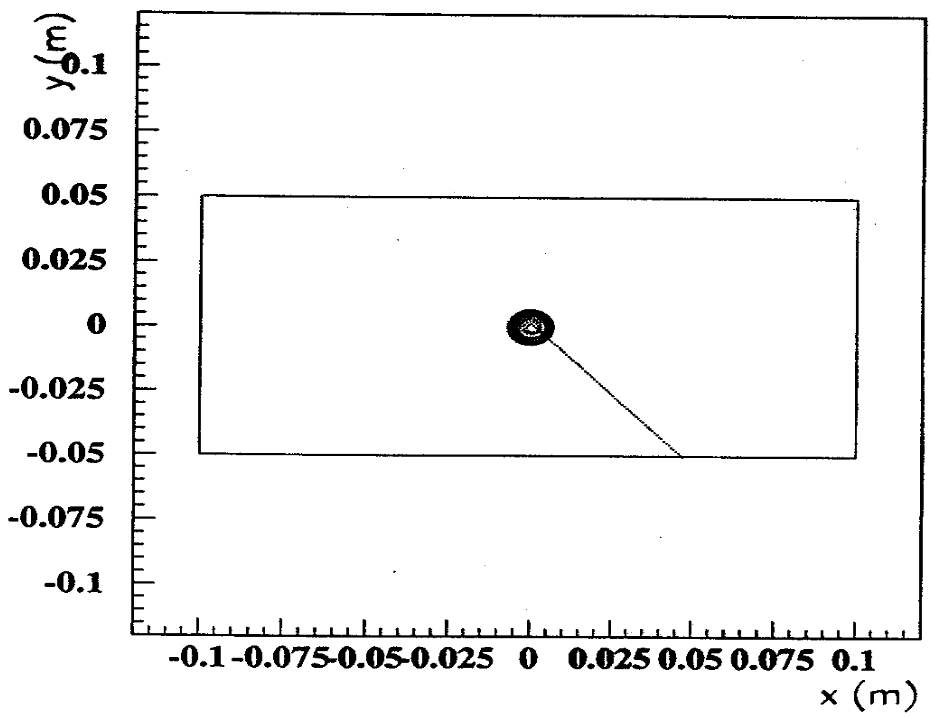



mars3.2gev-c-50.dat
Before Phase Rotation
After Phase Rotation
P_T (GeV/c)
p_z (GeV/c)
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16
0.16 0.17 0.18 0.19 0.2 0.21 0.22 0.23 0.24
cut ↓ in mars file


mars3.2gev-c-50.dat
χ²/ndf 87.63 / 26
Constant 89.75 ± 4.243
Mean −0.3364E−04 ± 0.1357E−03
Sigma 0.3302E−02 ± 0.9636E−04
Pz<150 MeV/c
100
80
60
40
20
0
−0.01
0
0.01
0.02
0.03
0.04
0.05
0.06
KEz (GeV) After Phase Rotation

Some pictures from simulation
(preliminary designs)

