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ADDENDUM TO PROCEEDINGS OF THE 10 MAY 1989 ANTIPROTON TECHNOLOGY WORKSHOP

A compilation of presentation materials from the workshop held at Brookhaven National Laboratory, jointly sponsored in accordance with the AL/DoE Memorandum of Agreement for Applied Research in Energy Storage support from Brookhaven National Laboratory

August 1989

Editor: Gerald D. Nordley

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Prepared for the **Astronautics Laboratory (AFSC)**

Air Force Space Technology Center
Space Systems Division
Air Force Systems Command
Edwards Air Force Base, California 93523-5000

89 9 22 035

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FOREWORD

This special report comprises the presentations provided by speakers at the Antiproton Technology Workshop held at Brookhaven National Laboratory (BNL) 10 may 1989 jointly sponsored under the Astronautics Laboratory (AFSC) / Department of Energy-BNL Memorandum of Agreement for support of Applied Research In Energy Storage (ARIES). This special report has been reviewed and approved in accordance with the distribution statement on the cover an on the DD form 1473.

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FOR THE DIRECTOR

ROBERT C. CORLEY
Chief, Astronautical Sciences Division

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FIELD	GROUP	SUB-GROUP
20	07	
20	08	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Antiproton Beams, Imaging, NDA/NDE, Radiotherapy, Condensed Antimatter, CP Violation

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This workshop, held at Brookhaven National Laboratory, 10 May 1989, was a follow-on to the Antiproton Science and Technology Workshops held at the RAND Corporation in Santa Monica through October 1987 following the Air Force Project Forecast II initiative in Antiproton Technology. The workshop was attended by about 50 researchers from a wide variety of disciplines, including medicine, particle physics, and the aerospace industry. New, more efficient technology for a variety of scientific, medical, and industrial uses could result from antiproton experiments proposed by workshop participants. Antiprotons are particles of antimatter which release highly penetrating radiation when they are stopped in normal matter. According to presentations at the Antiproton Technology Workshop this radiation can be used, in very small quantities, to image objects and determine their composition and density. In larger amounts, the radiation could be used to kill cancer tumors or produce highly localized heating and shock waves. DOE plans are contingent on potential user support.

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H. Takahashi, Brookhaven N. L

* Copies of viewgraphs were unavailable at the time of compilation (17 May 1989). They may be inserted if recieved later.

** Copies of presentation only in adendum.

Table 2. Attendees at the Antiproton Technology Workshop

Attendee	Organization	Dept/Code	Address	Location/Zip	Tel
Augenstein, Bruno	The RAND Corp		1700 Main St	Santa Monica CA 90406	213 393 0411
Baggett, Neil	BNL	Physics Dep	Bldg 510	Upton NY 11973	
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Carrick, Patrick	U Dayton	AL/LSX		Edwards AFB CA 93523-5000	805 275 5883
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Kenney, John	E. NM U	Dept of Physical Sciences		Portalas NM 88130	505 562 2152
Kenney, M. Inga	E. NMU	Dept of Physical Sciences		Portalas NM 88130	505 562 2152
King, Nick	LANL	P-15	D406	Los Alamos NM 87545	
LaPoint, Michael	NASA LeRC	SVT	MS 500-219	Cleveland OH 44235	216 433 8540
Lazareth, Otto	BNL		Bldg 701	Upton, NY 11973	
Leibenhaut, Mark, MD	Lahey Clinic	Radiotherapy	411 Mall Rd	Burlington MA 01805	617 273 8780
Lewis, R. A.	Penn State		303 Osmond Lab	University Park PA 16802	814 863 3342
Ludewig, Hans	BNL		Bldg 701	Upton NY 11973	516 282 2624
McClanahan, Jim	RI Rocketdyne	M/C WB 39	6633 Canoga Ave	Canoga Park, CA 91304	805 371 7422
Miley, George H.	U of Illinois	214 NEL	103 S. Goodwin	Urbana IL 61801	217 333 3772
Miller, James	Boston U	Dep Phys		Boson MA 02215	
Minor, Ellsworth. D.	Penn State U		303 Osmond Lab	University Park PA 16802	814 863 3537
Muratore, Robert	Syracuse U	Phys. Dep		Syracuse NY	315 443 5970
Nathan, A. M.	U. Illinois	Dep Phys		Champaign IL	217 333 0965
Nordley, Gerald	ARIES	AL/LSX		Edwards AFB CA 93523-5000	805 275 5653
Peaslee, David	U. Maryland	Phys. Dept		College Park MD 20742	
Pellegrino, Charles R			360 Shore Rd 3I	Long Beach NY 11561	
Powell, James	BNL	Nuc Energy	Bldg 701	Upton NY 11973	516 282 2440
Reeder, Don	U Wisconsin	Physics	1150 Univ. Ave	Madison WI 53706	
Rich, Arthur	U. Michigan	Phys. Dep		Ann Arbor MI 41809	313 764 2408
Sakitt, Mark	BNL	Phys. Dep	Bldg 510	Upton NY 11973	516 282 3812
Sivera, Isaac	Harvard U	Dep Phys		Cambridge MA 02318	
Smith, Gerald	Penn State U	Dep Phys	303 Osmond Lab.	University Park PA 16802	814 863 3076
Takahashi, Hiroshi	BNL	Nuc Energy	Bldg 130	Upton NY 11973	516 282 4099
Tarpley, Kip			4313 Knox # 206	College Park MD 20740	301 277 3846
Thornton, Dr Steven	U. Virginia	Dep Phys		Charlottesville VA	804 924 6808
Toothacker, W. S.	Penn State		303 Osmond Lab	University Park PA 16802	814 863 3297
Von Herzen, Dr Brian	AntiM Corp		2379 Kalanianaole St	Hilo HI 96720	808 969 7061

STOPPING POWER OF MeV PROTON AND ANTIPROTON BEAMS

R. A. LEWIS

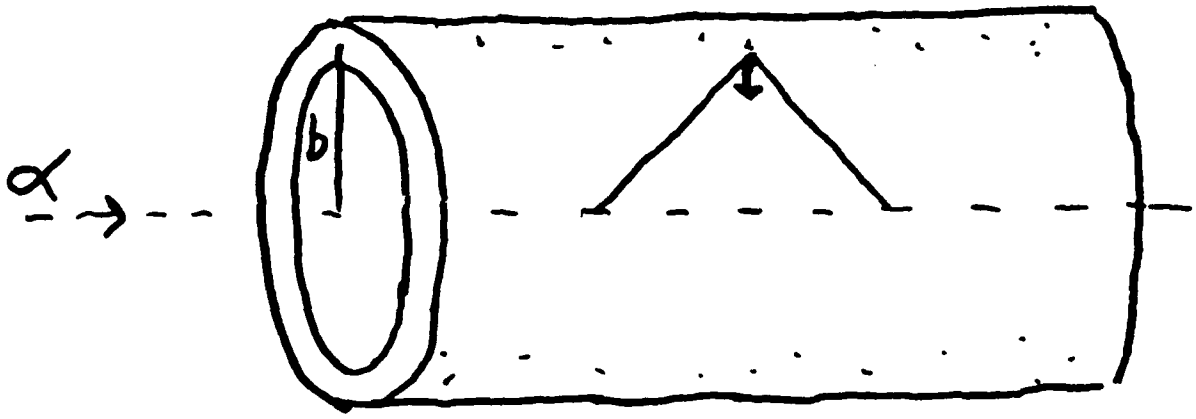
LABORATORY FOR ELEMENTARY PARTICLE SCIENCE
THE PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY PARK, PA

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

Stopping Power of MeV Proton and Antiproton Beams

R.A. Lewis, R. Kauzleiter, G.A. Smith,
W.S. Toothacker, M.G. Willis
Penn State University

Antiproton Technology Workshop
May 10, 1989
BNL



$$\Delta p_e \simeq F \Delta t$$

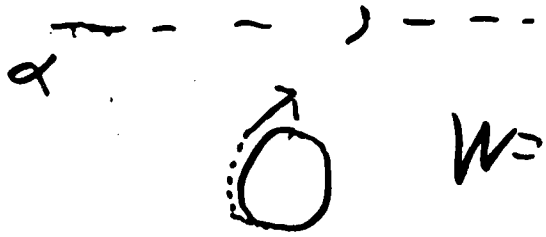
$$\Delta E_e = \frac{2 Z_\alpha^2 e^4}{m_e V^2} \cdot \frac{1}{b^2}$$

$$\frac{dE}{dX} \simeq 4\pi n_e \cdot \frac{Z_\alpha^2 e^4}{m_e V^2} \int \frac{db}{b}$$

Impact Parameters

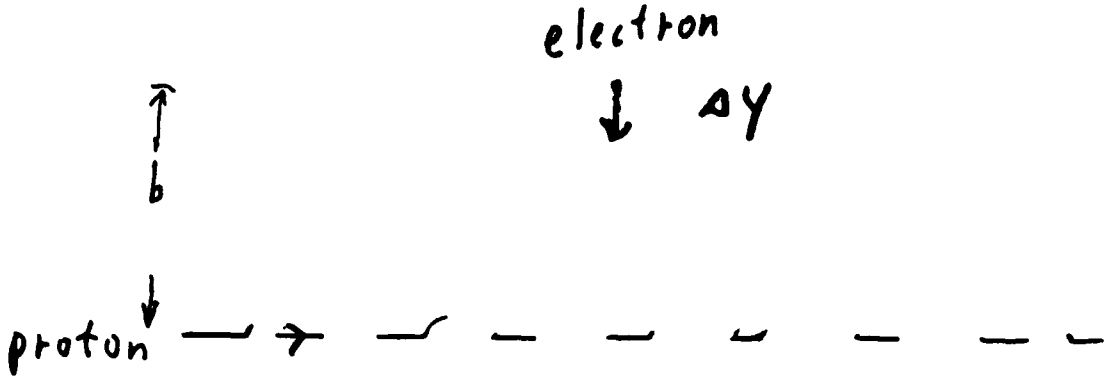
2 MeV α

$\Delta E = 43\,eV$	0.27 Å	
$\omega = v/b$	1.5 Å	b_{max}
distance of closest approach	0.05 Å	
de Broglie $\lambda\!\!\!^{-}$	0.12 Å	b_{min}



