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ELECTRO- AND PHOTONUCLEAR PHYSICS WITH POLARIZED BEAMS AND TARGETS

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ABSTRACT

    Two long-standing issues in photonuclear physics, the
giant M1 resonance in Pb and deuteron photodisintegration, have
been studied recently with polarized photons at Urbana and
Frascati, respectively. The implications that this work has for
settling these key issues will be discussed. In addition, the
advantages of the internal polarized target method for electron
scattering studies will be discussed and the technology of
internal polarized target development will be reviewed. The first
results from a spin-exchange, optically-pumped polarized H and D
source will be presented.

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I. INTRODUCTION

    It is now widely recognized that polarization methods in
electromagnetic studies of nuclei are potentially a powerful technique. The
internal polarized target technique which was discussed by Professor Popov in
the previous paper[1] has led recently to many suggestions[2] for experiments and,
in addition to the work in progress here at Novosibirsk, to proposals[3] for
electron rings and internal target facilities at the MIT-Bates Laboratory and
NIKHEF. The primary difficulty with this method is generating the polarized
target and I shall discuss some novel developments in this field. Two key
experiments[4] will be discussed as internal target experiments: (i) polar-
ization in electron-deuteron scattering and (ii) the charge form factor of the
neutron. The need for $\vec{D}$ and $^3\vec{He}$ targets is emphasized for these experiments.

Nuclear studies involving the use of polarized photons have burgeoned during the past few years owing to the development of the LADON Facility at the ADONE storage ring and the development of the selective residual-electron tagging technique at Urbana. In addition, the LEGS Facility at Brookhaven is expected to begin operation this Fall and provide tagged, polarized photon beams in the energy region of the delta resonance. Thus, I would like to highlight some initial findings from these new facilities.

II. GIANT M1 RESONANCE IN THE Pb REGION

The ^{208}Pb nucleus is expected to represent an ideal example of the collective M1 resonance since both the $i_{13/2}$ neutron and $h_{11/2}$ proton shells are filled while their spin-orbit partners are vacant. After substantial effort[5] approximately one-third of the expected strength for the M1 isovector sum rule has been observed for ^{208}Pb. This result led to much quandary since the theoretical calculations, even with 2p-2h and Δ-h admixtures, could not account for such a large quenching of the M1 resonance. The primary difficulty with ^{208}Pb is that most of the M1 strength is expected to lie above the photoneutron threshold (7.4 MeV) where the experiments are exceedingly difficult. Laszewski et al. have pointed out that ^{206}Pb might be a better nucleus to search for the giant M1 resonance since the (γ,n) threshold is much higher (8.1 MeV), and resonance fluorescence methods with polarized photons would be a powerful method for identifying the spin, parity, and transition strengths of the resonances.

In order to perform the experiment, Laszewski et al.[6] at Urbana have recently enhanced the polarization in bremsstrahlung production by selectively tagging the residual electron as indicated schematically in the upper part of Fig. 1. Since the photon tagging spectrometer at Urbana is double-focusing, a

fixed collimator was placed in the magnet gap in order to tag electrons slightly out of the bremsstrahlung production plane. This has the effect of enhancing the photon polarization by a large factor as shown by a comparison of the lower graphs of Fig. 1. This novel technique was applied[7] successfully to search for the collective M1 excitation in ^{206}Pb. The results of this work are shown in the upper panel of Fig. 2. A B(M1,↑) of $19\pm2\mu_0^2$ was found below 8 MeV and is consistent with the M1 sum rule[8] for isovector transitions in Pb. This work clears up a long-standing puzzle in nuclear physics.

The presently known B(M1,↑) for excitations in ^{208}Pb are compared with that in ^{206}Pb in the lower panel of Fig. 2. Although the known M1 strength in ^{208}Pb is only B(M1,↑) ≈ $7\mu_0^2$, its distribution may be consistent with that in ^{206}Pb as suggested in Fig. 2. Thus, it is expected that further work will yield more M1 strength in ^{208}Pb and there will not be an anomalous quenching effect as previously suggested.

III. PHOTODISINTEGRATION OF THE DEUTERON

In recent years much progress has been made in the study of the D(γ,n)p reaction owing to the development of new techniques which can yield high-accuracy results. The development of the Compton back-angle scattering facility[9] (LADON) at Frascati has permitted measurement[10] of the polarization-dependent component, pI_1,(θ), of the D(γ,n)p cross section. The differential cross section for the photodisintegration process with linearly polarized photons of polarization p is given by

$$\frac{d\sigma}{d\Omega} = I_0(\theta) + pI_1(\theta)\cos(\phi)$$

where I_0 is the cross section for unpolarized particles and ϕ is the azimuthal

angle between the reaction plane and the polarization plane of the incident photon. In terms of the Partovi coefficients[11] these cross sections are given by

$$I_0 = a + b \sin^2\theta + c \cos\theta + d \sin^2\theta \cos\theta + e \sin^4\theta$$

$$I_1 = f \sin^2\theta + g \sin^2\theta \cos\theta + h \sin^4\theta$$

The primary advantage of the LADON Facility for these studies is that the polarization of the photon beam can be maintained at 99% over a wide range of photon energies, and much systematic uncertainty in the asymmetry measurement is minimized. Results[10] from the work at LADON are reproduced in Fig. 3. Both the cross sections for unpolarized photons (solid points) and $I_1(\theta)$ tend to be shifted more forward in angle than the theoretical calculations. This discrepancy is particularly acute at the smallest energy of the measurements, 19.8 MeV. The effect of this forward shift is to require a smaller absolute value of the Partovi coefficients, d and g, than predicted,[11] and consequently, points to smaller E1-E2 terms in the predicted transition amplitudes.

