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A MONOENERGETIC POLARIZED NEUTRON BEAM AT THE ZGS

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ABSTRACT

The feasibility of a monoenergetic polarized neutron beam produced by the dissociation of polarized deuterons from the Argonne ZGS is investigated. Intensities on the order of 10^5 neutrons per pulse with polarizations of 50 percent seem achievable, based on calculations of Coulomb photodisintegration using a Weizsäcker-Williams approximation. Several plans for realizing such a beam are presented.

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I. INTRODUCTION

The recent advent of high energy polarized proton beams at the Argonne Zero Gradient Synchrotron(1) has opened new areas of strong interaction physics for investigation. For the first time proton-proton scattering experiments can be done with the spin states of both the incident and target protons known(2). Polarized protons have also been very useful in investigating inelastic reactions, both quasi-two body(3) and inclusive(4).

To do a complete set of nucleon-nucleon scattering experiments a beam of polarized neutrons would be required. Such a beam could be obtained from Coulomb dissociation of high energy deuterons. Such a dissociation technique has been developed by a group from the University of California at San Diego, working at the Lawrence Berkeley Laboratory.(5)

This technique is illustrated schematically in Fig. 1. A beam of deuterons strikes a nuclear target, interacting either with the hadrons in the nucleus or with its Coulomb field. In the process the neutron and proton become separated and one or both emerges as a free particle with about half the momentum of the original beam. In the case where both particles emerge a measurement of the proton momentum also gives a more precise value for the neutron momentum.

This report presents an evaluation of this technique for producing a polarized neutron beam of useable quality. In Section II a brief discussion of the problems involved in accelerating polarized deuterons is presented. Section III contains the results of a Weizsäcker-Williams calculation of the photodissociation cross section of a deuteron in the Coulomb field of a heavy nucleus. In Section IV several different plans of varying cost and utility are presented and their relative merits discussed. Finally, in Section V the results are summarized and conclusions presented.

II. ACCELERATION OF A POLARIZED DEUTERON BEAM[+]

The existing polarized proton source could be modified to produce polarized deuterons quite easily. In its present form the polarization produced would be only about 30 percent, but for a modest amount of money another radio-frequency cavity could be added which would increase the polarization to about 65 percent. The current produced would be about the same as presently obtained with protons.

The ZGS linac design is far from ideal for deuterons. It is necessary to reprogram it because of the charge-to-mass ratio difference between protons and deuterons. (For example the deuteron must stay in the drift tubes for 3/2 cycles instead of 1/2 cycle.) However this has been done and deuterons have been accelerated through the linac with an observed transmission about one-fifth that for protons. There appears to be no way to avoid this loss.

[+] I am grateful to Dr. E. Parker for most of the material presented in this section.

The ZGS is able to accelerate deuterons, but one major problem must be overcome. The frequency range of the ZGS radio frequency system is 4 to 14 Mhz and deuterons require 2 Mhz at injection. Therefore it would be necessary to inject at the 16th harmonic (instead of the usual 8th) accelerate the beam to as high an energy as possible, flat top the ring magnets, and turn off the rf. The rf would be turned on again at the 8th harmonic, thus rebunching the beam, which can then be accelerated to the full ZGS energy. This technique loses about half the beam.

Fortunately, there are no depolarizing resonances below 12 GeV/c of the kind so troublesome with polarized protons. Thus it is expected that the full polarization produced by the source could be delivered in an accelerated beam.

In summary, one could expect the ZGS to produce a beam of 5-10 x 10^7 deuterons/pulse (about 10 percent of the intensity of the ZGS polarized proton beam) with a polarization of about 65 percent.

III. PHOTODISSOCIATION OF THE DEUTERON

At the heart of this method is the splitting of a deuteron into a free proton and a free neutron. Since there is a very high correlation between the nucleon spins in a deuteron (the deuteron is about 95 percent ^3S state) the polarization will be retained by the free nucleons if the splitting process does not flip either spin.

There are three primary processes which will split a deuteron: 1) nuclear stripping, where the proton undergoes a strong interaction leaving the neutron free, 2) nuclear dissociation where the deuteron as a whole picks up enough energy from a strong interaction to break apart, and 3) Coulomb dissociation, where the deuteron undergoes an electromagnetic interaction with the nuclear Coulomb field and breaks apart. For light nuclei the nuclear stripping process dominates the other two by an order of magnitude, but for heavy nuclei the stripping and Coulomb dissociation are almost equal and are each an order of magnitude stronger than nuclear dissociation.(6)

Because it does not also give a free proton which can be used to tag the neutron momentum, the stripping process is not as useful for producing a neutron beam; thus the remainder of this report will concentrate on the Coulomb dissociation.

The Coulomb interaction can be estimated quite easily using a Weizsäcker-Williams approximation.(7) The calculation is performed in the rest frame of the deuteron, where a heavy nucleus of charge Z at high energy strikes the deuteron. The Coulomb field of the nucleus is represented as a spectrum of virtual quanta; in the low frequency limit (which is good for this application) the number of quanta per unit energy is

$$N(\hbar\omega) \simeq \frac{2}{\pi}\left(\frac{q^2}{\hbar c}\right)\left(\frac{c}{v}\right)^2 \frac{1}{\hbar\omega}\left[\ln\left(\frac{1.123\gamma v}{\omega\, b_{min}}\right) - \frac{v^2}{2c^2}\right] \qquad (1)$$

where $q = Ze$ is the charge of the heavy nucleus, v is its velocity, γ is the usual relativistic factor for the heavy nucleus and b_{min} is the minimum impact parameter allowed, chosen to be the approximate radius of the heavy nucleus. Note the inverse of the decay length in the ground state of the deuteron, $r_{0t} = 1.7 \times 10^{-13}$ cm is the ^3S effective range for np scattering, and $a_s = 2.37 \times 10^{-12}$ cm is the scattering length in the ^1S state of the np system. Expressions (2) and (3) integrated over $d\Omega$ are plotted in Fig. 2.