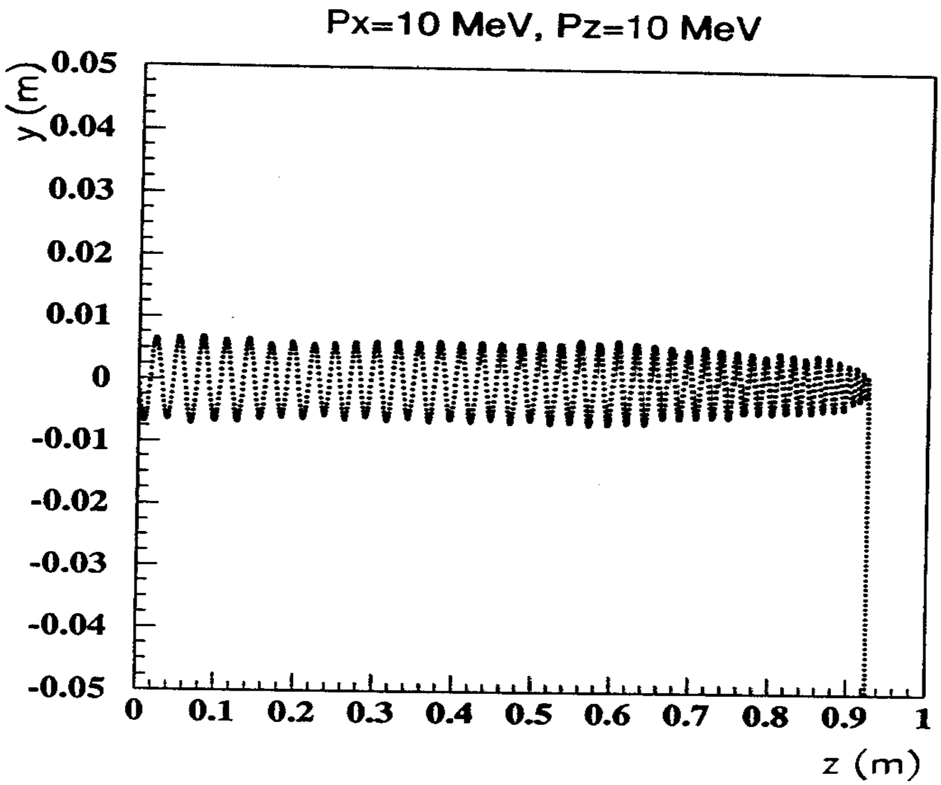
Px=10 MeV, Pz=10 MeV



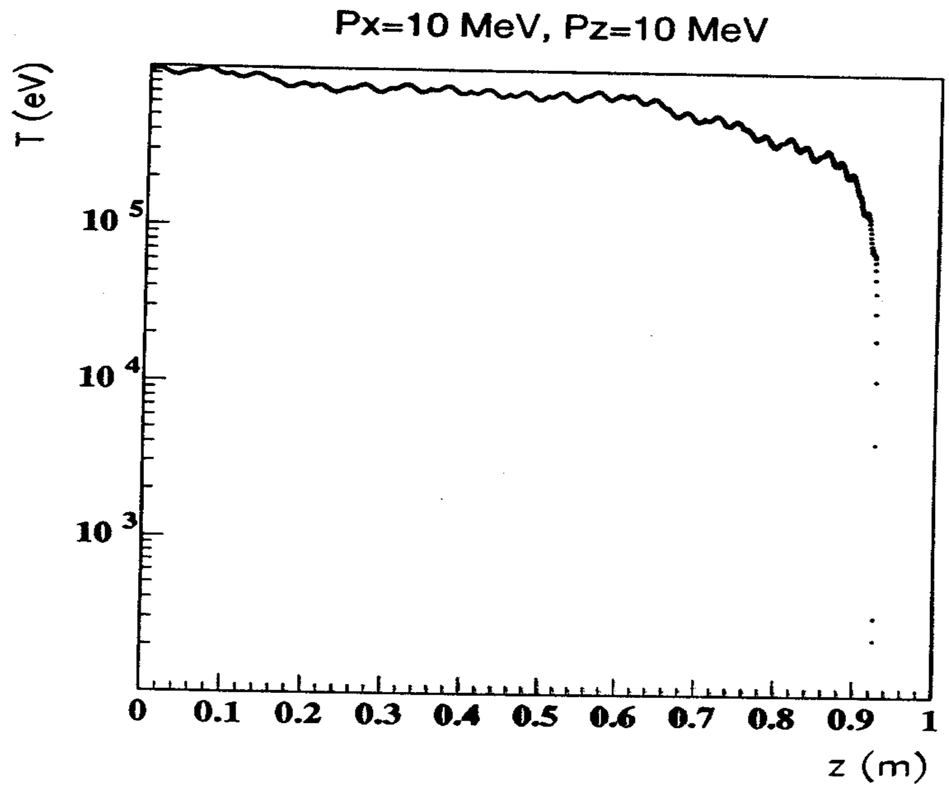
$$F_x = qE_x + qv_yB - \frac{dE}{dx}\left(\frac{\beta_x}{\beta}\right)$$