$$W = \int \vec{F} \cdot \vec{v}\, dt$$

Barkas Effect



$$\frac{\Delta y}{b} = \frac{\overset{3\pi/2}{2}\, e^2 \omega}{m v^3} z = B$$

adiabatic

$$\frac{dE}{dx} * (1 \pm B)$$

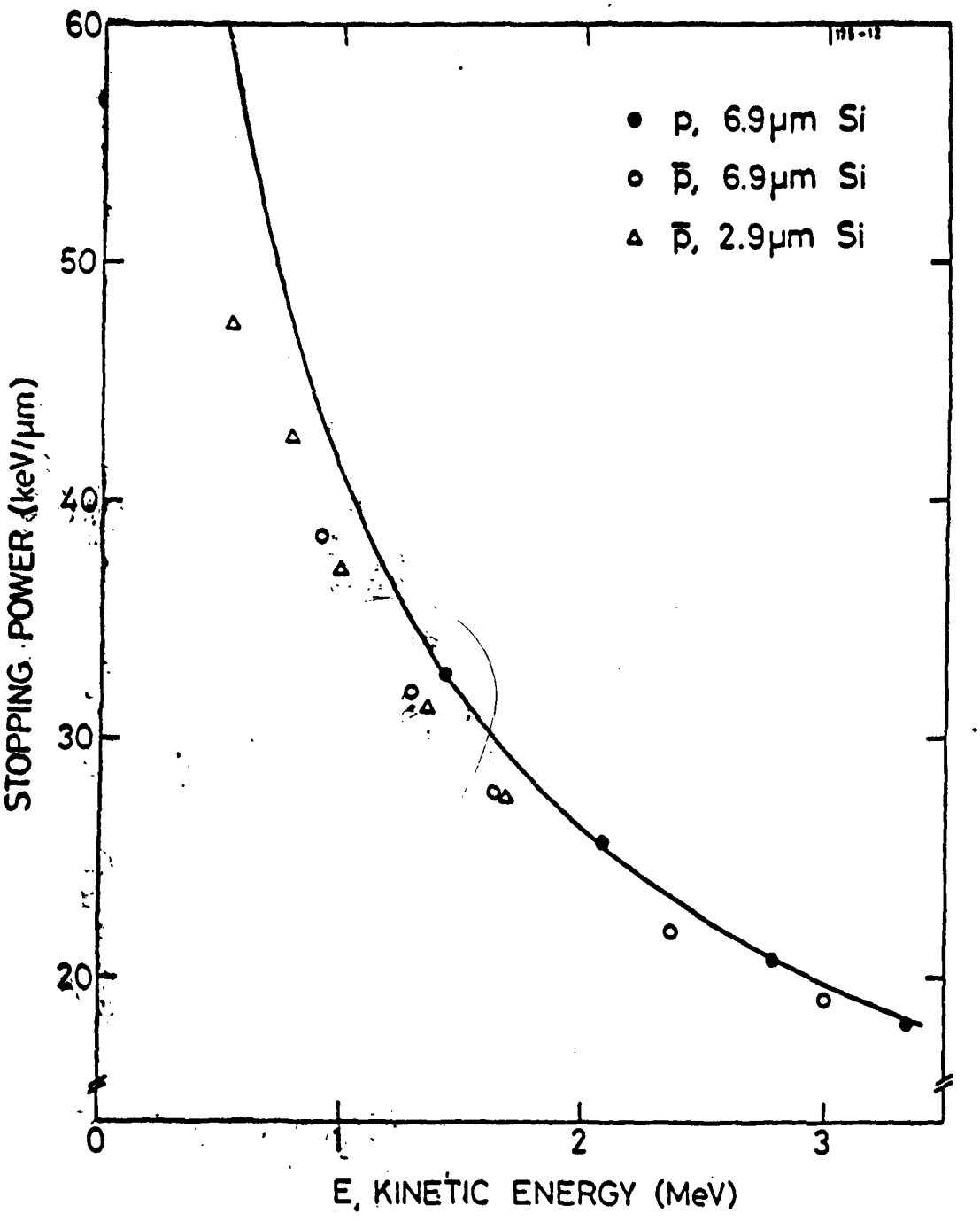
- Z^3 effects important for media with large ω, projectiles with small v^3:

  Antiproton trapping
  $\bar{p}$ ICF
  Plasmas

  Ion surface science
  Stopping ions
  (Z^4 effects)

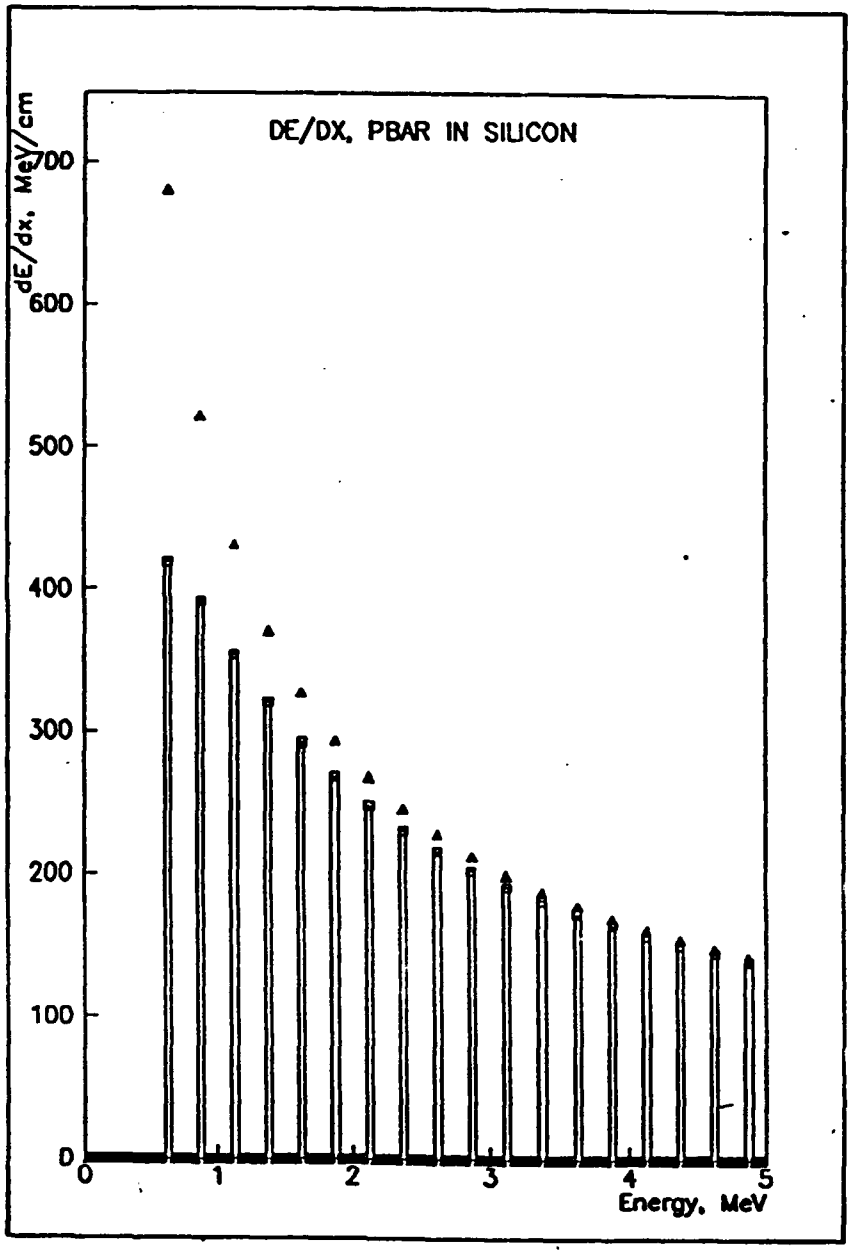
- Agreement with Lindhard may be fortuitous

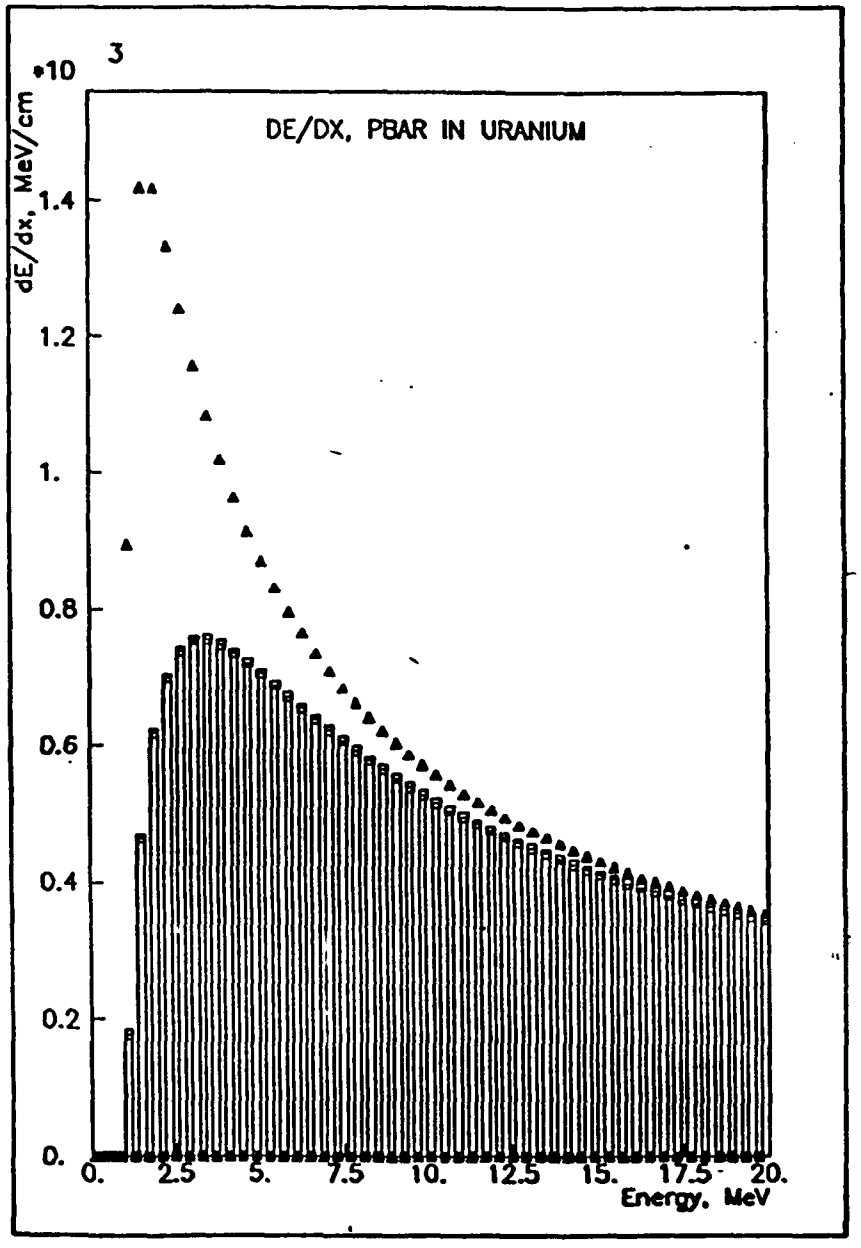
  Jackson, McCarthy version
  Quantum mechanical Z^3 effects