To calculate the cross section for E1 or M1 Coulomb dissociation of the deuteron in the lab frame at a fixed angle and neutron momentum all that is necessary is to multiply expression (1) by either expression (2) or (3) and by the appropriate kinematic Jacobian, then make a Lorentz transformation to the laboratory frame.

The result is a doubly differential cross section in $d\Omega$ and dp, the angle and momentum of the neutron. For fixed angle the cross section as a function of p shows a sharp peak at about $p = p_D/2$, where p_D is the deuteron momentum. This is illustrated in Fig. 3 for deuteron momenta of 5.8 and 12 GeV/c. The width of both peaks is about ±2%.

The angular distributions defined by

$$\frac{d\sigma}{d\Omega} = \int_{.45\ p_D}^{.55\ p_D} \frac{d^2\sigma}{d\Omega dp}\, dp$$

are plotted in Fig. 4. For the E1 distribution we find almost all the events going into a cone at a small finite angle which decreases with increasing energy. There are no E1 events at zero degrees. The M1 distribution shows the opposite behavior; there is a sharp forward peak with very little tail at larger angles. These distributions simply reflect the angular distributions of the E1 and M1 transitions.

A very striking feature of Fig. 4 is the large increase in the peak value of the cross section between 5.8 and 12 GeV/c. This is due almost entirely to the angular distributions being folded forward by kinematics. The total E1 cross section, shown in Fig. 5, increases by only 30 percent from 5.8 to 12 GeV/c, while the peak value of the differential cross section increases by a factor of five. The total M1 cross section is an order of magnitude lower than the E1 total cross section but because of its different angular distribution the M1 transition can dominate in the forward direction.

In order to get a high counting rate it will be necessary to use a thick target of high-Z material; this means there will be appreciable multiple scattering of the incident deuteron beam and this can wash out much of the angular structure of Fig. 4. This can be included in the calculation, however, and the result is shown in Fig. 6. The assumptions used were a 1.25 inch Uranium target, and a multiple scattering angle which can be approximated by a Gaussian distribution of width $\theta_0 = .021 \sqrt{t}/(\beta_D p_D)$, where t is the target thickness in radiation lengths and β_D and p_D are the velocity and momentum (in GeV/c) of the incident beam.

Fig. 6 shows that the forward valley in the E1 distribution is mostly filled in and that the peak is substantially reduced. There is still about 20 percent more beam in the peak than in the forward direction, but more importantly the ratio of E1 to M1 is much greater at the peak, giving a higher polarization. In fact the M1 background at the peak only reduces the polarization from 65 percent to about 55 percent. The small D wave component of the deuteron would further reduce this to about 50 percent.

The smeared 12 GeV/c cross section in Fig. 6 can be used to estimate a yield. An answer of 10^5 neutrons per pulse results from the following assumptions: 1) the ZGS gives 10^8 polarized deuterons per pulse, 2) a 1.25 inch uranium target is used (about .3 collision lengths), 3) the experimental target subtends a solid angle of 1.36×10^{-5} sr (a 2 inch diameter target 40 feet from the stripping) and 4) the collection and momentum tagging efficiency is 50 percent. Even allowing for some additional unexpected losses this is an adequate flux for a number of experiments.

IV. BEAM DESIGNS

There are many ways this idea could be implemented, depending on the physics to be done and the resources available. Four of these are presented in Figs. 7a-7d.

Plan A (Fig. 7a). An external polarized deuteron beam strikes a uranium target; the forward charged particles are swept out by a magnet and a collimator forms the beam at the appropriate angle to the deuteron beam. No attempt is made to recover the associated protons. The disadvantages of this plan are relatively poor neutron momentum resolution (2-3%) and the difficulty in measuring the neutron polarization. Because neutrons from nuclear stripping would also be included the polarization many differ from what one would get from Coulomb dissociation. The advantages are simplicity and low cost.

Plan B (Fig. 7b). This is the plan used by the San Diego group at Berkeley. It is the same as A with the addition that the associated protons are collected by a quadrupole magnet and their momentum measured by a bending magnet and counter hodoscope. This arrangement gives better momentum resolution than plan A (the San Diego group measured it to be much better than 0.7%) but still does not measure the neutron polarization.

Plan C (Fig. 7c). The associated protons are collected and reconstructed into a polarized proton beam. The requirements on the beam line are about the same as for normal secondary beams so no significantly new beam designs would be required. The polarization of the proton beam would be the same as that of the neutron beam and so could be used to monitor the polarization. The proton beam could also be used for physics experiments.

Plan D (Fig. 7d). This plan uses an internal target in octant 4 of the ZGS to produce the beam. The neutron beam would go along the former 7° neutral beam line and the protons would travel into the L3 straight section where a momentum hodoscope would be located. This plan would give a much higher intensity because of multiple transversals of the target and would have much less multiple scattering. However, like plans A and B it offers no easy way to measure the neutron polarization. Detailed studies of this plan have not been performed so its feasibility is not presently known.

V. CONCLUSIONS

There are many experiments which could use this beam, some of the more obvious being total cross sections and elastic and charge exchange scattering. The availability of deuterium and polarized proton targets increases the number of experiments still more. Of course, inclusive reactions and two body inelastic reactions could also be studied.

In conclusion, the technology to produce a monoenergetic polarized neutron beam of momentum up to 6 GeV/c with an intensity of about 10^5 neutrons/pulse and a polarization of 50 percent presently exists.

Such a unique beam could provide much useful physics at the ZGS.

ACKNOWLEDGEMENTS

I would like to thank Dr. Charles Ward for his strong encouragement and many helpful discussions. As noted earlier, Dr. Everett Parker has been very helpful in supplying information about the ZGS. Finally I would like to thank Prof. O. Piccioni of the University of California at San Diego and Mr. Mark Richardson of the Lawrence Berkeley Laboratory for useful discussions of their related work.