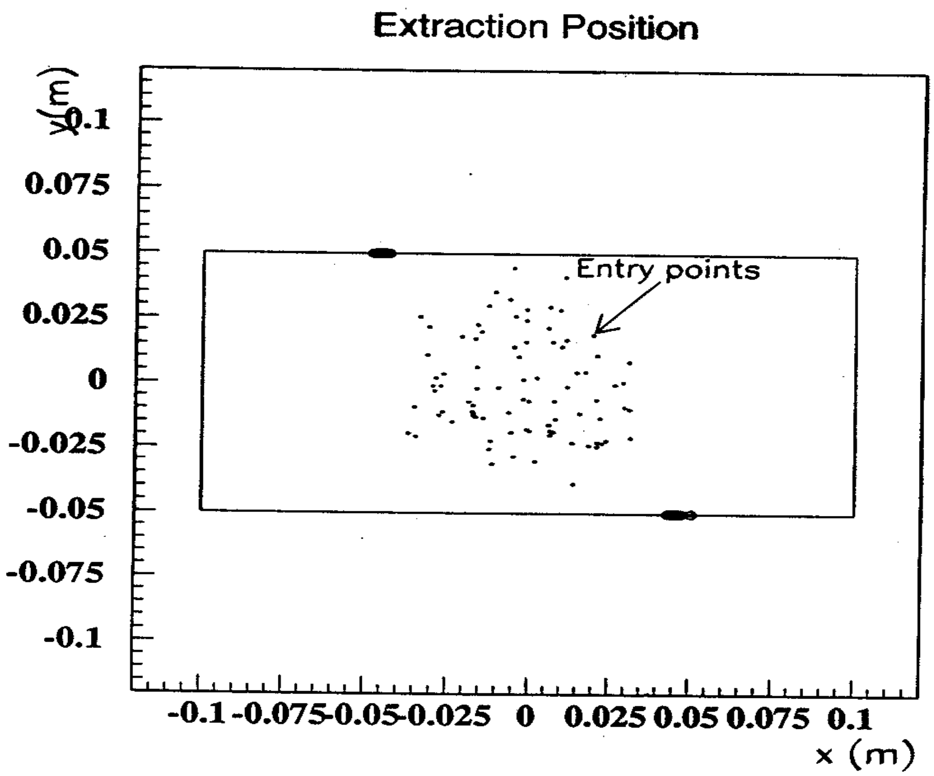
$$F_y = -qv_xB - \frac{dE}{dx}\left(\frac{\beta_y}{\beta}\right)$$