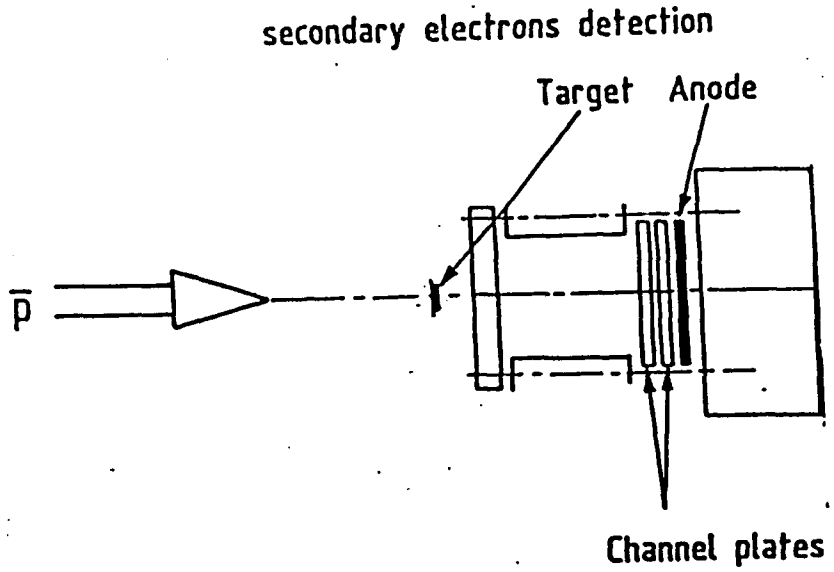
L.H. Andersen et al.,
CERN EP/89-14
Phys. Rev. Letters

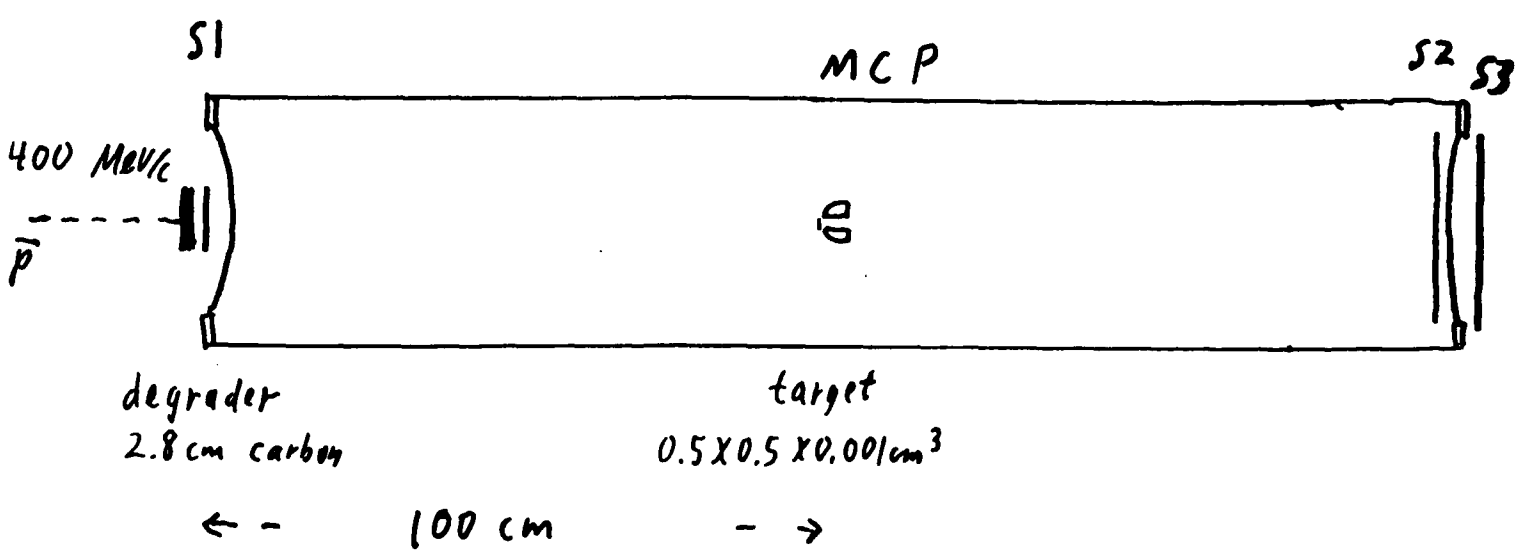
Fig. 2

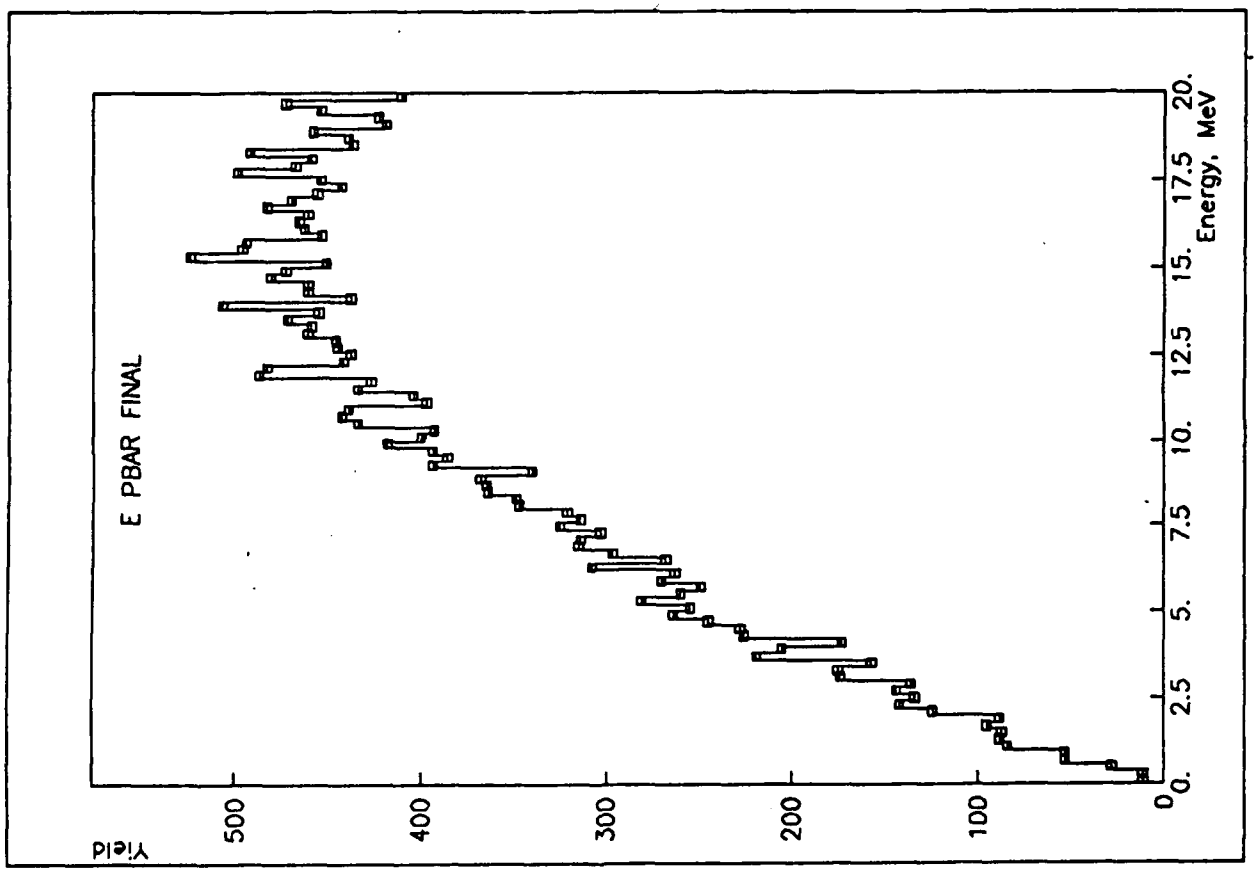

DE/DX, PBAR IN SILICON
dE/dx, MeV/cm
700
600
500
400
300
200
100
0
0
1
2
3
4
5
Energy, MeV


DE/DX, PBAR IN URANIUM
dE/dx, MeV/cm
*10 3
1.4
1.2
1.
0.8
0.6
0.4
0.2
0.
0.
2.5
5.
7.5
10.
12.5
15.
17.5
20.
Energy, MeV

1-8


secondary electrons detection
Target
Anode
p̄
Channel plates


S1
MCP
S2
S3
400 MeV/c
p̄
degrader
2.8 cm carbon
target
0.5X0.5 X0.001cm³
100 cm


E PBAR FINAL
Yield
500
400
300
200
100
0
0.
2.5
5.
7.5
10.
12.5
15.
17.5
20.
Energy, MeV

Yield, Sensitivity Calculations

Event Rate

$\bar{p}$ beam intensity @ 400 MeV/c	500/spill
# spills/hour	1000
degrader effic., $E_{\bar{p}} < 2.5$ MeV	0.29/sterad
solid angle of target	25 μsterad
MCP efficiency	0.84
annihilations	0.95

Product: 3 events/hour below 2.5 MeV

Energy Loss Resolution at 2 MeV

Nuclear scattering in target	0.003 MeV
Electronic loss fluctuations (13 μ Silicon)	0.015 MeV
Time of flight resolution (0.4 nsec)	0.028 MeV
Quadrature sum	0.032 MeV

Sensitivity

Energy loss difference 13 μ Silicon 0.525 − 0.50 MeV	0.025 MeV
# events 1.4 to 2.2 MeV, 30 hours	55
Uncertainty in difference $0.032 \cdot \sqrt{2} / \sqrt{55}$	= 0.008 MeV

$\frac{4}{3}$ s.d. Barkas effect

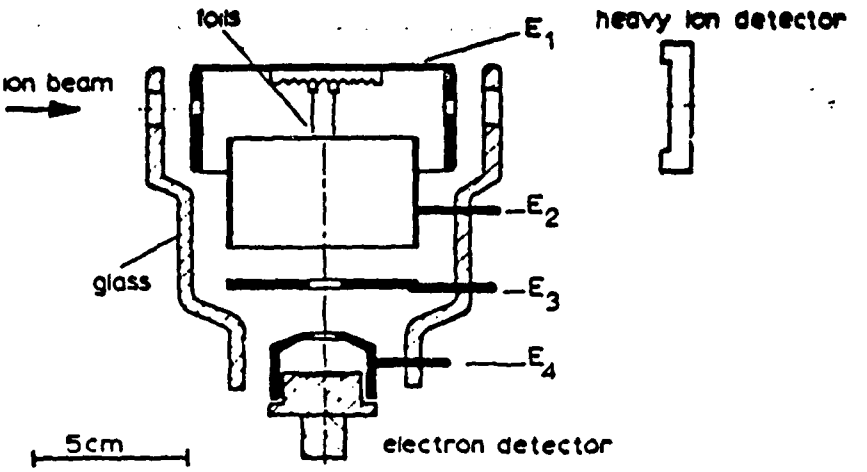


Fig. 1. Apparatus for secondary electron detection.