REFERENCES

1. For information about the polarized proton beam see: The Proceedings of the Symposium on the High Energy Physics of Polarized Beams, Argonne National Laboratory, February 1974, ANL/HEP 7440. See also the following reference.
2. E. F. Parker, et al., Phys. Rev. Lett. 31, 783 (1973).
3. A. B. Wicklund, et al., Inelastic Polarized Proton Interactions at 6 GeV/c, Report to the XVIIth International Conference on High Energy Physics, London, July 1974.
4. I. Ambats, et al., Inclusive Production of Λ^0's Using a Polarized Proton Beam, Report to the XVIIth International Conference on High Energy Physics, London, July 1974.
5. P. Bowles, et al., Deuteron Stripping at 6 BeV/c and Production of a Tagged Neutron Beam, Bull. of the Am. Phys. Soc., 1 December 1972 (abstract); C. Leeman, et al., in the Proceedings of the International Conference on Instrumentation for High Energy Physics, Frascati, Italy, 1973, p. 731.
6. Göran Fäldt, Phys. Rev. D5, 846 (1970).
7. J. D. Jackson, Classical Electrodynamics, John Wiley and Sons, New York, 1962.
8. John M. Blatt, and Victor F. Weisskopf, Theoretical Nuclear Physics, John Wiley and Sons, New York, 1952.

FIGURE CAPTIONS

1. The deuteron dissociation process.
2. The Weizsäcker-Williams virtual quata flux for uranium (right hand scale) and the E1 and M1 deuteron photodisintegration cross sections (left hand scale).
3. The spread in untagged neutron momentum at the production angle giving the maximum intensity.
4. Neutron angular distributions from E1 and M1 transitions at incident deuteron momenta of 5.8 and 12 GeV/c, integrated over the peak in Fig. 3.
5. The total E1 induced cross section as a function of incident deuteron momentum.
6. The neutron angular distributions with multiple scattering included (solid line). The dashed lines are the unsmeared distributions of Fig. 4.

7a-7c. Plans for beam lines using an external deuteron beam.

7d. A plan for a beam from the internal ZGS deuteron beam.

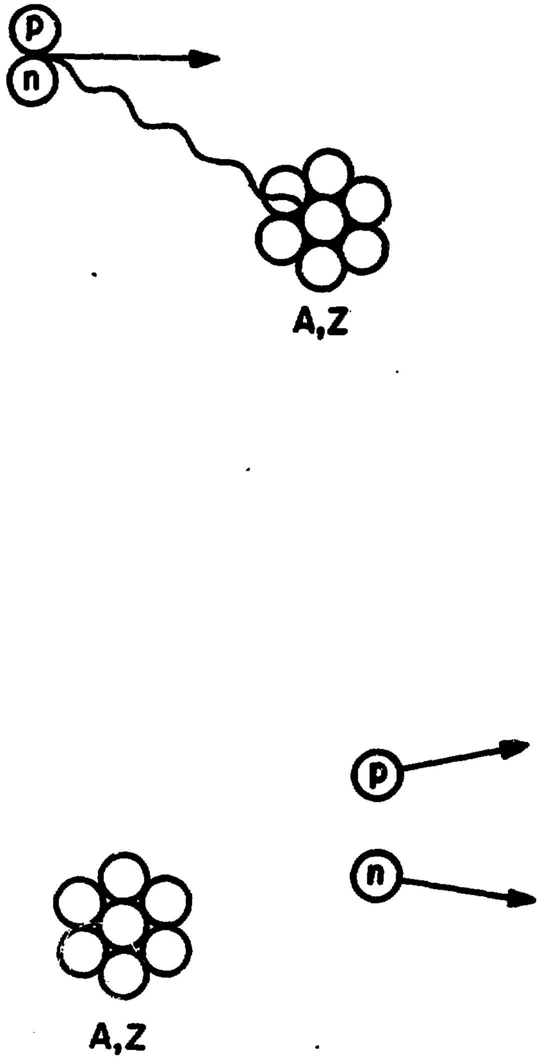
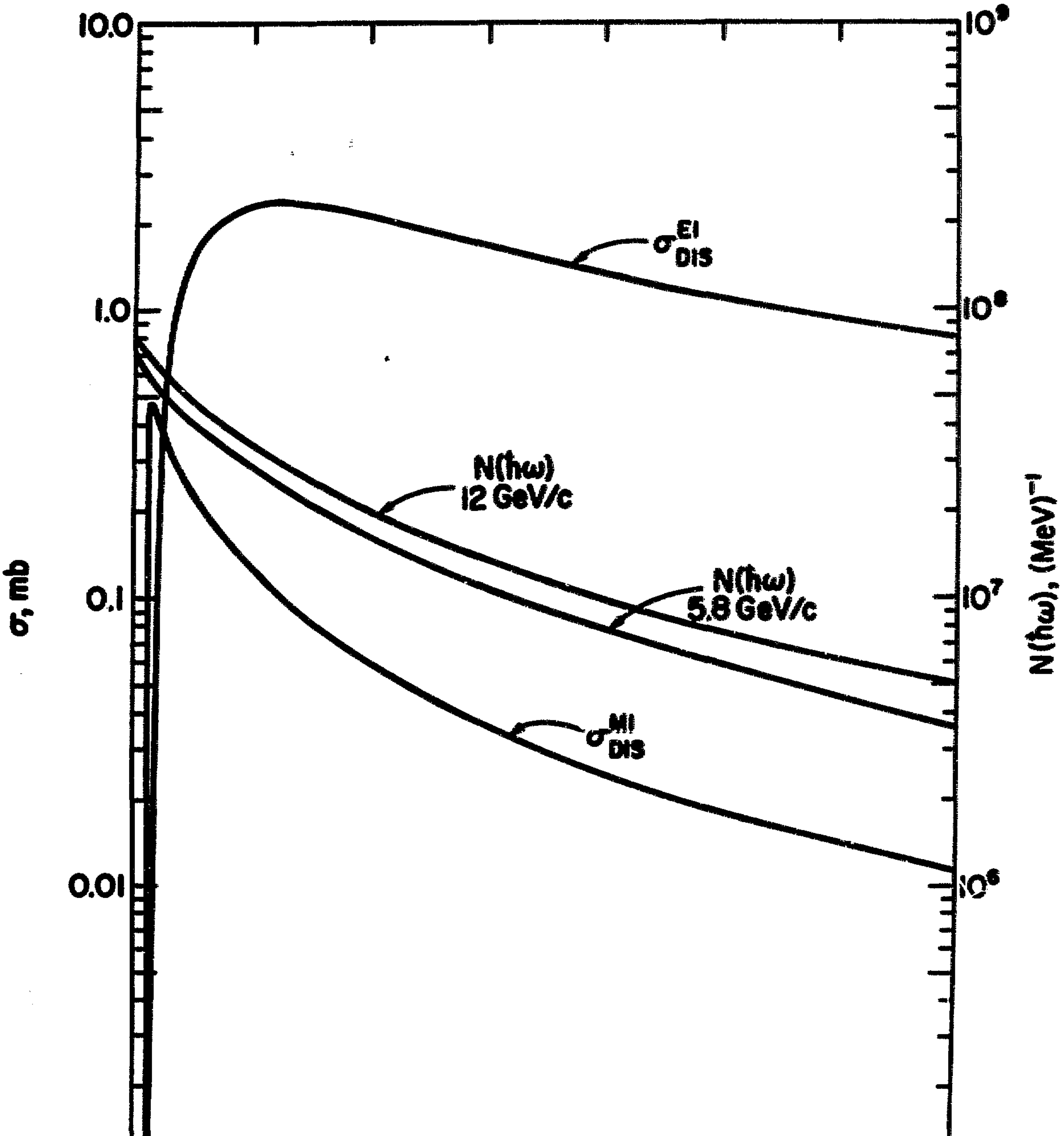