$$F_z = -\frac{dE}{dx}\left(\frac{\beta_z}{\beta}\right)$$

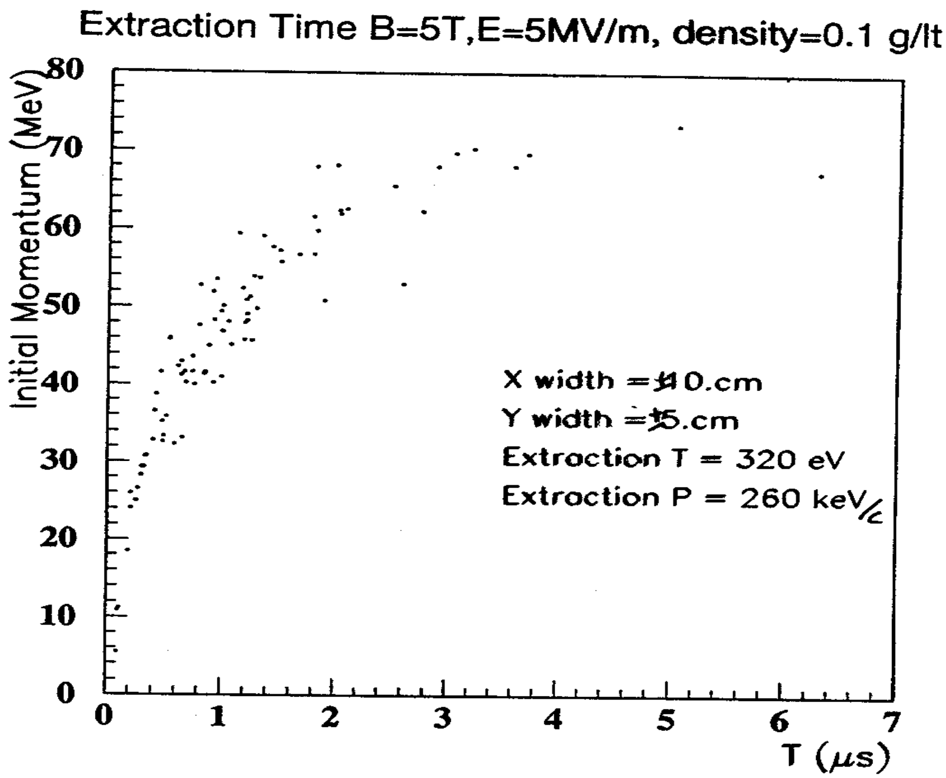


Px=10 MeV, Pz=10 MeV
y (m)
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z (m)

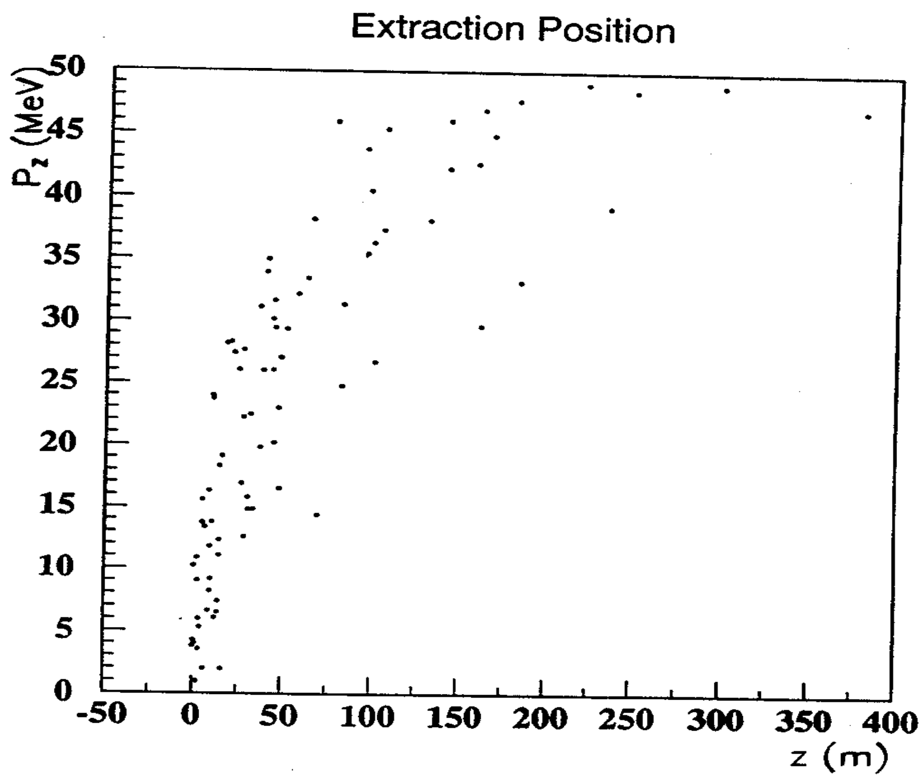

Px=10 MeV, Pz=10 MeV
T (eV)
10 5
10 4
10 3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z (m)



assumes orbits centered on x=y=0



Extraction Time B=5T,E=5MV/m, density=0.1 g/lt
Initial Momentum (MeV)
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6
7
T (μs)
X width =±10.cm
Y width =±5.cm
Extraction T = 320 eV
Extraction P = 260 keV/c



Extraction Position
P_z (MeV)
50
45
40
35
30
25
20
15
10
5
0
-50
0
50
100
150
200
250
300
350
400
z (m)