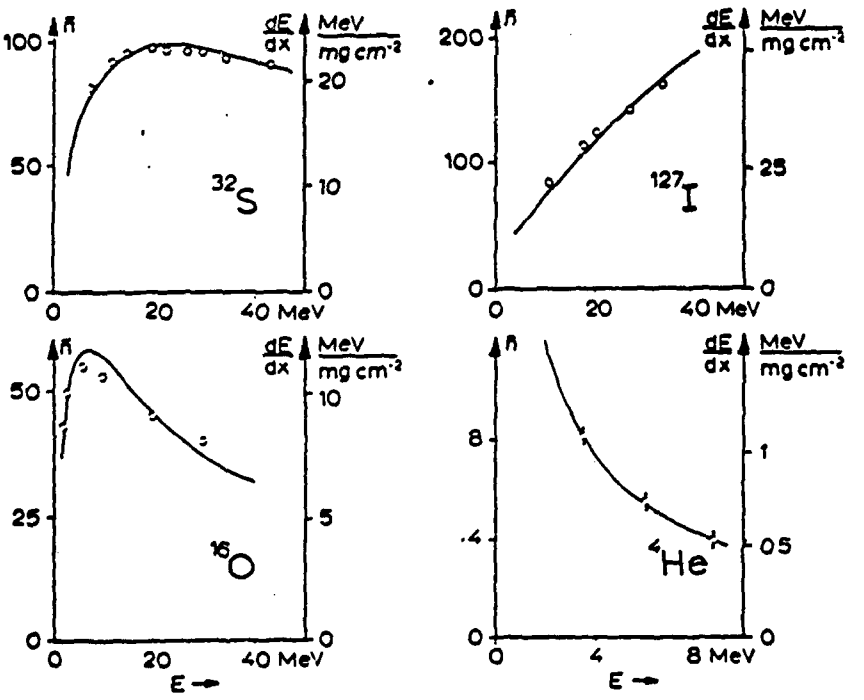
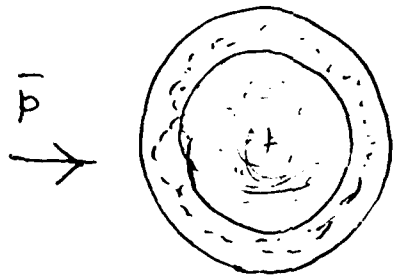
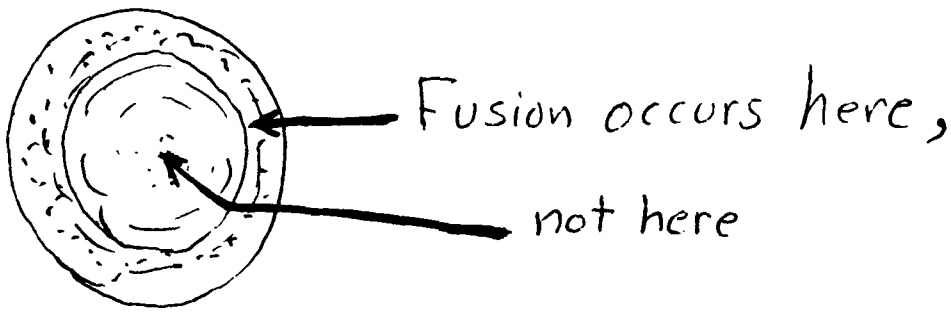


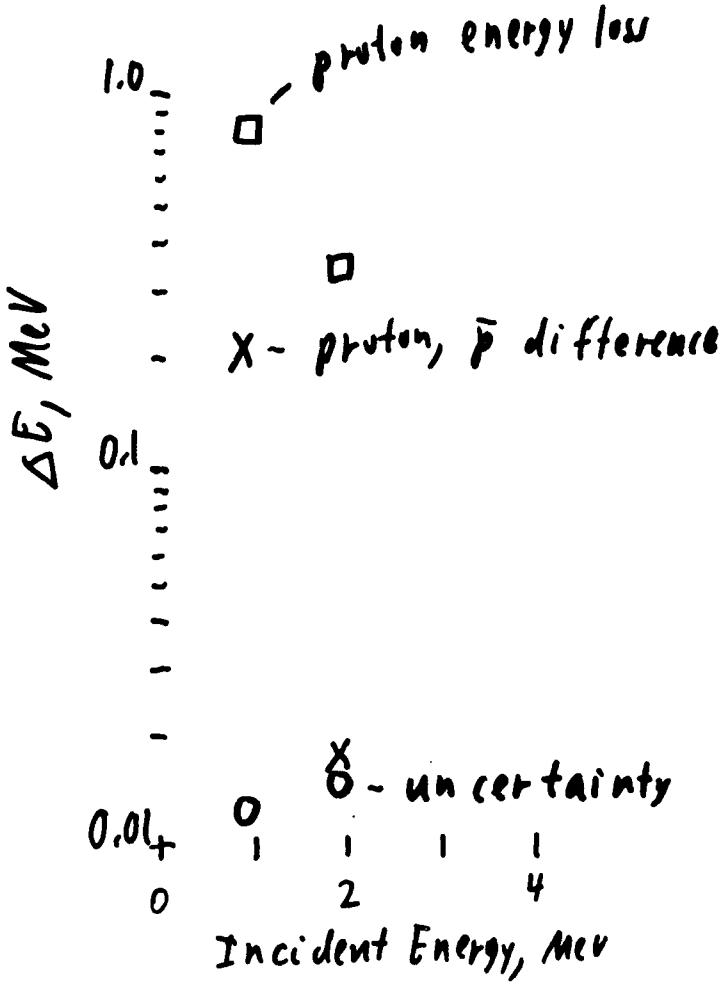
Fig. 7. Average number $\bar{n}$ of secondary electrons (left scales) emitted from one foil as a function of ion energy. Solid lines: Differential energy loss according to Northcliffe and Schilling[12]) (right scales). The normalization is different for different ions: $dE/dx = 1$ MeV/mg cm^{-2} corresponds to the following average numbers of secondary electrons: 7.4 (^{4}He), 5.0 (^{16}O), 4.2 (^{32}S), 3.8 (^{127}I).