It is worth noting that results[12] from Argonne indicate the opposite effect below 16 MeV! (See Fig. 4.) Here, the cross sections for the $^2H(\gamma,n)H$ process were measured relative to that at $\theta_{lab} = 90°$ and the measured ratio at forward angles is less than the predictions. This would imply that the coefficient d is larger in magnitude than expected below 16 MeV. The reason for either discrepancy is not understood. However, the fact that the Argonne results are in reasonable agreement with the theoretical prediction at 16 MeV and the Frascati work are in disagreement with the calculation at 19.8 MeV suggests that there is an inconsistency between the two data sets.

The photoneutron polarization has been studied extensively below 14 MeV and the results are summarized in Fig. 5. It is surprising that all published measurements[13] are smaller in magnitude than the calculations[14] which include meson-exchange currents in the M1 component, but agree with the impulse calculation of Partovi. This is another indication that our understanding of the most basic nuclear process, deuteron photodisintegration, is not understood completely even at low energy and further work is necessary.

IV. ELECTRON-DEUTERON SCATTERING

Professor Popov has already introduced[1] the issue of measuring polarization in electron-deuteron elastic scattering. It is now widely recognized that polarization methods provide the only means of isolating the charge and quadrupole form factors for the deuteron. The existing measurements of t_{20} in e-d scattering are shown in Fig. 6. These data represent the entire collection of polarization data presently available in electron scattering studies. The two data points at high momentum transfer were measured[15] with a deuteron tensor polarimeter at the MIT-Bates Laboratory, while the lower q data were determined[1,16] with an internal polarized target here at Novosibirsk. Clearly, these measurements must be extended to high q^2 and efforts are underway both at MIT and Novosibirsk.

A comparison of the relative scales of these two experiments is indicated schematically in Fig. 7. The experiment at MIT required the use of two large magnetic spectrometers to detect the scattered electrons and deuterons; whereas, the internal target experiment (shown approximately on the same scale in the inset figure) was performed with detector arrays. The Novosibirsk apparatus also is shown with a magnified scale on the same figure so that the individual components can be seen. The detector hardware is

simplified in the internal target geometry because of the purity of the
polarized target, the high duty factor of the ring and the low background from
the thin internal target.

Of course, the primary limitations of the internal target geometry
is the relatively small target thickness, 10^{11} nuclei/cm^2. Efforts[17] are
underway at Argonne to produce a high flux, laser-driven polarized H or D
source and to develop a storage cell for the polarized atoms. I shall discuss
the recent progress of this work in a few moments. Work is also in progress
at Wisconsin[18] to develop storage cells for polarized H or D and much progress
has been reported[19] for teflon surfaces. The goal is to produce a polarized
target thickness of 10^{14} nuclei/cm^2 in order to achieve a luminosity of $\gtrsim 10^{32}$
cm^{-2}s^{-1}.

V. ELECTRIC FORM FACTOR OF THE NEUTRON

The power of the polarization method is most readily demonstrated[20]
for measurements of small amplitudes such as the charge form factor of the
neutron. The standard Rosenbluth separation is relatively insensitive to the
small form factor in this case and the polarization method permits one to
observe the product of the charge G_E and magnetic form factors G_M. The
expression for the cross section for electron scattering from a free nucleon
is given below for an incident electron beam with polarization p_e and a target
nucleon of polarization p_N

$$\sigma(\theta_e, \theta^*, \phi^*) = \sigma_M f_{rec}^{-1} \{ V_L (1+\tau)^2 G_E^2 + 2 V_T \tau (1+\tau) G_M^2$$

$$- 2 p_e p_N [\tau(1+\tau) V_T^1 G_M^2 \cos\theta^* - (2\tau)^{1/2} (1+\tau)^{3/2} V_{TL}^1 G_E G_M \sin\theta^* \cos\phi^*] \}$$

where f_{rec}, V's, τ are defined by Donnelly and Raskin.[21]

Here, θ^* and ϕ^* define the direction of polarization of the target
as shown in Fig. 8. Maximum sensitivity to G_E is achieved when $\theta^* = \pi/2$ and
$\phi^* = 0, \pi$. Of course, the primary difficulty in performing this experiment is
providing the polarized neutron target. The magnitude of the uncertainty in
the electric form factor of the neutron can be gauged by the two analyses[22,23]
of data indicated in Fig. 9. In addition to the use of polarized deuterons
for this measurement, it has been suggested[24] that polarized ^{3}He would also
provide a neutron target since the proton spins are paired off in the S-state
of ^{3}He. R. Milner[25] and R. McKeown[26] at Caltech have shown that with the
advent of new laser technology it should be feasible to fabricate an internal
^{3}He target of thickness $\gtrsim 10^{15}$ nuclei/cm^2, and thus, measurements of G_E should
be practical. This problem is particularly challenging, however, since
longitudinal polarized electrons are required at the target location.
Although there are several proposals[27] for preserving electron polarization in
a ring, there has been no experimental test of these concepts.