Some results using $\pi^\pm, \mu^\pm$ files from N. Mokhov

http://www-ap.fnal.gov/mokhov/mumu/target99/

mars3.16gev-hg-50.dat

16 = E_p, hg = target, 50 = 50 cm target

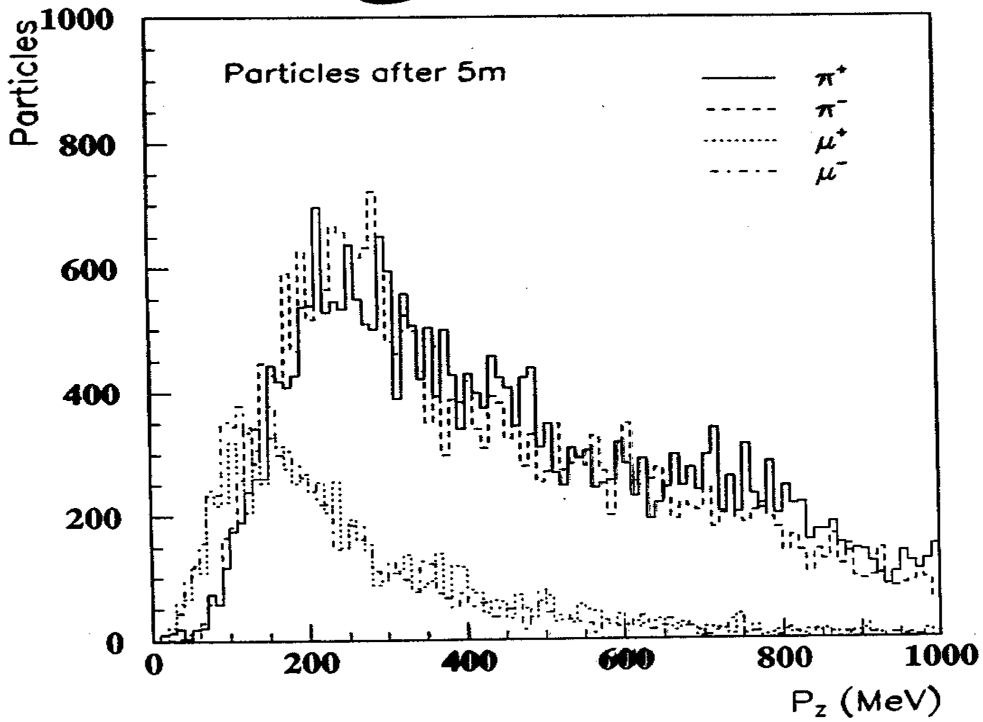
Not clear (to me) how many protons generated (event number reaches 60 k)

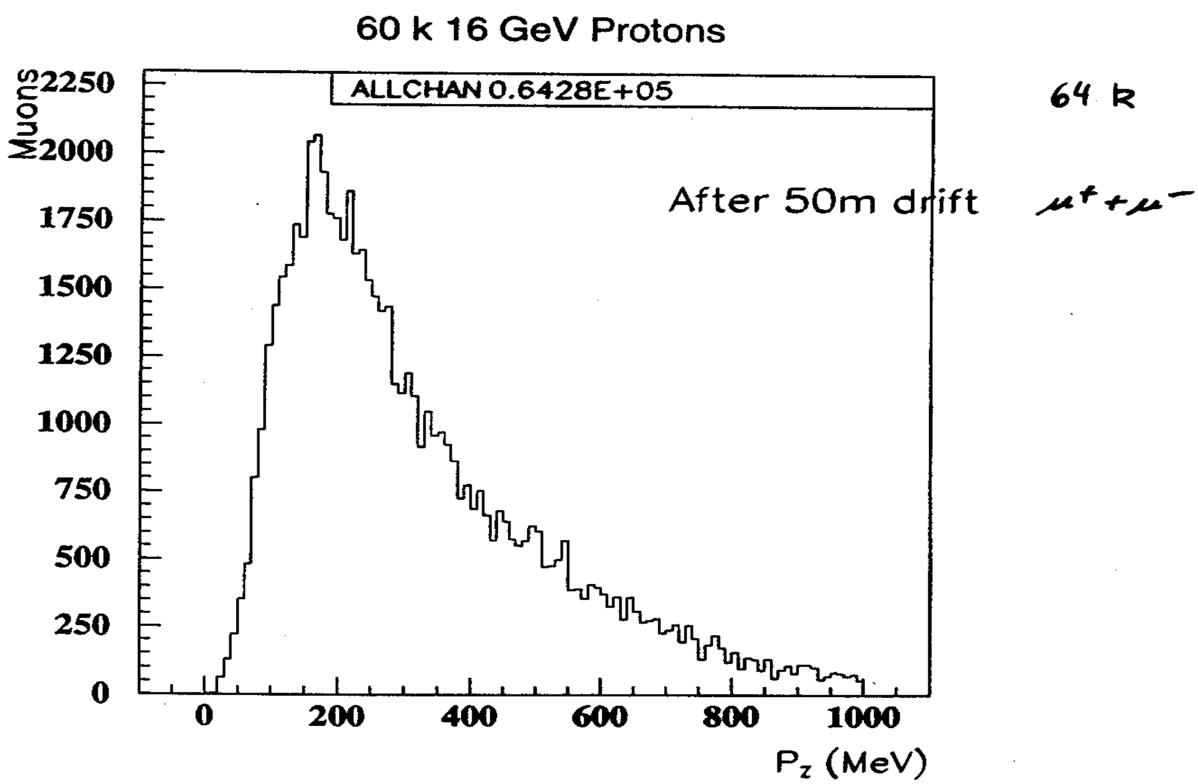
	π^+	π^-	μ^+	μ^-
After 5 m	35000	32110	8348	8465
50 m drift			~~34840~~ 33820	~~33820~~ 32780
phase rot ($P_z > 0$)			19080	18030
survive He drift (exit x, y or z = 200 cm)			7547	7393
Exit cooling channel at $T \simeq 300$ MeV			4365	4866