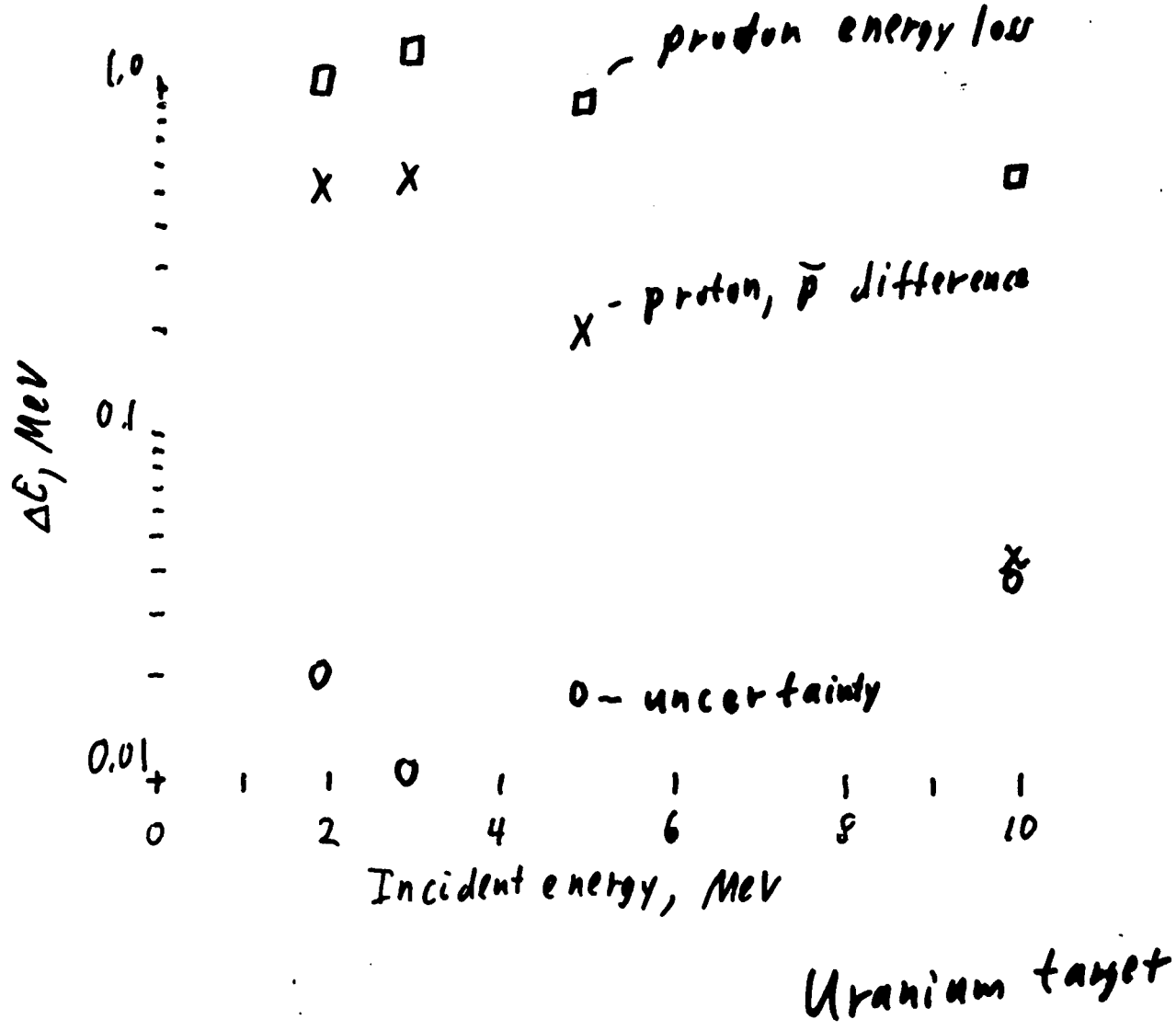
Warm Fusion Shell





Carbon Target




proton energy loss
proton, p̄ difference
0 – uncertainty
ΔE, MeV
1.0
0.1
0.01
0
2
4
6
8
10
Incident energy, MeV
Uranium target

```
E PROTON VS COS TH

HBOOK     ID =      122                                   DATE  18/04/89              NO = 13

CHANNELS 100 U 0                                                                                                   1 O A
         10 N 0         1         2         3         4         5         6         7         8         9         0 V B
          1 D 1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890 E N
          ****************************************************************************************************************
  ABN     *
  OVE     *
    .999  *      + + ++     3+ +32++ ++ 2 4223222427+2+  23 23+5 24442327+244276+68553656722746526633696 83G3456797 *
    .998  *     +   +  +    3 +  + 222+ 2 2+++  22  3543 + 4+2322 ++3 4 24 345344+344346262343+3424455654333583+33 *
    .997  *         + +++2 3 +  2    ++   +2+2+ 23 + +634 + +2+22 + + + 2  ++2+2+ 7+ 532323+3+2355++2 ++2 2334+225 *
    .996  *               + + +++ +2+  ++2++ ++   +22+2+ 3 +22+3+2+2+  +2 + 33232+  3+2+  +3+3 +442+2+3+33  +2+32 *
    .995  *       + +   +        +2+  + +   ++  3    ++2   +2 + + +     ++3+  2  +  2+++++++++ 2+ 2+ +2++ 42+++ +  *
    .994  *     +   +        + 2+ 3 ++  3   +++     + 2   +   +++ + + 23++2   + 2+  ++++   +22+2++ ++   +2+2 +     *
    .993  *          + +       +          +     +         +++  + + +     +     + ++ +  + ++    +  ++3 2++     ++2+ *
    .992  *            +                  +         +    2     ++ + 2   + + 2     +         + + +               2 + *
    .991  *   +    + ++  ++ ++          +      ++ ++   ++++      +           +       ++       +     ++   ++2     2 2 R
    .99   *    ++                +   +       +    +   +     ++ +   ++                  +   2    +   +     +       O
    .989  *           +      +       +  +       +     +++    +    + ++            2  2 +          +    ++ ++       E
    .988  *            +     +               +  +                                  + +    +         +       ++      G
    .987  *                                +       + + +          +   + +        ++  +                            C
    .986  *           +    +         +   +                      +      +  +                                      4
    .985  *<10      + degrees              + + + + +       +                            +                          5
    .984  *            +                                +                        +                  +            3
    .983  *            +        +              +             +     +   +                        +               2
    .982  *         +                                                                  +                         2
    .981  *                                                        +           +                          +  +
    .98   *                                                                                                      2
    .979  *                                                                                                      2
    .978  *                                                                                                      +
    .977  *                                                      +          +                                   2
    .976  *                                                                                      +
    .975  *                                                                          +                   +
    .974  *           +
    .973  *                                  +                                                   +           3
    .972  *                                                        +
    .971  *                                                                                        +
    .97   *                                                                                                      3
    .969  *
    .968  *                                                                                                      2
    .967  *
    .966  *<- 15 degrees                                                                         +            +
    .965  *                                                                                                      2
    .964  *
    .963  *                                                                                                      +
    .962  *
    .961  *                                                                                                      3
    .96   *
  UND     *                  2 MeV >  +   +                    +                                   +       + D
          ****************************************************************************************************************
 LOW-EDGE  1.          1111111111222222222233333333334444444444555555555566666666667777777777888888888899999999999
           0   0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789

 *                                                  I         I
 * ENTRIES =     4779                PLOT         ---------I---------
 * SATURATION  AT=          31                     I 1092    I  380
 * SCALE  .,+,2,3,.,., A,B,          STATISTICS   ---------I---------
 * STEP =    1     * MINIMUM=0                     I    5    I   13
```

Summary

- 1-5% dE/dx measurements for 1-10 MeV $p, \bar{p}$ at BNL
  Sensitive to 5-50% Barkas effect

- 6 targets @ 30 hours, $\bar{p}$ beam — 180 hours
  10 hours, p beam — 60
  240 hours

carbon, silicon, iron, copper, silver, uranium

Sensitive to w/v^3 dependence

Energy Loss by Particle Beams

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ANTIPROTON INDUCED FUSION REACTION

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HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

Antiproton Induced Fusion Reaction

by

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PENN STATE UNIV

Supported by JPL (NASA)

Antiprotons which stop in Uranium cause fission 100% of the time.

Ref

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Zeit für Phys A, 1988

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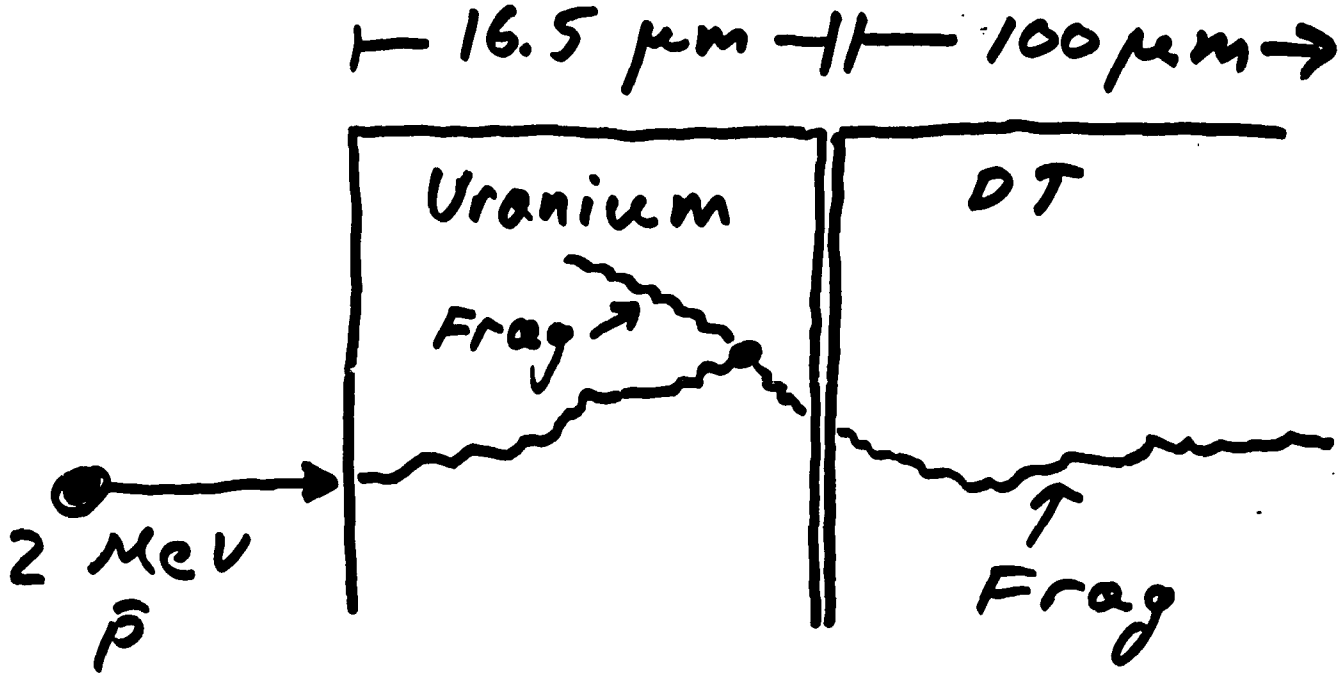
Zeit für Phys A,
in press

Applications ?

- Ability to deposit large amounts of energy in a very small volume
- Ability to create very large pressure and temp
- Ability to induce fusion in a DT pellet



Monte Carlo Code

- Track $\bar{p}$ through U until stop
- Model fission
- Track fission fragment through U
- Track fission fragment through DT
- Track suprathermals through DT
- Calculate & model fusions
- Track alphas through DT