Figure 1



10.0
1.0
0.1
0.01
0.001
σ, mb
10^9
10^8
10^7
10^6
10^5
N(ħω), (MeV)$^{-1}$
σ_{DIS}^{E1}
N(ħω) 12 GeV/c
N(ħω) 5.8 GeV/c
σ_{DIS}^{M1}
2
4
6
8
10
12
14
16
E_γ, MeV

Figure 2

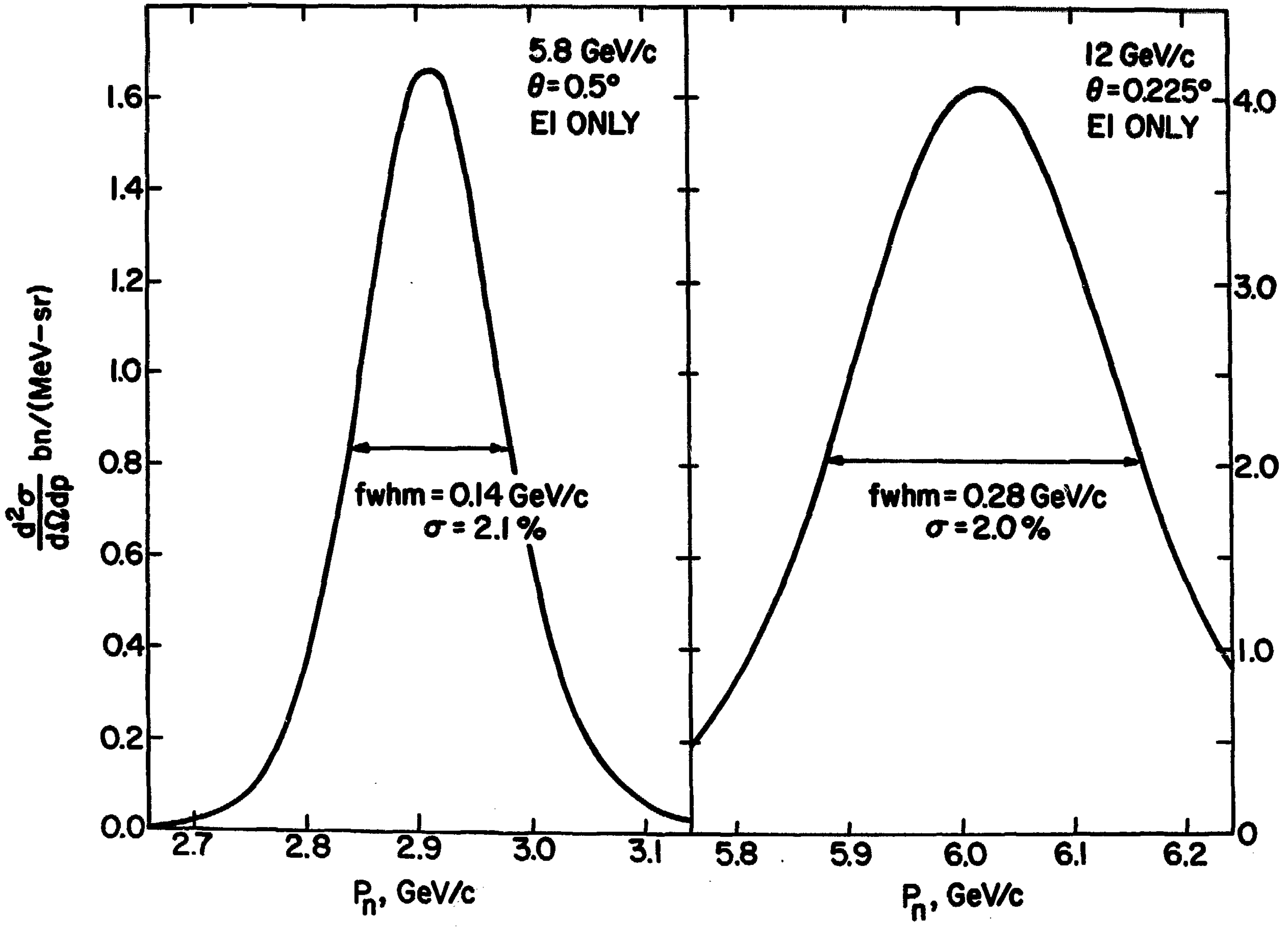

$\frac{d^2\sigma}{d\Omega dp}$ bn/(MeV–sr)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2.7
2.8
2.9
3.0
3.1
P_n, GeV/c
5.8 GeV/c
θ=0.5°
EI ONLY
fwhm = 0.14 GeV/c
σ = 2.1 %
12 GeV/c
θ=0.225°
EI ONLY
fwhm = 0.28 GeV/c
σ = 2.0 %
4.0
3.0
2.0
1.0
0
5.8
5.9
6.0
6.1
6.2
P_n, GeV/c