VI. INTERNAL TARGET DEVELOPMENT

Now I would like to focus on some recent developments in laser-
driven polarized H, D and ^{3}He targets. A high-flux polarized source of H and
D atoms based upon an optical-pumping spin-exchange technique is being
developed[17,28] at Argonne. The method involves a two-step process in which an
ensemble of alkali atoms, K say, are polarized by optical pumping and the
polarization is transferred to H or D atoms via spin-exchange scattering.
This method is attractive since the flux of H or D atoms is limited, in
principle, by only available laser power and since the gas load to a storage
ring would be minimal.

The primary technical challenges is efficient optical-pumping of the K atoms without the presence of a buffer gas. This means that the spectrum of the laser light must be carefully matched to the Doppler broadened line width of the K atoms and that the surface in the spin-exchange cell must inhibit spin-relaxation of the K and H atoms. The polarization was determined by observing flourescence from K atoms in the spin-exchange cell when the Zeeman transition frequency for the H atoms was swept with an RF coil. A Breit-Rabi diagram for the H atom in shown in the upper panel of Fig. 10, while the apparatus is shown schematically in the lower half of the figure. If the H atoms are partially polarized we expect to observe two Zeeman transitions in the intermediate magnetic field region. These transitions are observed and shown in Fig. 11. Clearly, the relative intensity of the two transitions reverses as expected between σ^+ and σ^- light. Here we see the first evidence for $\vec{H}$ from an optically-pumped, spin-exchange source! Thus far, a vector polarization of 10% with a flux of 6×10^{16} s^{-1} for the H atoms has been achieved.[28] With the assumption that the H atoms are in equilibrium with the K atoms, and consequently, that the populations $N(m_F)$ of the atoms in H follow a spin-temperature distribution, i.e. $N(m_F) \propto e^{\beta m_F}$ where β is the spin temperature and m_F is the total magnetic quantum number, the polarization of the protons in the spin-exchange cell is found to be 10% from these data. Further improvement in the polarization is expected as we gain more experience with the source. Note that during this experiment only 20 mW of laser power was absorbed in the spin-exchange cell with an H flow rate of 6×10^{16} atoms/s! This is a strong indication that the flux from the source could improve by at least an order of magnitude with a readily available laser power of 0.5 watt.

The goal is to provide a target of D atoms with a thickness of 10^{14} cm^{-2} and a tensor polarization of $t_{20} \gtrsim 0.3$ which could be used in an electron-deuteron scattering experiment. Again, in order to achieve this thickness it is essential to store the atoms in a windowless bottle and permit the atoms to leak away before the spins relax. In order to achieve this goal the high flux and polarization expected from the laser-driven source is essential.

A novel internal polarized ^{3}He target is being developed[29] at Caltech. The ^{3}He nuclei are polarized by the well-known method of optically-pumping metastable ^{3}He atoms. This method has benefited recently from the development of lasers which can operate at 1.083 μm so that $\gtrsim 3 \times 10^{16}$ $^3\vec{H}e$/s are produced. It is expected that an internal target of $^3\vec{H}e$ with a thickness of $\gtrsim 10^{15}$ cm^{-2} is feasible.

SUMMARY

It is already clear that photonuclear physics has benefited dramatically from the development of polarized photon sources and that much more work will be performed in the next few years as the new facilities are brought into operation. Electron scattering studies with polarization techniques are potentially a very powerful probe of nucleus and, if development of the methods continues at the present pace, will have a major role in the near future.
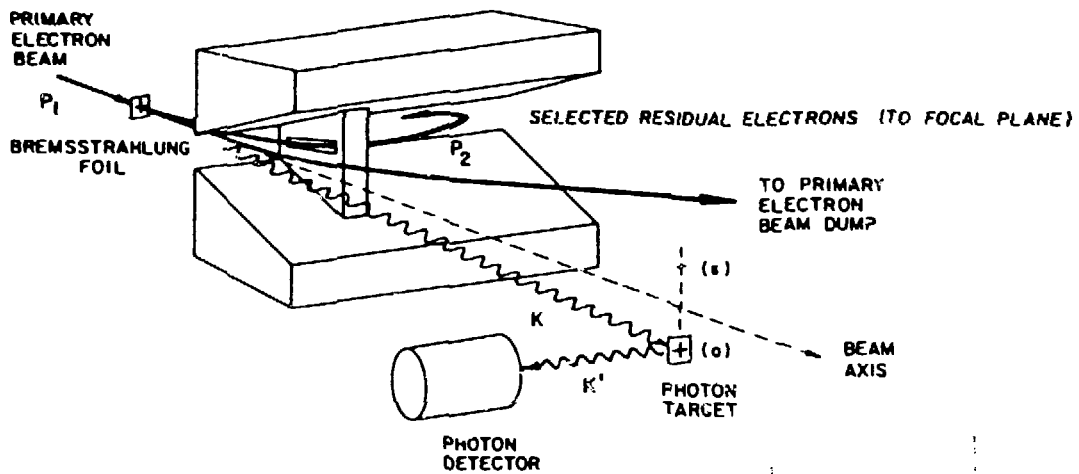
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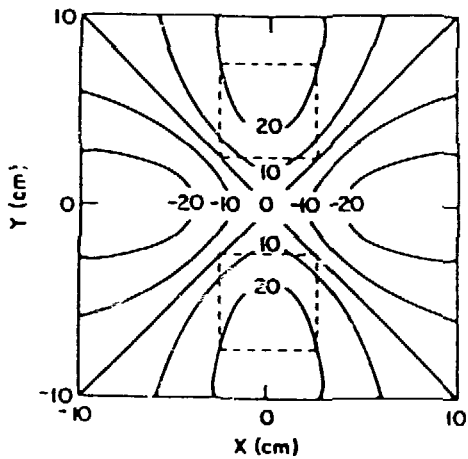16. D. K. Vesnovsky et al., Inst. for Nucl. Phys., Novosibirsk, preprint 86-75.

