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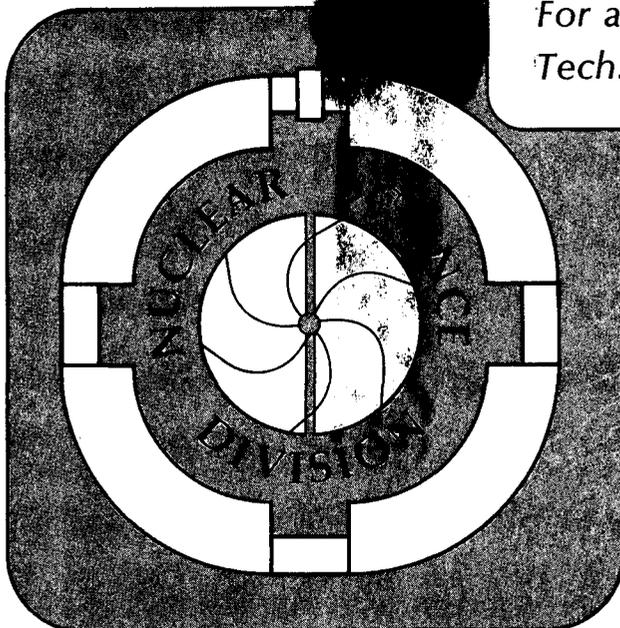
ANALYZING POWER MEASUREMENTS FOR ^{3}He($\vec{p}$,p)^{3}He
ELASTIC SCATTERING BETWEEN 20 AND 50 MeV

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ANALYZING POWER MEASUREMENTS FOR ^{3}He($\vec{p}$,p)^{3}He ELASTIC SCATTERING[*]
BETWEEN 20 AND 50 MeV

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Abstract

Analyzing power data $A_y(\theta)$ have been obtained for $\vec{p}$ + ^{3}He elastic

scattering at eleven energies between 21.4 and 49.6 MeV for laboratory

angles between 20° and 160°. Errors typically are less than 0.01. These

data are compared with fits obtained in a single energy phase-shift

analysis and R-matrix predictions.

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1. <u>INTRODUCTION</u>

The four-nucleon system is of fundamental interest to nuclear physics. It is the lightest system to exhibit the basic nuclear structure property of excited states. Similarly, it is the lightest system to have been studied in terms of the shell model[1] and the cluster (resonating group) model. The cluster model of Tang, Le Mere and Thompson[2] describes the collision of composite nuclei in terms of the individual nucleon-nucleon interactions, employing totally antisymmetric wavefunctions so that the Pauli principle is immediately satisfied. Sherif[3] has had considerable success in describing $p + {}^3He$ scattering below 20 MeV in terms of an optical model whose real potential includes an ℓ-dependent exchange term. This term is required by the finding of resonating group calculations that antisymmetrisation resulted in different potentials for the even and odd ℓ states. Recently, Paez and Landau[4] have constructed a microscopic optical model of $p - {}^3He$ scattering based on antisymmetrised nucleon-nucleon amplitudes. Additionally, there have been substantial efforts in the past few years to develop generalisations of the Faddeev three-body formalism. The first results of such rigorous mathematical formulations for four-nucleon systems have now appeared in the literature.[5,6]

More traditionally, scattering data for four nucleon systems such as $p + {}^3He$ are interpreted via single energy and energy dependent phase-shift analyses, and the R-matrix formalism can be used to characterise any resonant behaviour of the phase shifts.

To assist in the testing and critical development of various modern approaches to the four-nucleon system, a substantial program has been

undertaken to obtain high-quality data on the p + ^{3}He system in the 20 to 50 MeV range. (Extensive data exists for proton energies below 20 MeV). In this paper we report analyzing power data $A_y(\Theta)$ for $\vec{p}$ + ^{3}He scattering at eleven energies between 21.4 and 49.5 MeV. Other measurements in this program include total reaction cross-sections,[7] differential cross-sections[8] and p + $^3\vec{He}$ analyzing powers[9] using a polarised $^3\vec{He}$ target.

There are four previous published $\vec{p}$ + ^{3}He analyzing power measurements for proton energies between 20 and 50 MeV. These are at energies of 21.3 MeV,[10] 30 MeV[11,12] and 50 MeV.[13] The statistical uncertainties in some of these older measurements are as large as 25%.