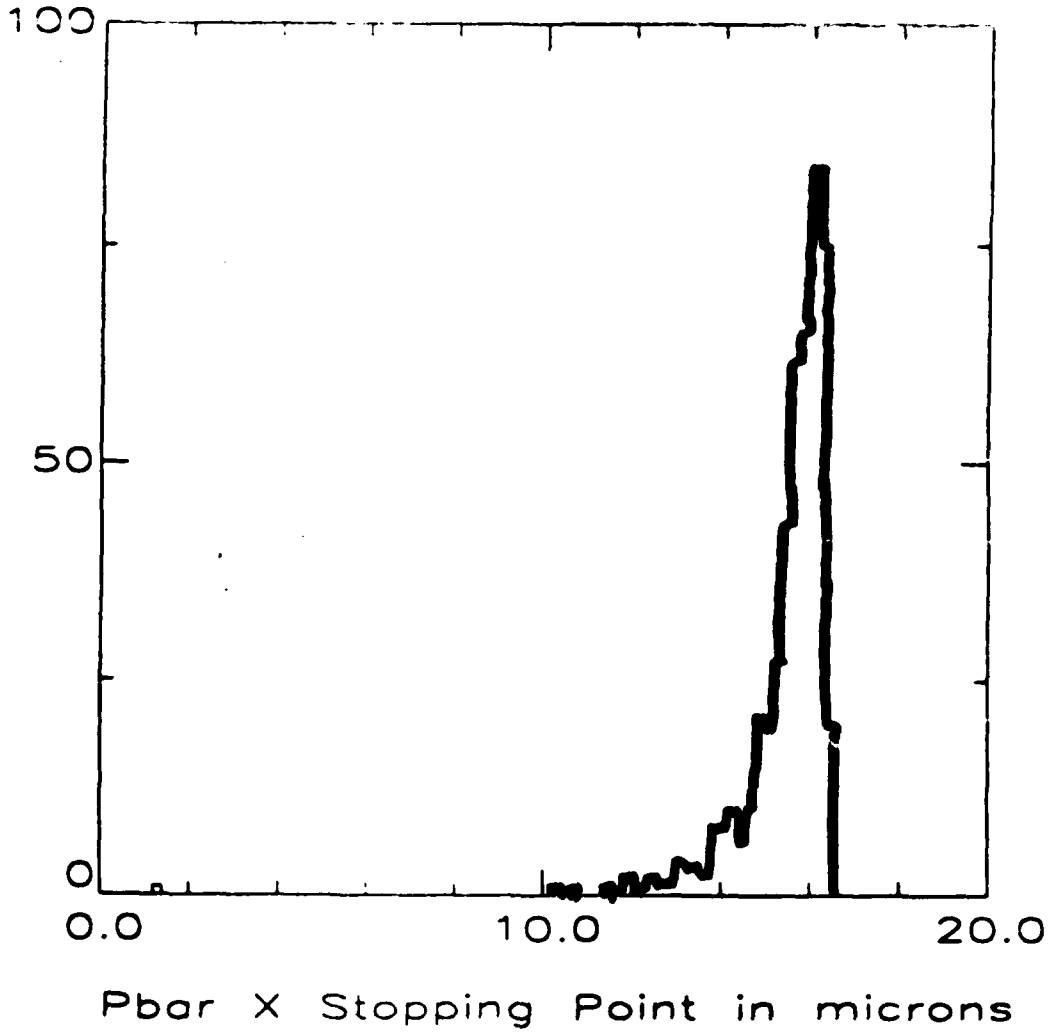


Figure 2

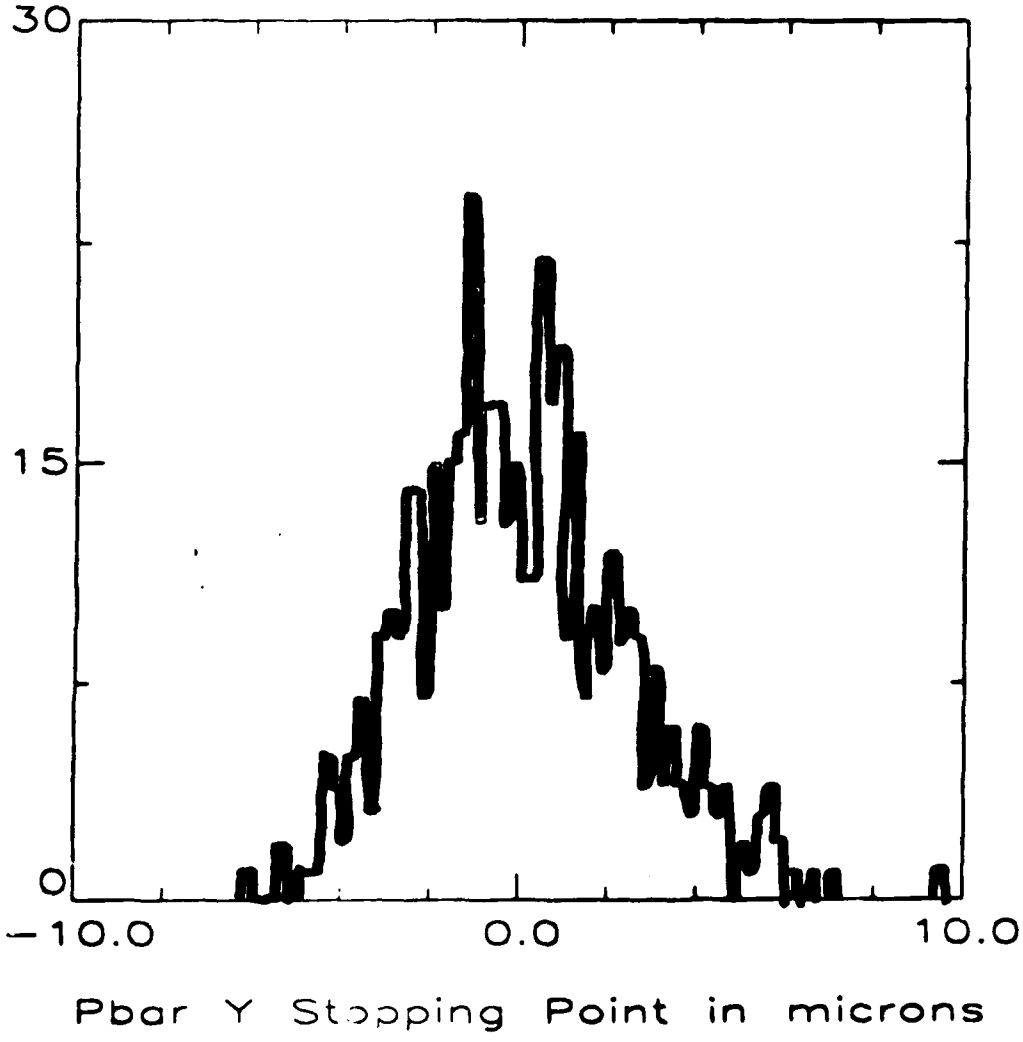


Figure 3

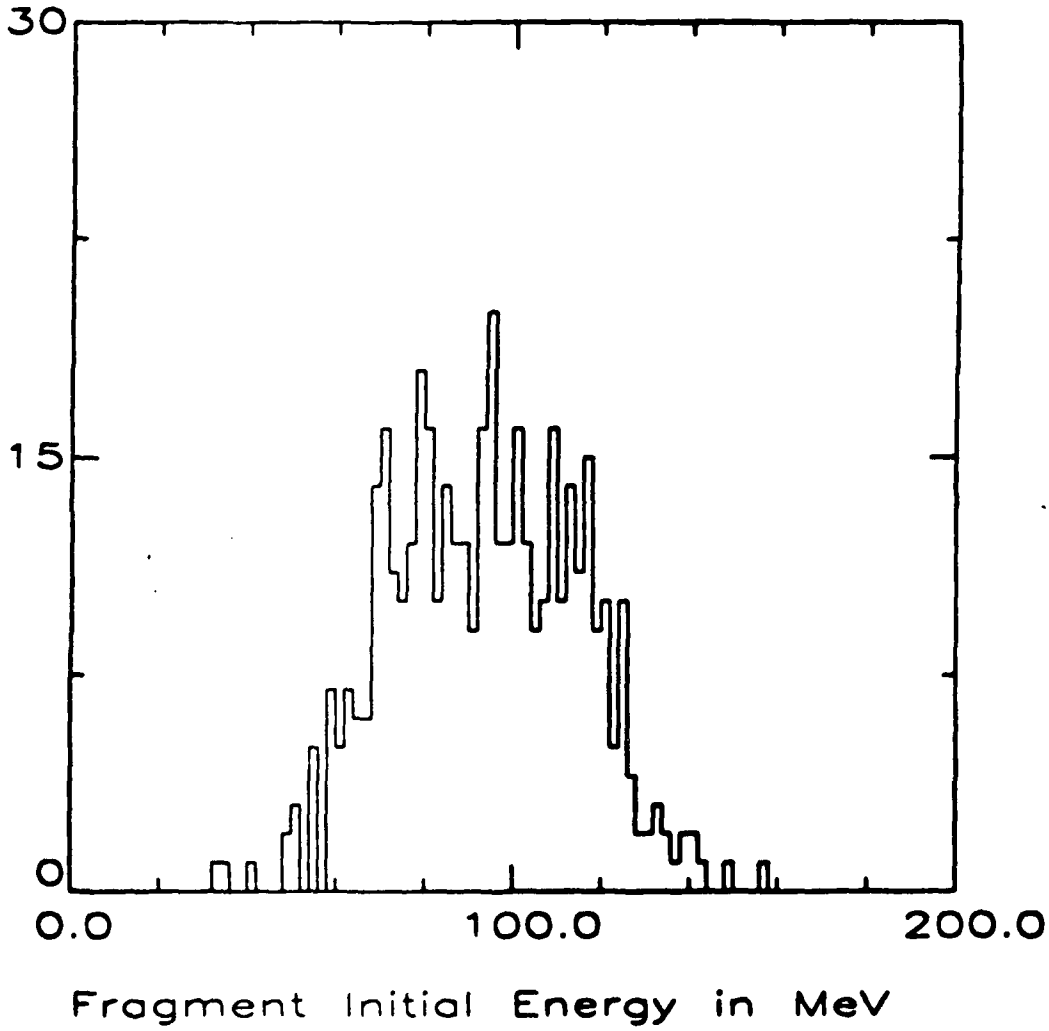