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FIGURE CAPTIONS

Fig. 1   Schematic diagram of the selective-residual electron tagging method
is shown in the upper figure. Lower left: distribution of photon
polarization at the target position for E_e = 18.4 MeV, E_γ = 11.4 MeV
and without selective-residual electron tagging. The target size is
given by the dashed lines. Lower right: distribution of photon
polarizations with selective-residual-electron tagging. Note the
dramatic improvement in the polarization at the target position.

Fig. 2   Distribution of average B(M1,↑) in ^{206}Pb from Ref. 7 is given in the
upper panel. This is compared in the lower panel with the known
distribution in ^{208}Pb from Ref. 5.

Fig. 3   Results from LADON for the ^{2}H(γ,n)H reaction at four photon
energies. The cross section for unpolarized (I_0) and polarized (I_1)
photon beam is given. Note that the data at low energy are shifted
dramatically toward smaller reaction angles than the calculations.

Fig. 4   High-accuracy ratios of angular distributions for the ^{2}H(γ,n)H
reaction from Ref. 12. Note that at low photon energy the data are
shifted dramatically toward larger reaction angles with respect to
the theoretical calculations of Partovi.

Fig. 5   Summary of the results for the ^{2}H(γ,$\vec{n}$)H reaction below 14 MeV.
Surprisingly, the inclusion of meson-exchange currents in the M1
amplitude[14] worsen the agreement between experiment and theory.

Fig. 6   Summary for all polarization data in electron-deuteron elastic
scattering. The two data points at low values of q were determined
with an internal polarized target method while the two higher q
points were measured with a deuteron polarimeter.

Fig. 7   Schematic diagram of the apparatus required to measure t_{20} in e-d
elastic scattering in the external target geometry. Inset figure on
left illustrates the apparatus on approximately the same scale for
the internal target experiment at Novosibirsk. The figure is also
shown with an expanded scale for ease of identification of the
components.

Fig. 8   Orientation of the spins of the electrons and the nucleon target in
electron-nucleon elastic scattering.

Fig. 9   A comparison of two analyses of the elastic form factor of the
neutron.

Fig. 10   Breit-Rabi diagram for the H atoms indicating the two available
Zeeman transitions. The apparatus to induce and detect these Zeeman
transitions is illustrated schematically.

Fig. 11   A comparison of Zeeman transitions for H atoms for σ^+ and σ^- laser
light incident on the spin-exchange cell. In this case the H
polarization is 10% and the flux is 6×10^{16} s^{-1}. These results
represent the first observation of polarized H from a spin-exchnage
optically-pumped source.

PRIMARY
ELECTRON
BEAM

P_1

BREMSSTRAHLUNG
FOIL

SELECTED RESIDUAL ELECTRONS (TO FOCAL PLANE)

P_2

TO PRIMARY
ELECTRON
BEAM DUMP?

(s)

K

BEAM
AXIS

K'

PHOTON
TARGET

PHOTON
DETECTOR

(o)

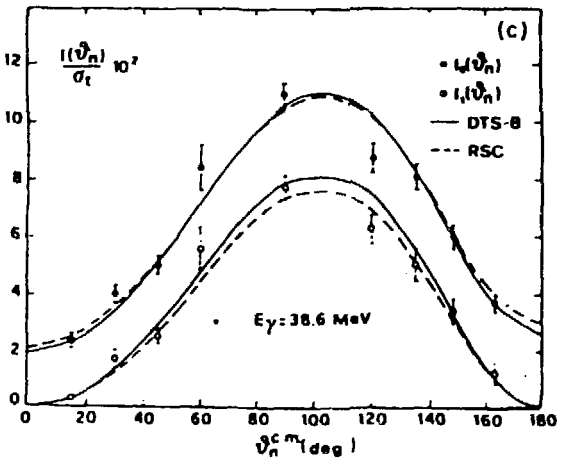TAGGED BREMSSTRAHLUNG POLARIZATION

TAGGED BREMSSTRAHLUNG POLARIZATION

Fig. 1

^{206}Pb

$6.7 \leq E_\gamma \leq 8.1$ MeV
$\sum B(\uparrow M1) = 19 \pm 2 \, \mu_0^2$

$\overline{B}(\uparrow M1) \, \mu_0^2$

5.0

4.0

3.0

$(5.8 \, \mu_0^2)$

2.0

1.0

0.0

7.0   7.5   8.0

E_γ(MeV)

4.0

$B(\uparrow M1) \, \mu_0^2$

^{208}Pb

3.0

$(6.6 \, \mu_0^2)$

2.0

1.0

0.0

7.0   7.5   8.0

Fig. 2

Fig. 3

Fig. 4

$^2H(\gamma, \vec{n})H$, $H(\vec{n}, \gamma)^2H$

$\theta = 90°$

MIT (1963)
YALE (1972)
ANL (1983)
WISCONSIN (1987)
PARTOVI (IA)
HADJIMICHAEL (IA+MEC)

$\theta = 135°$

PHOTONEUTRON POLARIZATION (%)