$\Rightarrow$ about 10% of initial $\pi^\pm, \mu^\pm$ result in $\mu^\pm$ exiting He at nominal T

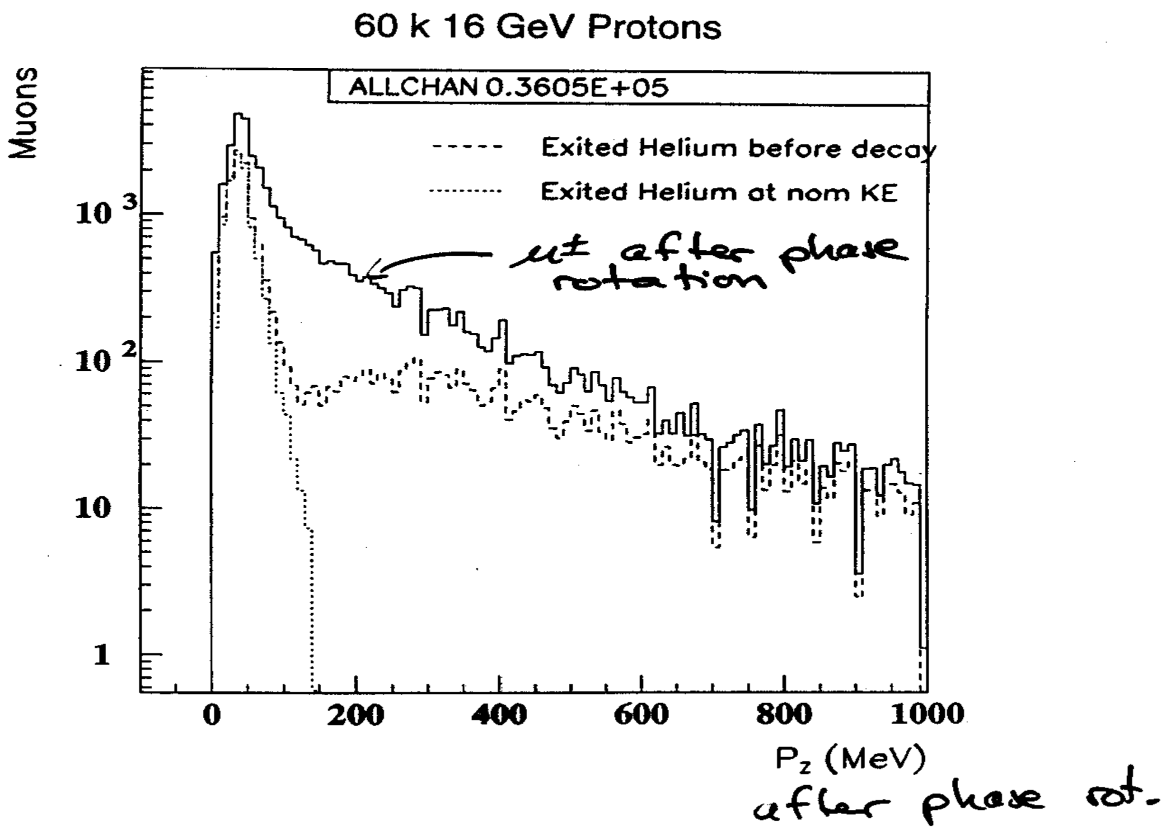
??