Figure 8

mean = 92 MeV

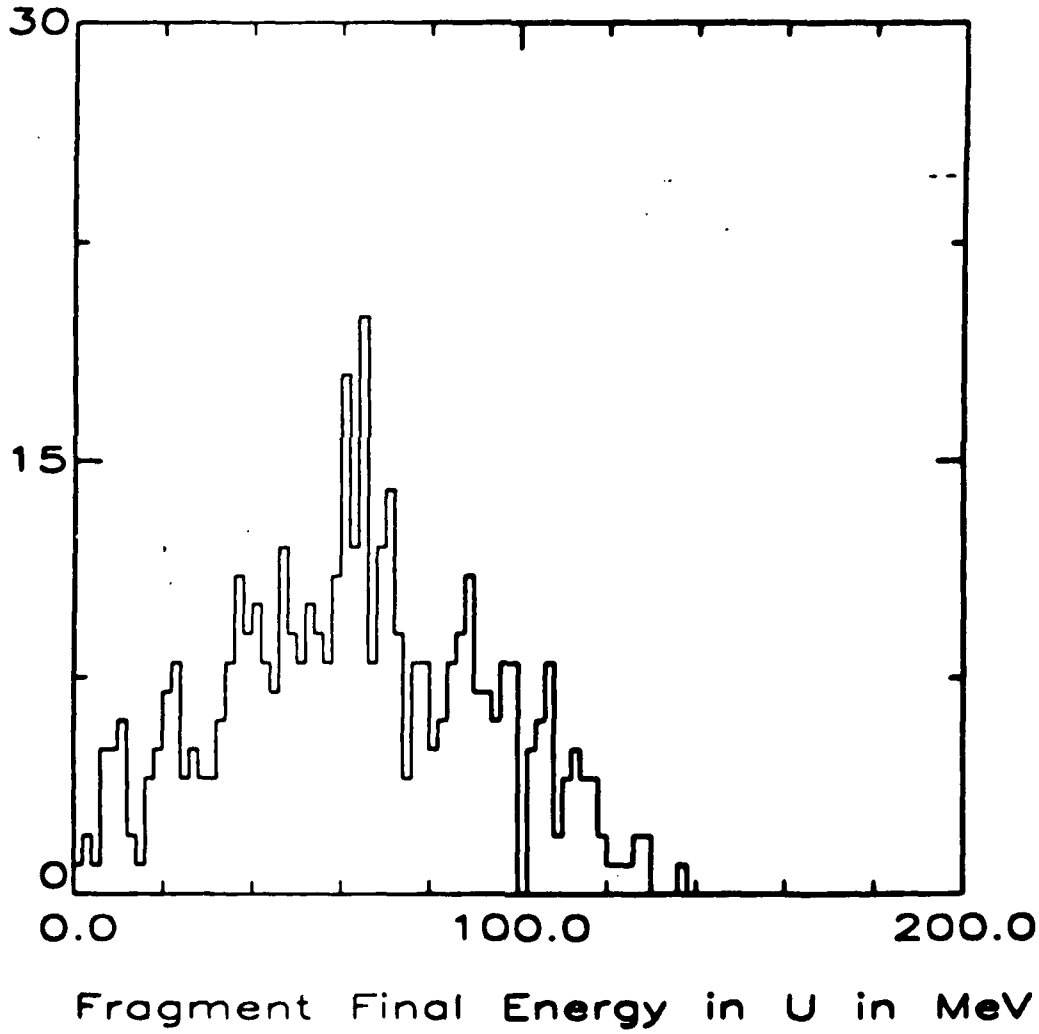
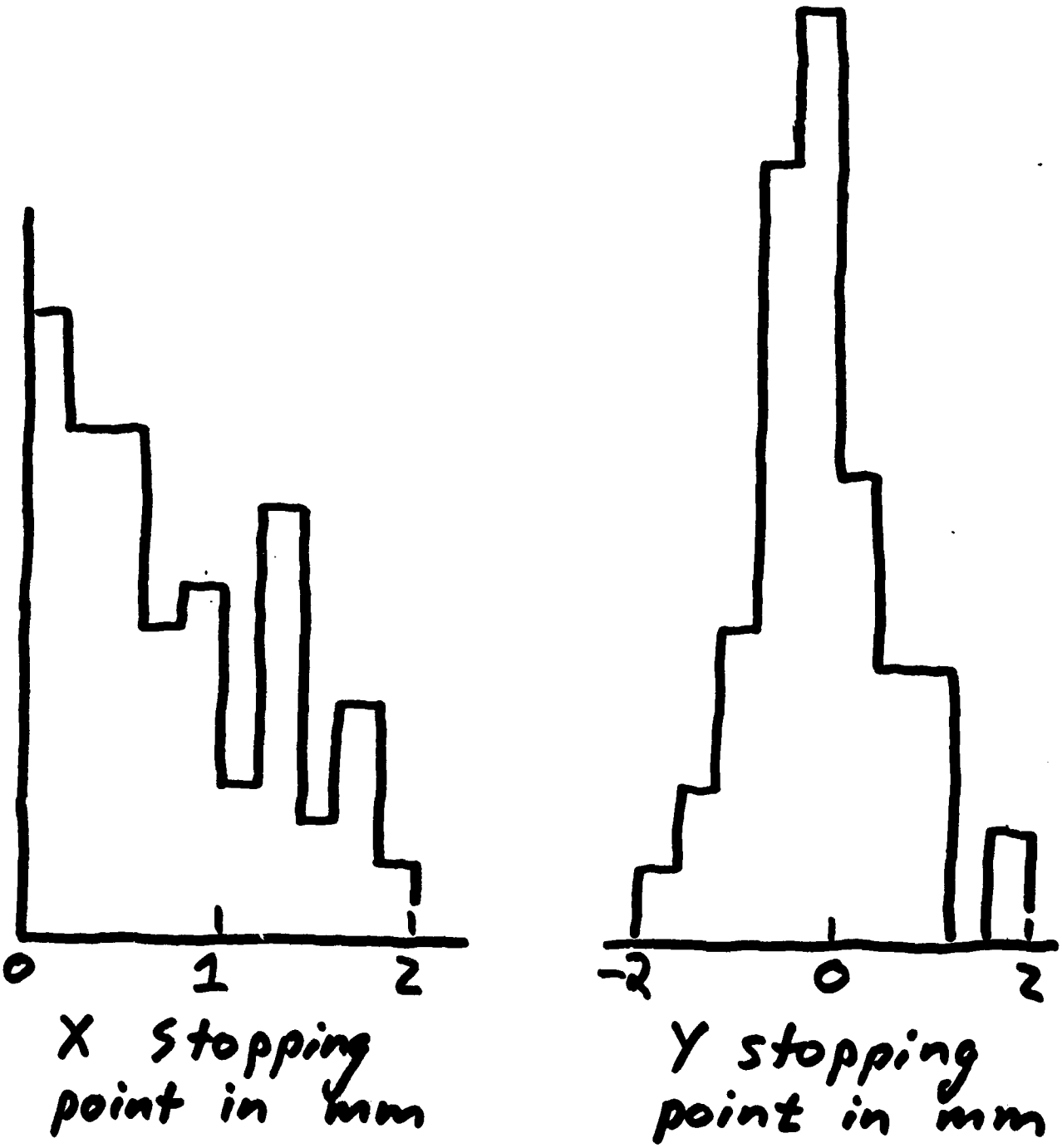