E_γ (MeV)
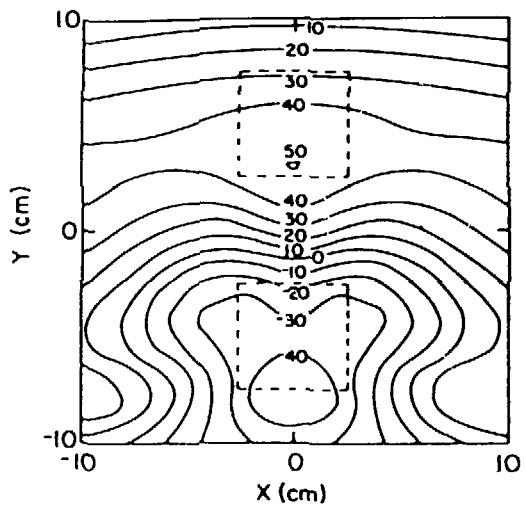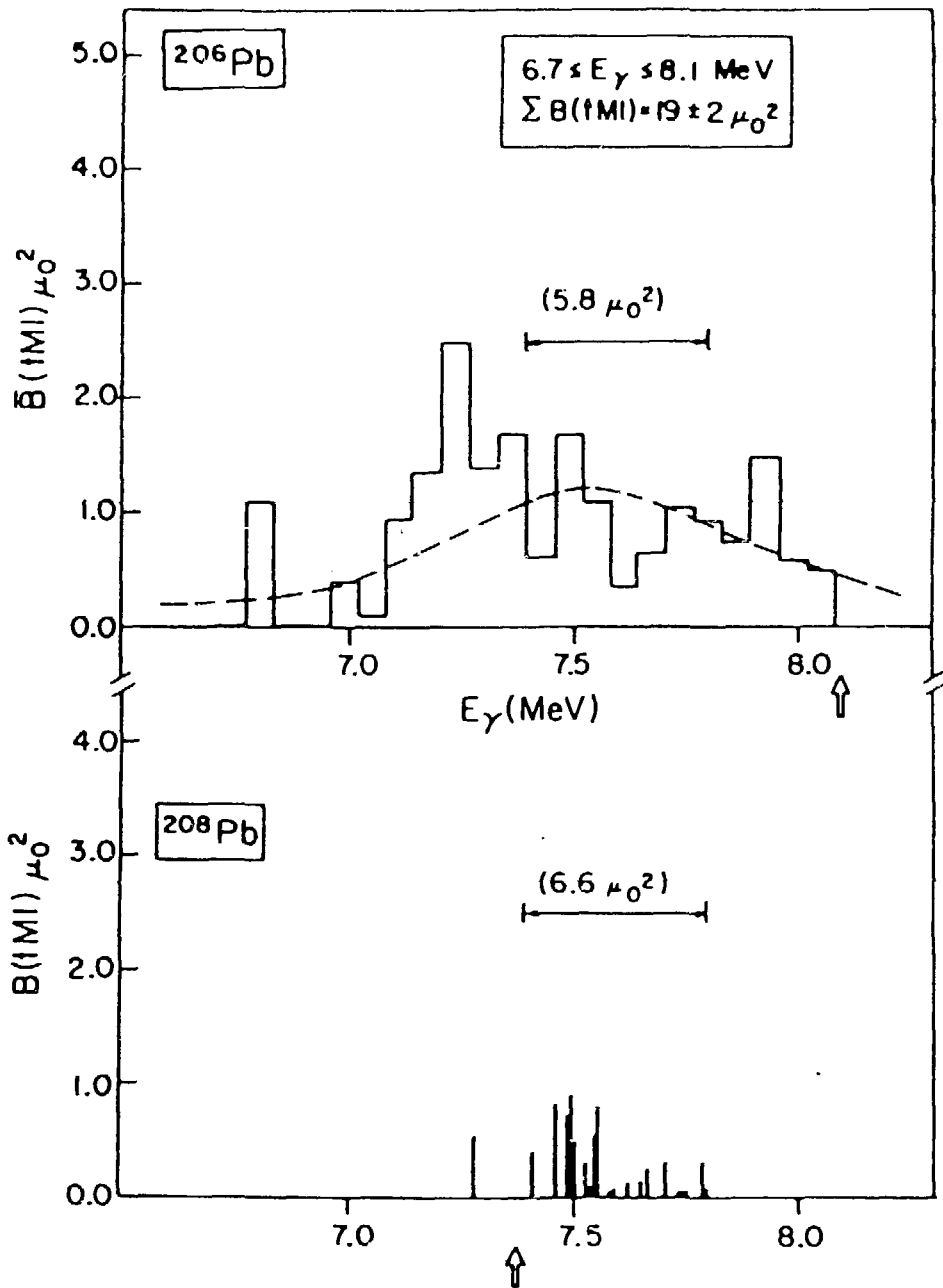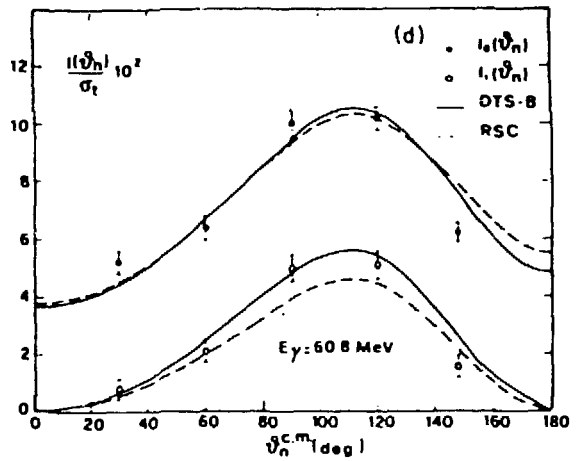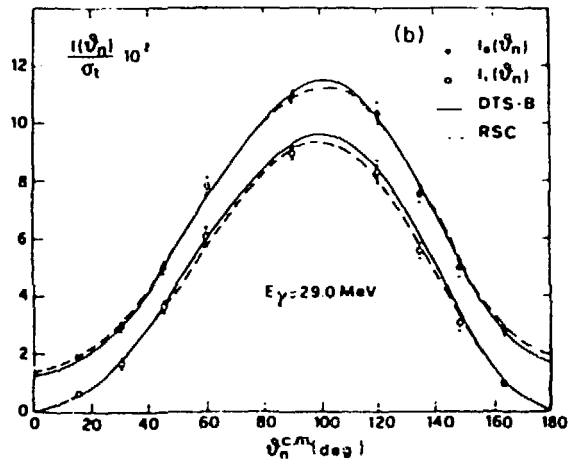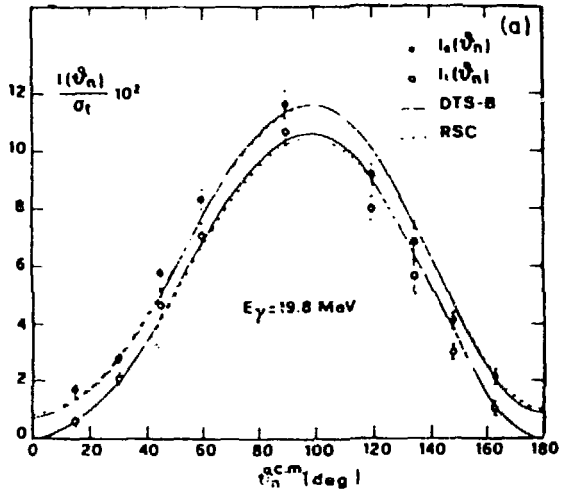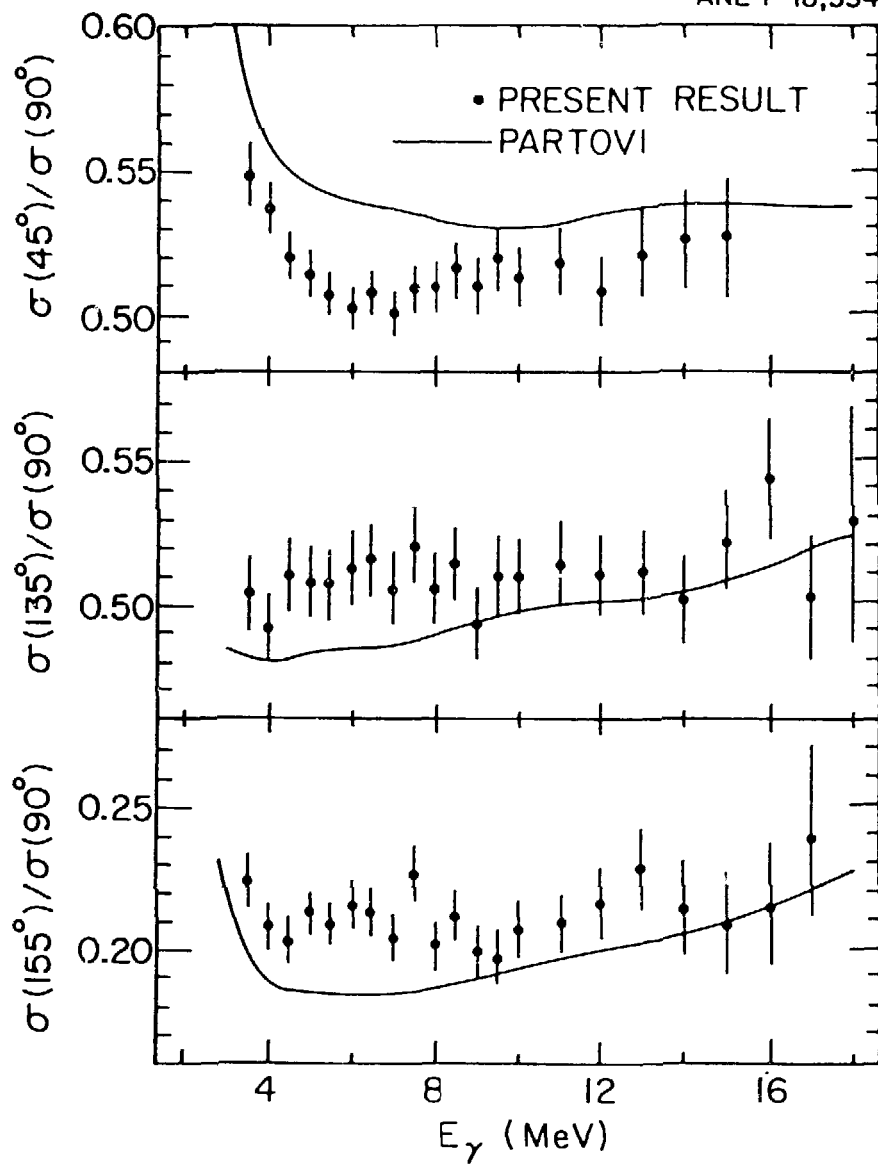