Figure 3

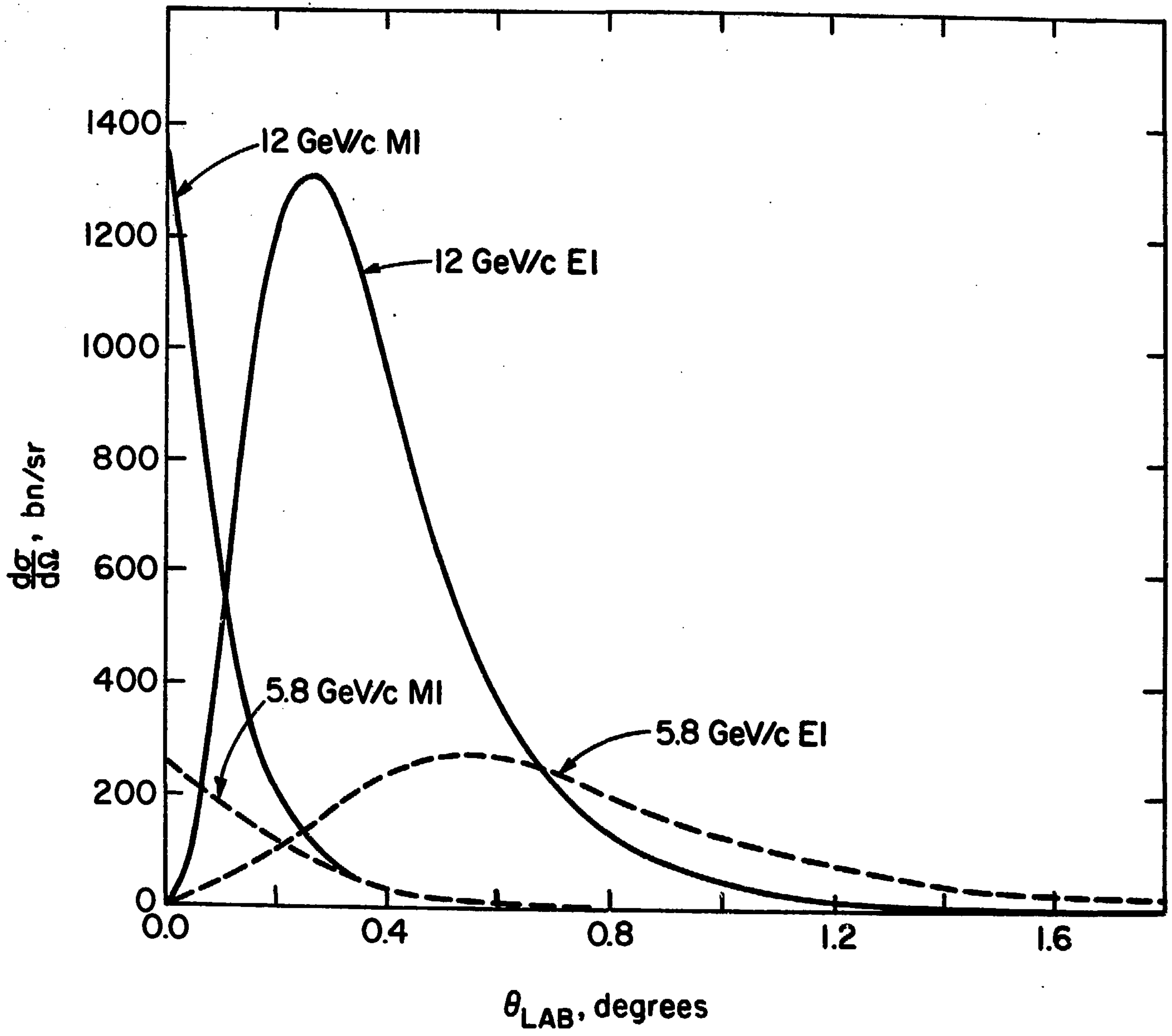

$\frac{d\sigma}{d\Omega}$, bn/sr
1400
1200
1000
800
600
400
200
0
0.0
0.4
0.8
1.2
1.6
θ_{LAB}, degrees
12 GeV/c MI
12 GeV/c EI
5.8 GeV/c MI
5.8 GeV/c EI