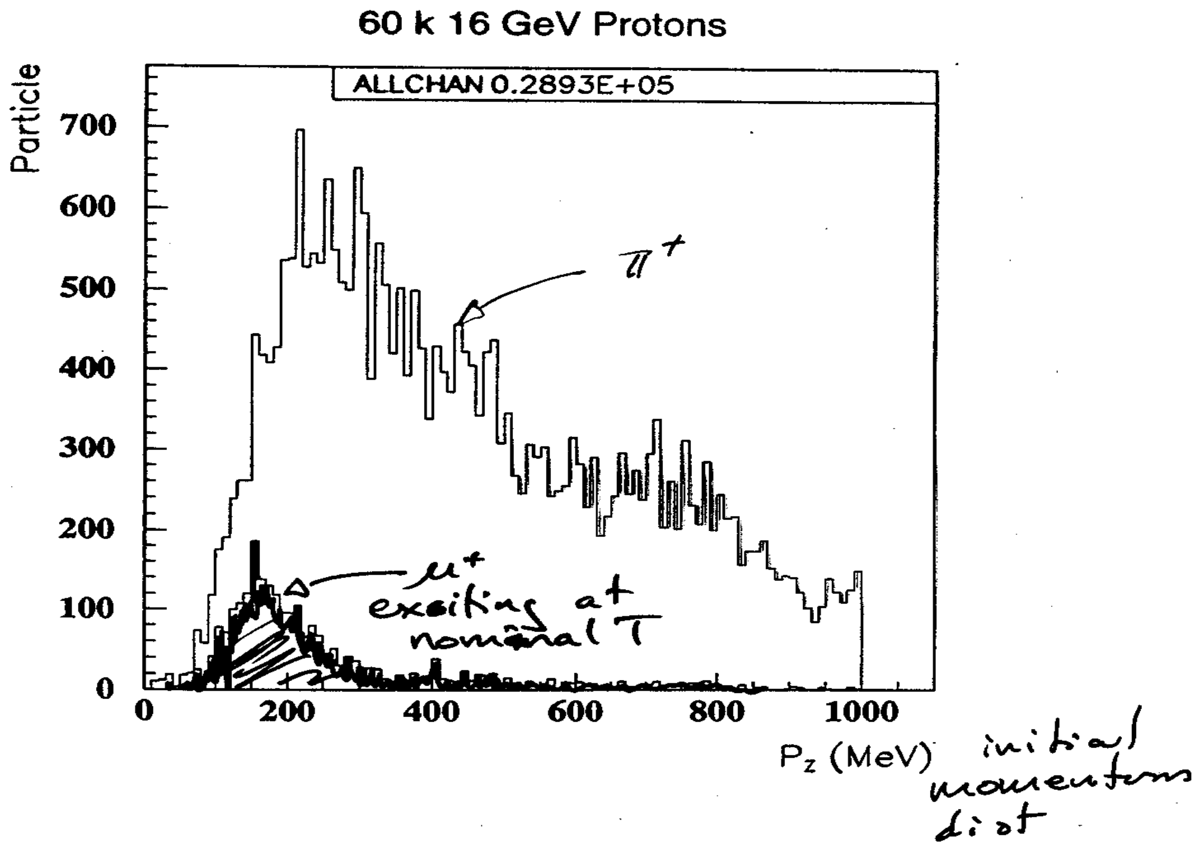
60 k 16 GeV Protons





60 k 16 GeV Protons
Muons
ALLCHAN 0.6428E+05
After 50m drift
0
250
500
750
1000
1250
1500
1750
2000
2250
0
200
400
600
800
1000
Pz (MeV)
64 k
μ+ + μ−


60 k 16 GeV Protons
Muons
ALLCHAN 0.3605E+05
Exited Helium before decay
Exited Helium at nom KE
μ± after phase rotation
10 3
10 2
10
1
0
200
400
600
800
1000
Pz (MeV)
after phase rot.