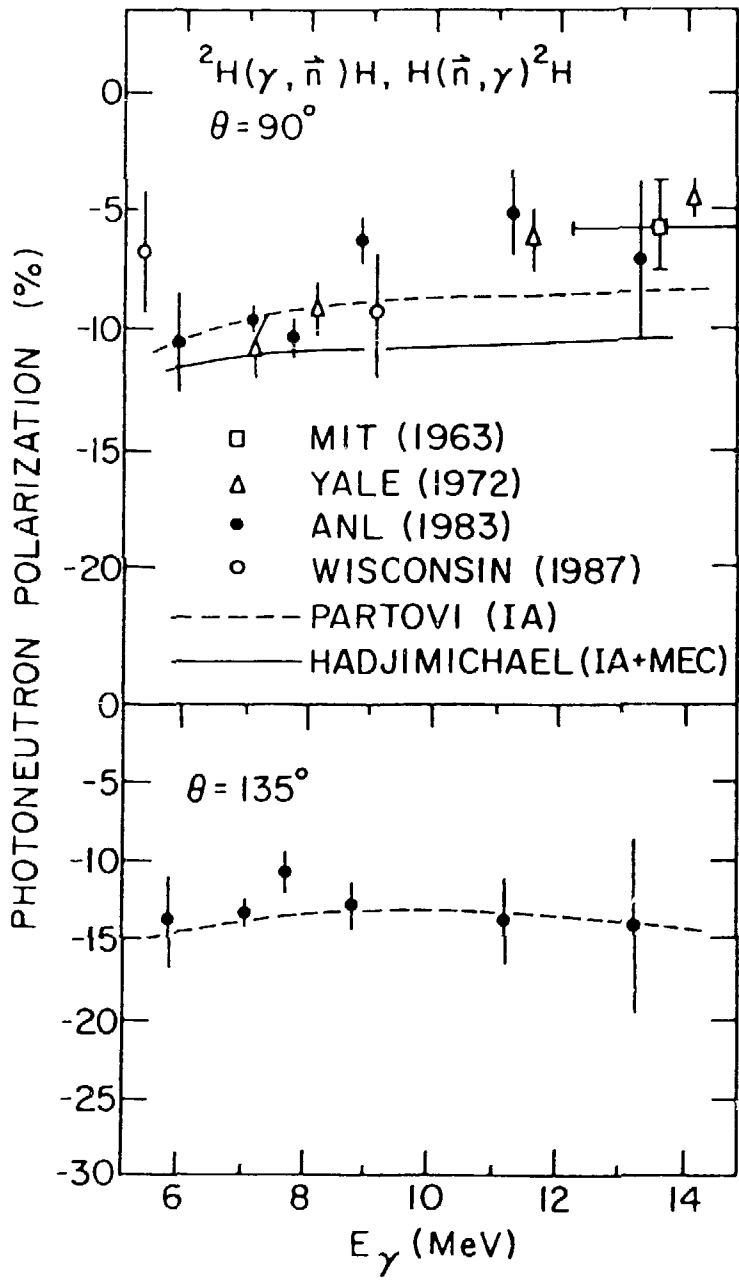
Fig. 5
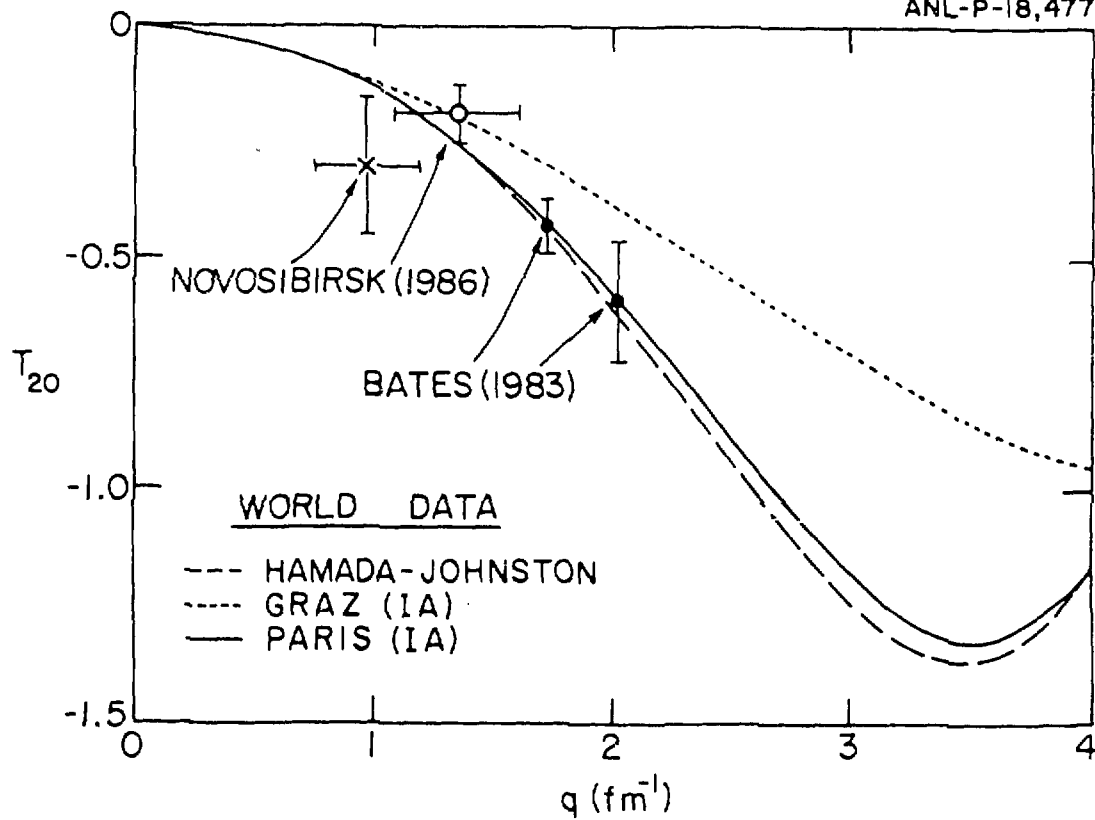
Fig. 6
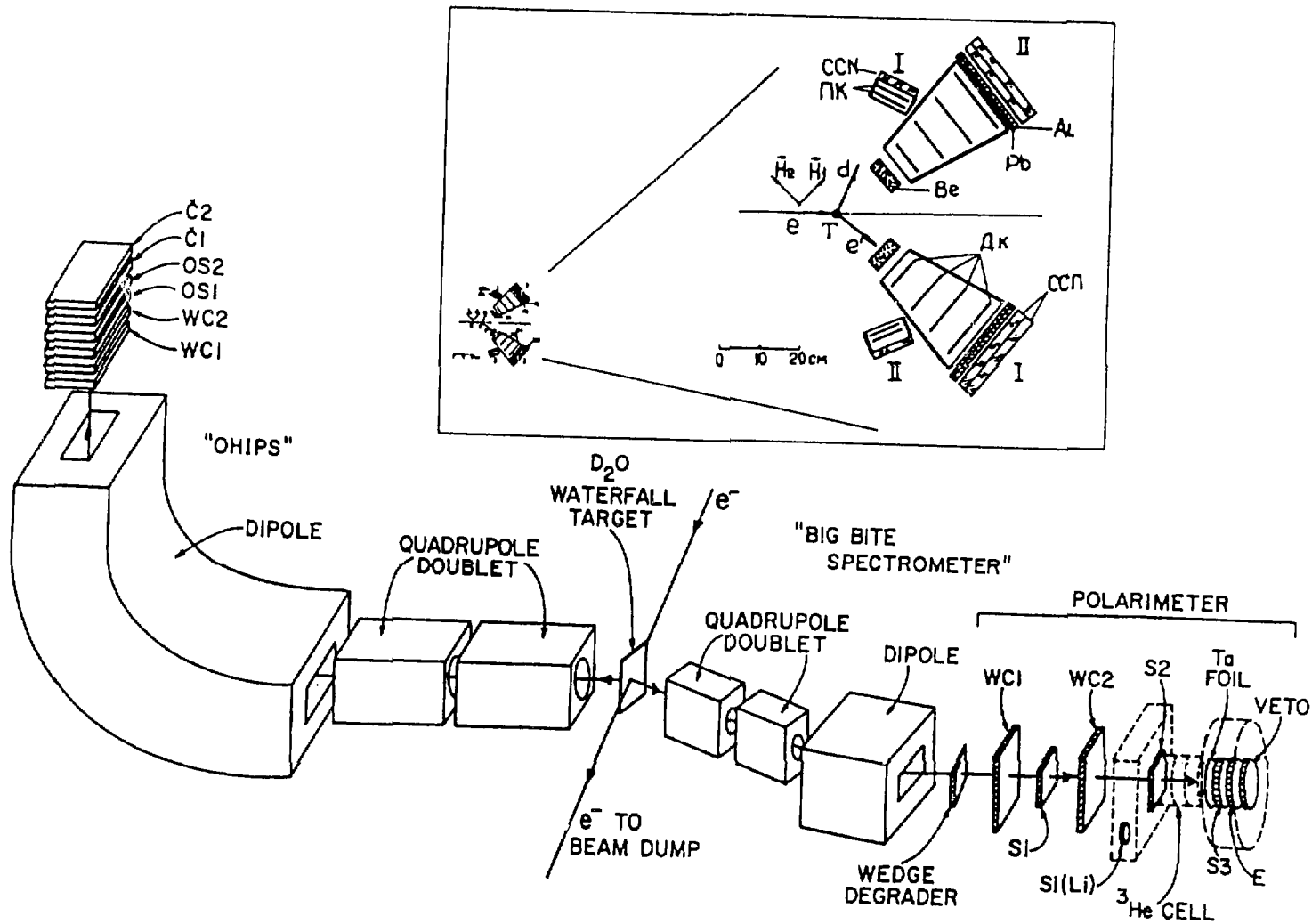
Fig. 7

ANL-P-18,497

Fig. 8

Fig. 9

B_N (gauss)

$F=1$

$m_f = 1$

$m_f = 0$

$m_f = -1$

$\Delta E_N(MHz) = 1.4\,B - 1.4 \times 10^{-3}\,B^2$

$\Delta E_N(MHz) = 1.4\,B + 1.4 \times 10^{-3}\,B^2$

$\Delta E / \Delta E_{HFS}$

ΔE_H (MHz)

$x = g_i \mu_0 B / \Delta E_{HFS}$

DIGITAL OSCILLOSCOPE

FUNCTION GENERATOR

Ar-ION PUMP LASER

MIRROR

RF DISSOCIATOR

CW DYE LASER

LOCK-IN AMP

RF SWEEP OSCILLATOR

K+D SPIN EXCHANGE CELL

MIRROR

σ^+

$\lambda/4$ PLATE

AMPLITUDE MODULATED RF

PHOTODIODE

B_0

Fig. 10

Fig. 11

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