Figure 4

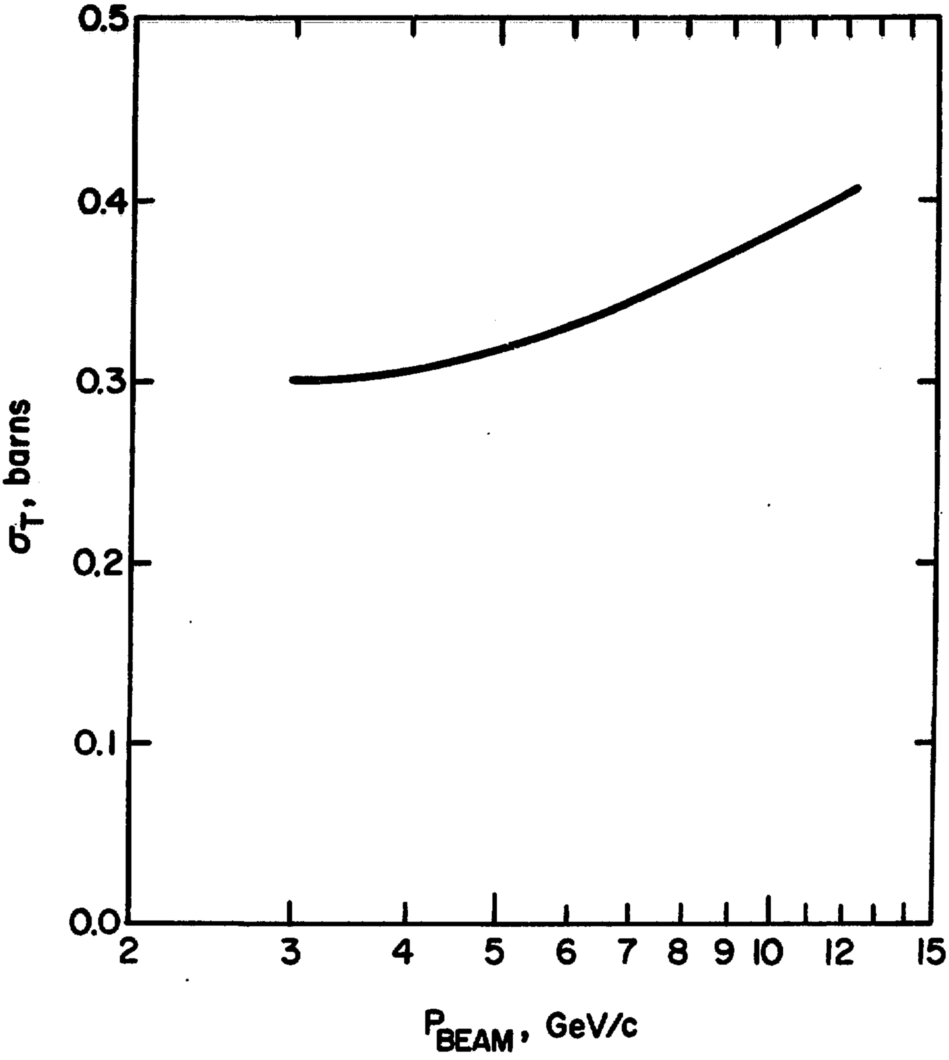


Figure 5

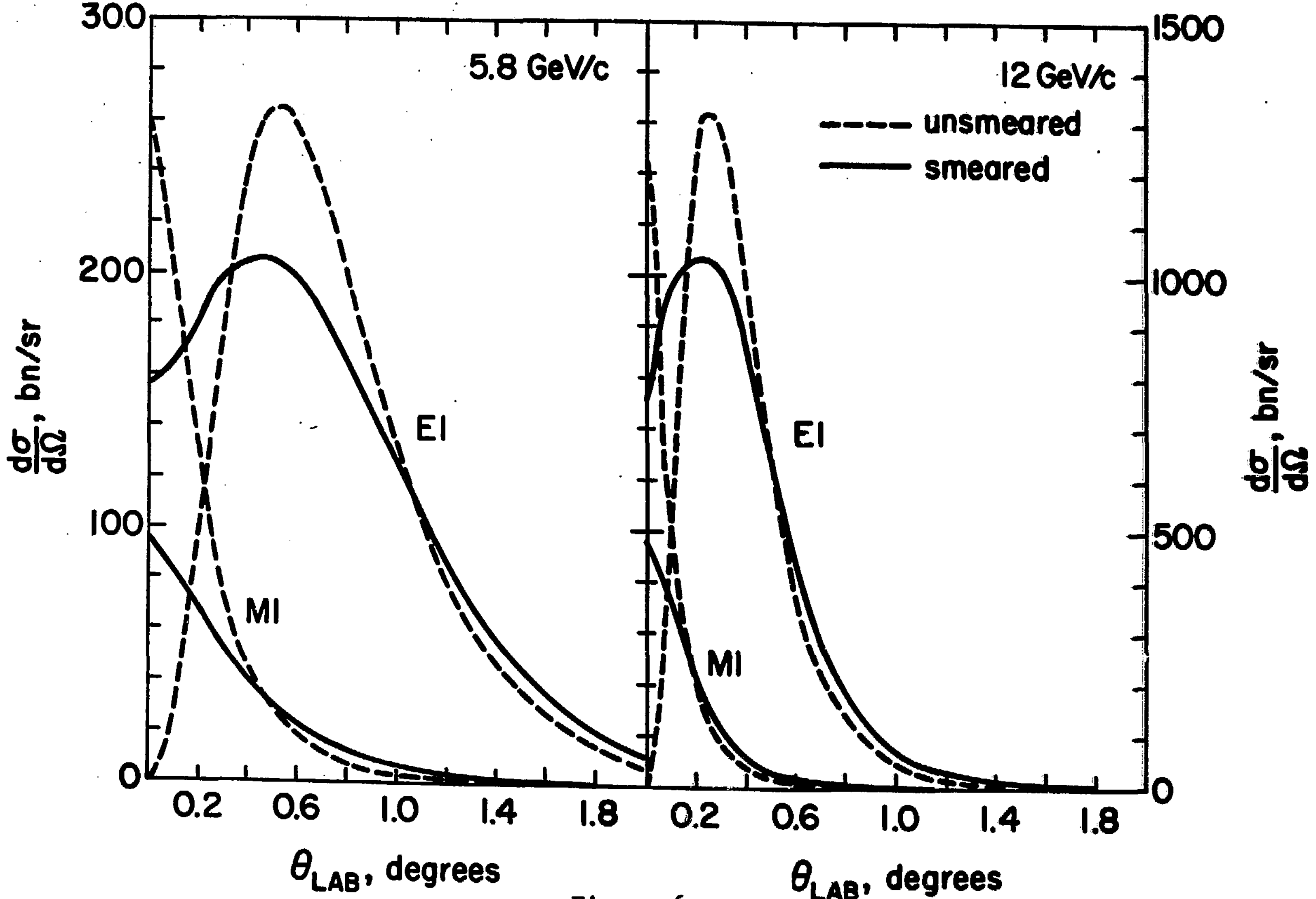

300
200
100
0
$\frac{d\sigma}{d\Omega}$, bn/sr
5.8 GeV/c
E1
M1
0.2
0.6
1.0
1.4
1.8
θ_{LAB}, degrees
12 GeV/c
unsmeared
smeared
E1
M1
0.2
0.6
1.0
1.4
1.8
θ_{LAB}, degrees
1500
1000
500
0
$\frac{d\sigma}{d\Omega}$, bn/sr