60 k 16 GeV Protons
ALLCHAN 0.2893E+05
Particle
0
100
200
300
400
500
600
700
0
200
400
600
800
1000
Pz (MeV)
π+
μ+ exsiting at nominal T
initial momentum dist

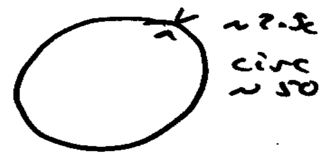
Phase space reduction:

consider phase space of particles which eventually come out at $T = 300\,eV$.
Just for rough orders of magnitude.

initial $\quad \sigma_x = \sigma_y \simeq 2.5\,cm \qquad \sigma_z = 138\,cm$ at $z = 5m$

$\sigma_{p_x} = \sigma_{p_y} = 25\,MeV \qquad \sigma_{p_z} = 125\,MeV$

final $\quad \sigma_x \cdot \sigma_y = (5\,10^{3}\,cm)(2.5\,cm)$



$$\sigma_z = \sigma_t \cdot \beta \cdot c$$

$$\beta = \frac{p_z c}{mc^2} \simeq 2\,10^{-3}$$

$$\sigma_t = 1 \cdot 10^{-6}\,s$$

so $\sigma_z = 60\,cm$

$\sigma_{p_x} = \sigma_{p_y} = \sigma_{p_z} = ?$ $\qquad T \pm 50\,eV$

$\rightarrow p \pm 20\,keV$

take for now $\sigma_p = 20\,keV$

exiting He channel not solved!

$$\frac{(\sigma_x \sigma_y \sigma_z \sigma_{p_x} \sigma_{p_y} \sigma_{p_z})^{final}}{(\sigma_x \sigma_y \sigma_z \sigma_{p_x} \sigma_{p_y} \sigma_{p_z})^{initial}} = 10^{-7}$$

norm emittance

Comments

- What are reasonable parameters for B, E ?
- How do we get $\mu^\pm$ out of the channel ?
- What happens after the channel ?
- μ^- capture cross sections

So far, looks intriguing. Please criticize and/or help!

Columbia Group Studies

L.Alhilali*,A.Boozer,A.Bozovic*,A.Caldwell,I.Shpiro*,F.Sciulli,W.Willis
*=student

Reducing the phase space occupied by the muons while keeping high efficiency is crucial for the success of a muon collider or a high intensity neutrino factory. The nominal scheme performs the cooling at T=200 MeV. We are investigating the possibility of reducing the phase space by bringing the muons to T ~ 1 keV and then reaccelerating.

We're investigating different options

Refs: K. Nagamine, At. Phys. 10, 225 (1987); K. Nagamine et al., Phys. Rev. Lett. 74, 4811 (1995).
E. Morenzoni, `The physics and applications of low energy muons', lecture notes of SUSSP51, PSI- PR- 98- 23.

Notes:

elvezio.morenzoni@psi.ch

Physics and applications of low energy muons*

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Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

1 Introduction

Among the various nuclear solid state techniques, muon spin research (μSR) is a relatively young technique. However, as with all fields of science, also in applied muon science novel methods and techniques have to be developed and the capabilities of the existing ones continuously extended in order to face the challenge offered by new objects of investigations. These developments in methodology are often driven by the needs of research communities. Conversely, the availability of new scientific instruments and methodologies leads to progress in scientific knowledge. An example is the discovery of the surface muon production mechanism (Pifer et al. 76). Surface muons, which originate from pions decaying at rest at the surface of a pion production target, offered decisive advantages with respect to the previously used muons obtained from the decay in flight of pions such as high degree of polarization, high stopping rate, and limited penetration depth (fraction of mm to mm) in relatively small specimens and gave a large impetus to μSR.

In the last decade, thin films, nanomaterials, multilayered compounds, and generally objects of restricted dimensionality have emerged as critical elements in science and technology. Different methods and particle probes such as polarized electrons, neutrons, photons, and

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* Lecture notes of SUSSP51, Scottish Universities Summer School in Physics, a NATO Advanced Study Institute on Muon Science, University of St. Andrews, Scotland UK, 17-28 August 1998