Figure 9

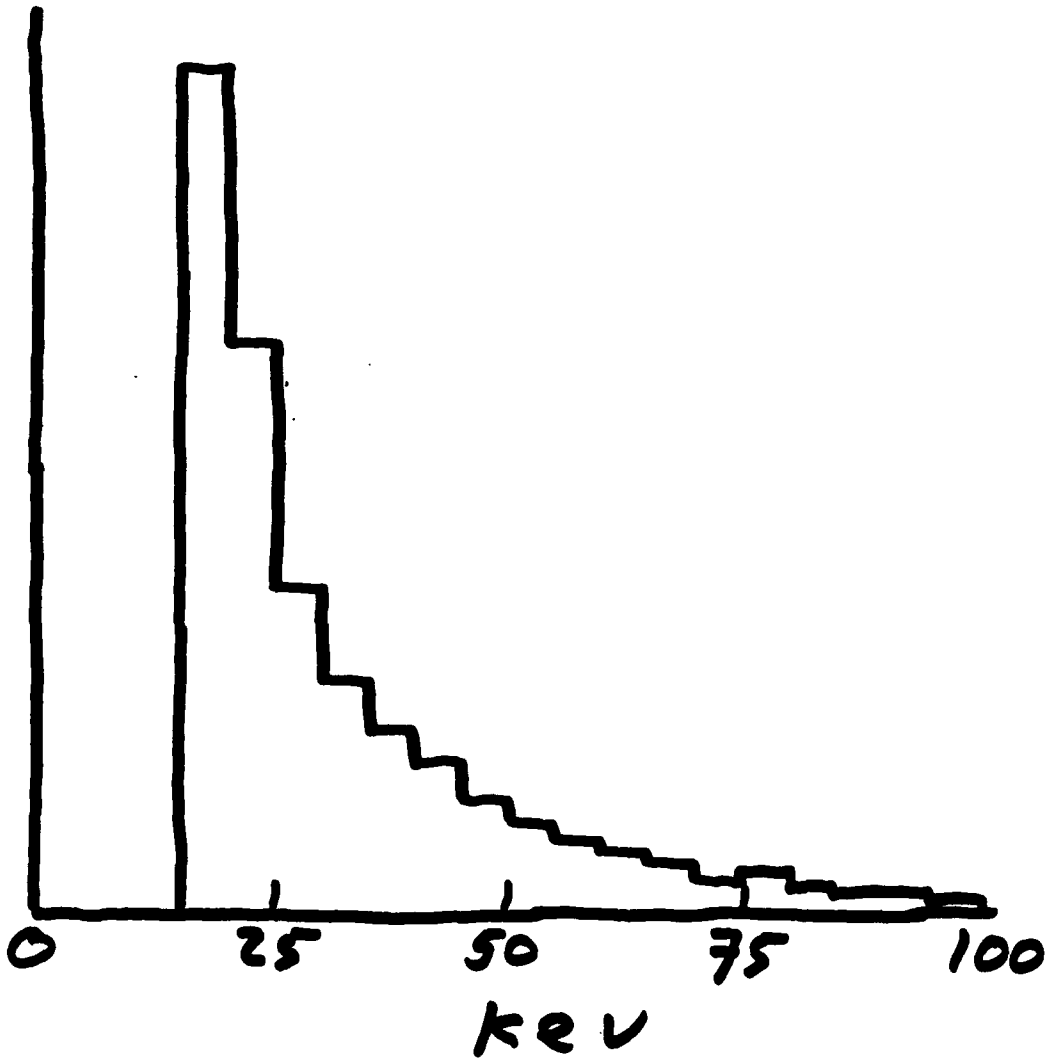
mean = 62 MeV

Fission Fragment Stopping Point in 10 keV OT

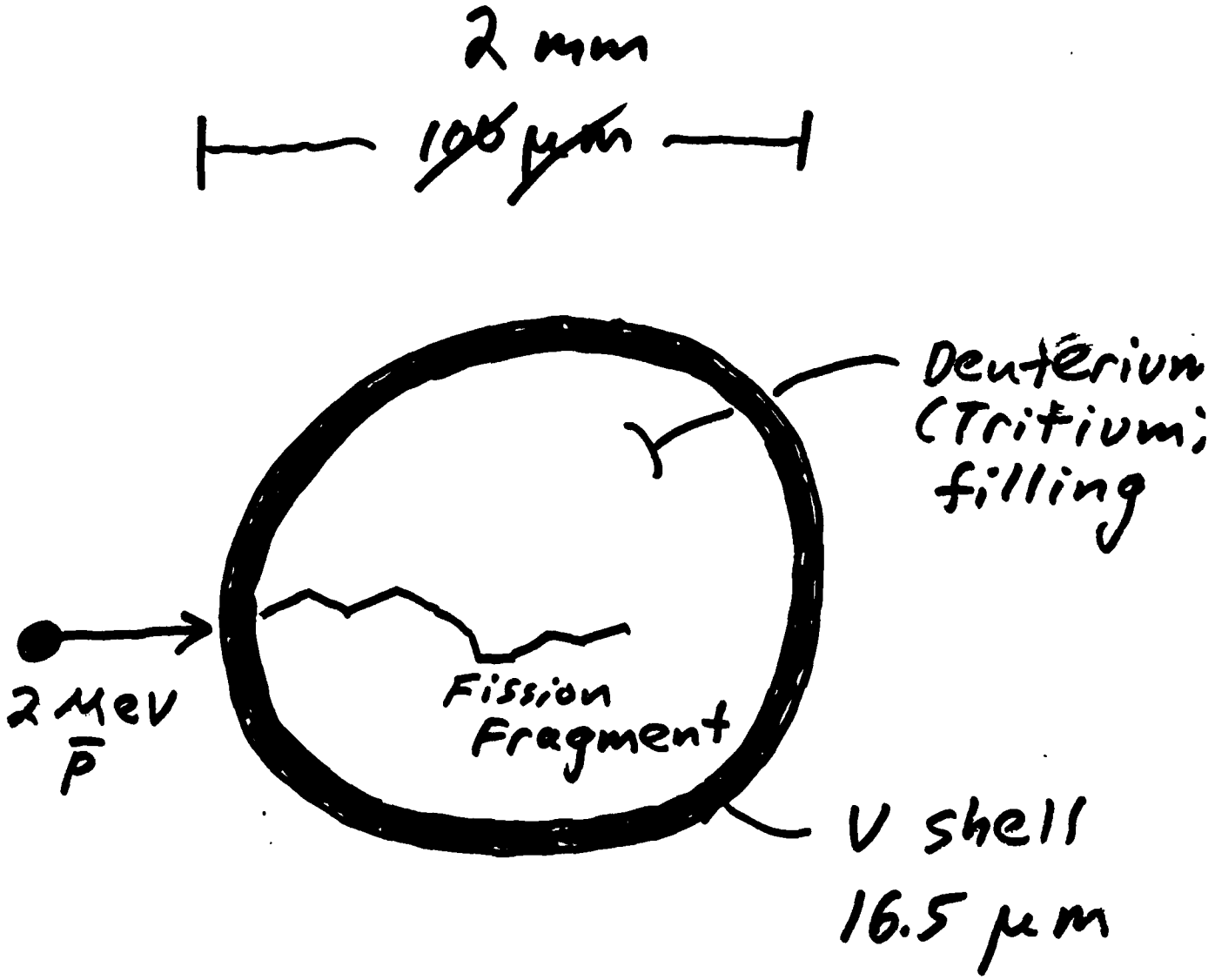


Energy of Suprathermal Deuterons in 10 keV DT

111 suprathermals per pbar



mean = 58 keV


2 mm
~~100 μm~~
Deuterium
(Tritium;
filling
2 MeV
$\bar{p}$
Fission
Fragment
V shell
16.5 μm

Assume: 2 mm dia DT pellet with 16.5 μ U shell

$3.3 \times 10^{15}\ \bar{p}$/ns for 30 ns

Results: 1) Gain ≃ 300 (~1100 $\frac{\text{fusions}}{\bar{p}}$)

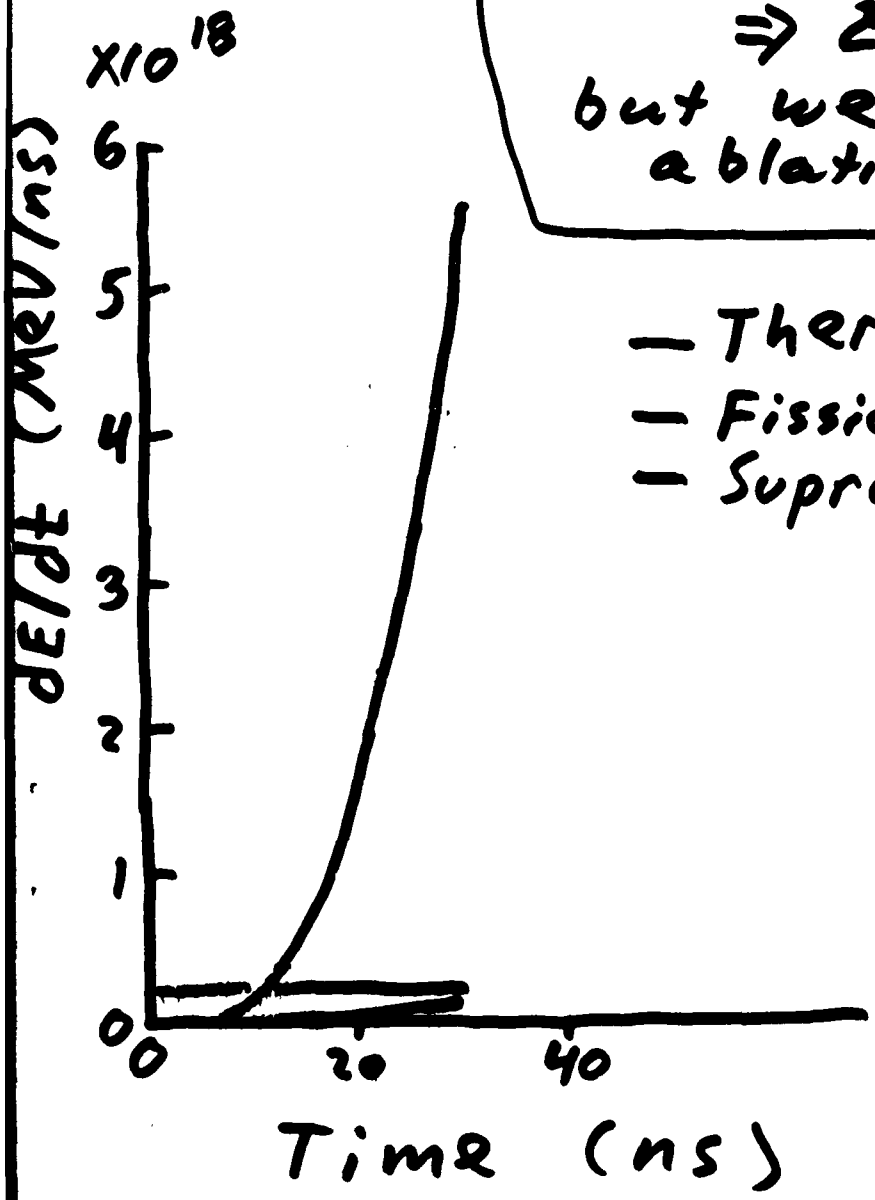
2) Too slow

Lawsons criteria

$n \tau \sigma v = 1$ (100% burn)

$\Rightarrow \tau = 360$ ns

but we estimate ablation time ≃ 10 ns



— Thermal fusions

— Fission fragments

— Suprathermal fusions

Need more help from supra thermals.

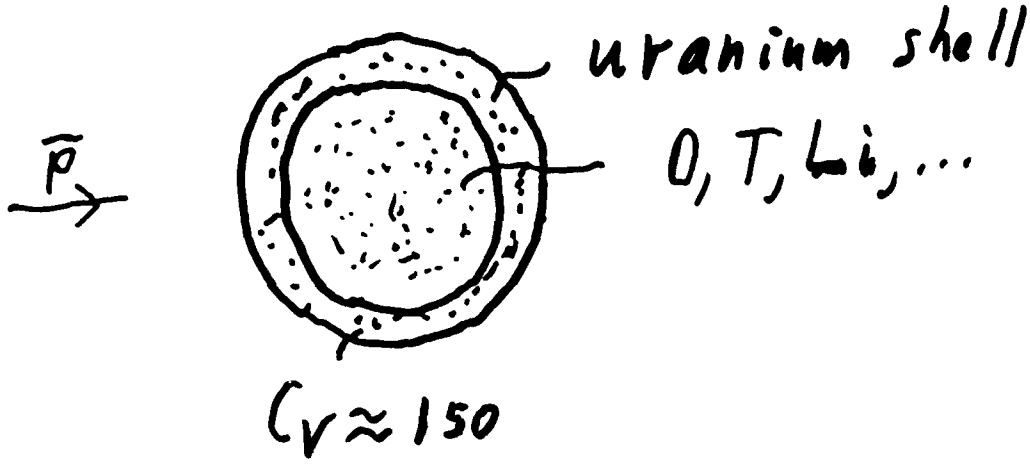
(1) Try adding a moderator like Li or look at reactions involving heavier atoms

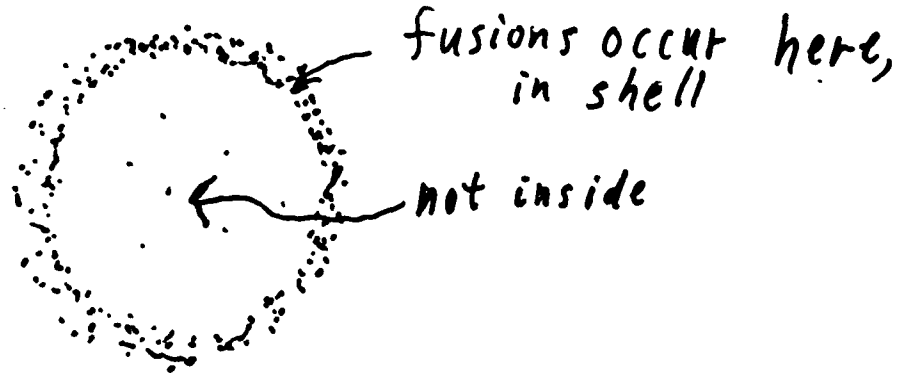
- better energy transfer
- increased stopping

Preliminary look at Li filled pellet:

- frags stop in < 0.25 mm (< 2 mm in DT)
- Suprathermal Li have mean energy ≃ 90 kev (58 kev in DT)

Warm Fusion Shell





$n \tau \sigma v$

J.C. Solem