Figure 6

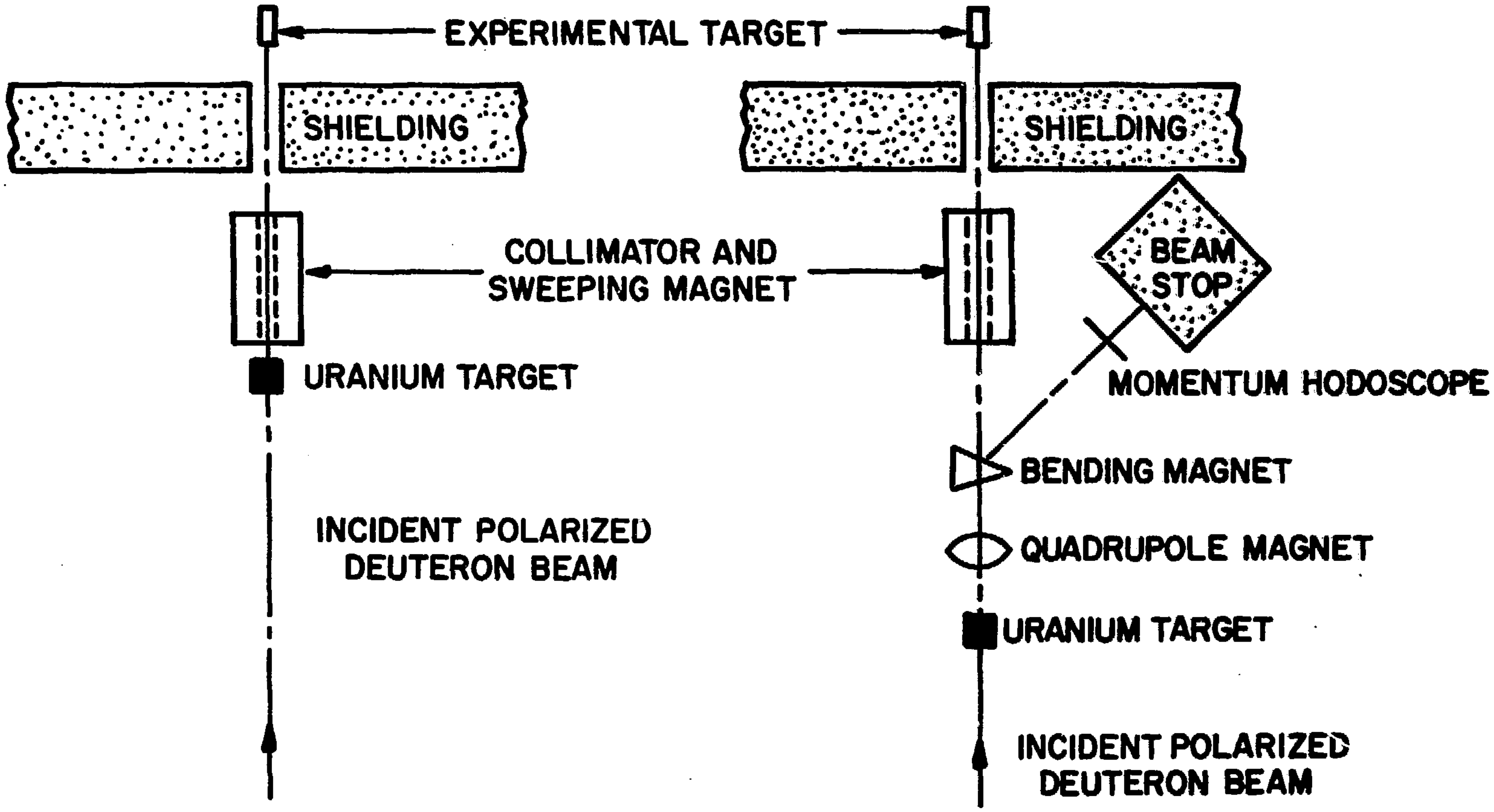


Figure 7a

Figure 7b

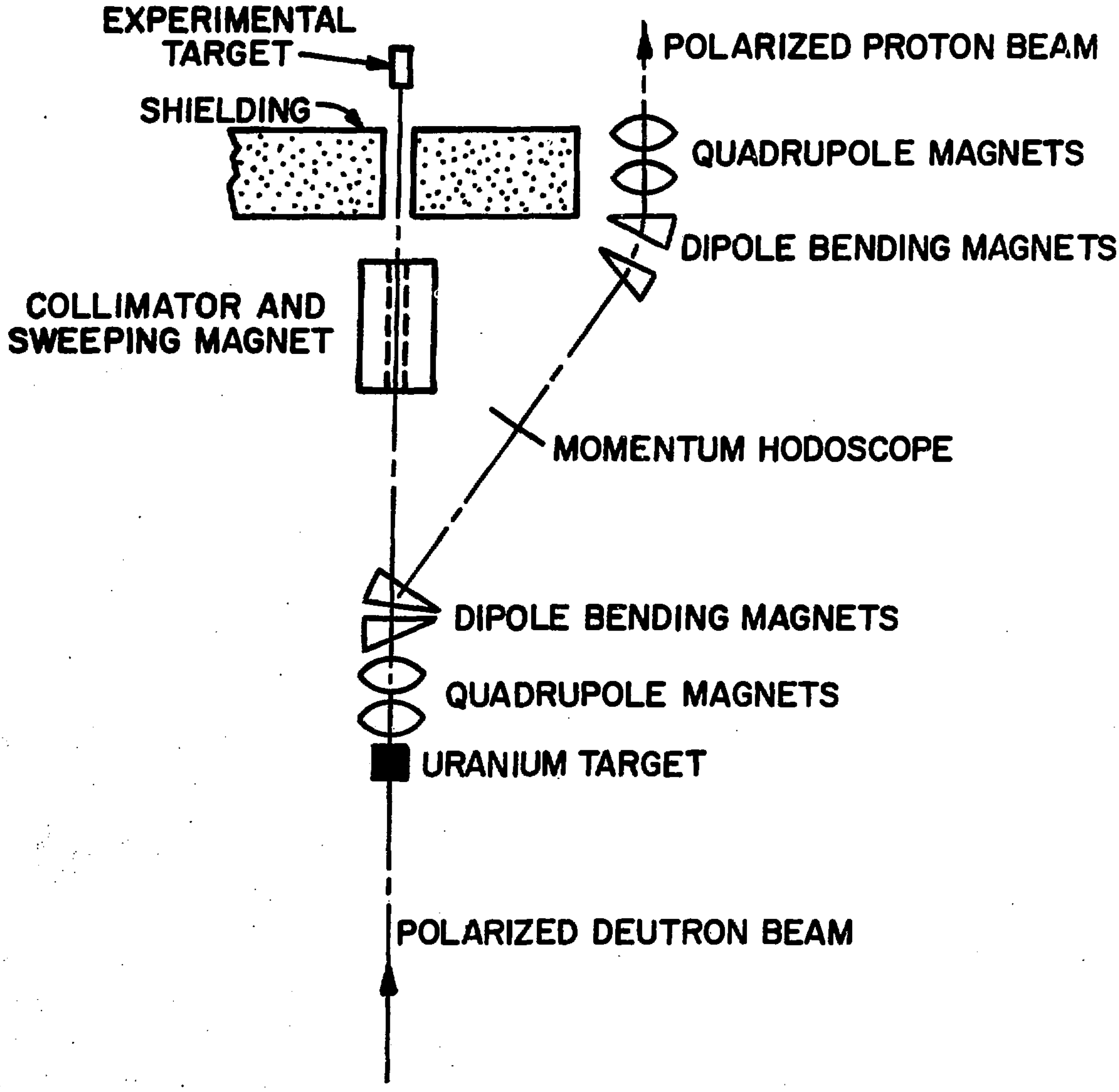

EXPERIMENTAL TARGET
SHIELDING
COLLIMATOR AND SWEEPING MAGNET
POLARIZED PROTON BEAM
QUADRUPOLE MAGNETS
DIPOLE BENDING MAGNETS
MOMENTUM HODOSCOPE
DIPOLE BENDING MAGNETS
QUADRUPOLE MAGNETS
URANIUM TARGET
POLARIZED DEUTRON BEAM

Figure 7c

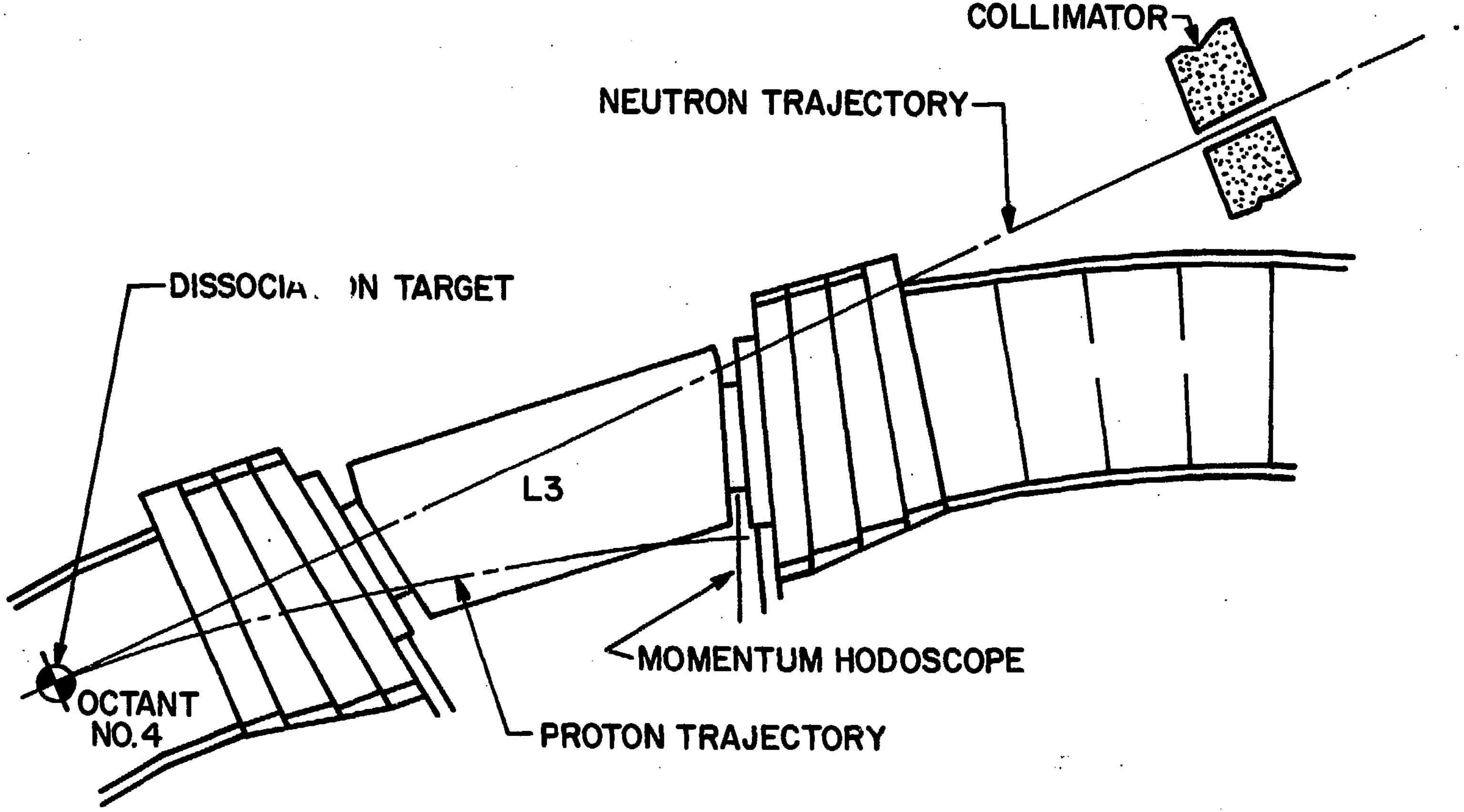

COLLIMATOR
NEUTRON TRAJECTORY
DISSOCIA. ON TARGET
L3
MOMENTUM HODOSCOPE
OCTANT NO.4
PROTON TRAJECTORY

Figure 7d