2. EXPERIMENT

The experiment was performed at the 88" cyclotron of the Lawrence Berkeley Laboratory and undertaken in three series of experimental runs. Series I was at 21.4, 24.8, 27.3 and 30.1 MeV, series II at 32.4, 35.1, 37.6 and 40.1 MeV and series III at 45.0, 47.6 and 49.6 MeV.

The target was a gas cell 7.6 cm. in diameter containing ^{3}He gas (of 99.9% purity) at pressures between 1 and 2 atmospheres. The windows were of havar 5 microns thick. Beam currents on the target varied between 10 and 100 nA, while the beam polarisation was typically 0.8. Horizontal and vertical current-reading collimators at the entrance and exit of the scattering chamber allowed beam drifts to be seen and to be corrected. Corrections were applied by adjusting beam transport elements so as to balance the currents on left-right and on up-down pairs of collimators. In the first and second series of runs beam was centred manually, whereas in

the third series an automated system was used. A further check of beam

alignment was afforded by the relative count rate of two monitor detectors

mounted in the lid of the chamber and collimated to view the ^{3}He target

at a scattering angle of 23° with respect to the proton beam.

The scattering chamber contained arrays of detectors positioned

symmetrically on either side of the beam. In the first and second series

of runs single lithium drifted silicon detectors were used at four pairs of

angles. In the third series passing surface barrier detectors were

required to identify protons and data were then acquired at two angles at a

time. The angular acceptance of the detector systems was 1.5° FWHM in each

case. Pulse-height spectra were recorded in a pulse-height analyzer and

were transferred to magnetic tape after each run.

A polarimeter downstream from the scattering chamber, containing one

detector system at either side of the beam, measured the left-right

asymmetry of protons scattered elastically from ^{4}He in series I and II

and from a ^{12}C foil in series III. Proton analyzing powers were obtained

from Bacher et al.,[14] and Kato et al.,[15] The energy of the beam at

the polarimeter was degraded to match that at which measurements of $\vec{p}$-^{4}He

or $\vec{p}$-^{12}C analyzing powers were available by means of an aluminium foil of

the appropriate thickness. This was accomplished with the aid of an

absorber wheel between the scattering chamber and the polarimeter which

held foils of the required thicknesses. The uncertainty in the absolute

magnitude of the polarimeter analyzing power was taken from refs. 14 and 15

and resulted in a scale uncertainty ranging between 1.9 and 3.1%.

Beam was collected in a Faraday cup at the exit of the polarimeter.

The polarisation of the beam was reversed manually after approximately

30 min. in series I. In series II and III the polarisation direction was reversed automatically after a preset charge had been accumulated in the Faraday cup. This occurred at the rate of a few Hertz. Subsequent tests showed that the automatic spin reversal resulted in the total charge collected for the two spin states differing by less than 0.1%, which made possible a consistency test outlined below.

3. DATA

The results are shown in Fig. 1. The statistical error bars when not shown are smaller than the size of the dots. Corrections for finite geometry were generally very small (<0.001) and have been incorporated only in the data at 32.4 and 35.1 MeV. Systematic uncertainties come almost entirely from scale uncertainties in the analyzing powers in refs. 14 and 15 used for the polarimeter and are in all cases $\leq 3\%$. The accuracy of setting detector angles was estimated to be $\pm 0.1°$. To allow for this uncertainty in angle, 0.1 times the slope of the analyzing power (per degree) has been added in quadrature with the statistical error in A_y. The effect of this was to increase error bars by no more than 0.001. Data in numerical form may be obtained by request from the author.

A check of the data was provided by the quantity Ω:-

$$\Omega = SQRT(L^+R^+/L^-R^-)$$

which should have a value close to 1.0. The average of all results in series II and III was 0.998 ± 0.002. A further check of the internal consistency of the data was made possible in series II and III by the use

of the automatic spin flipper. Namely, a comparison was made between the spin up - spin down asymmetries ε_L, ε_R in the left and right detectors:-

$$\varepsilon_L = (L^+-L^-)/(L^++L^-)$$

$$\varepsilon_R = (R^--R^+)/(R^-+R^+)$$

The weighted mean-square difference between ε_L and ε_R provided an estimate of the uncertainty in a single measurement due to the combined effects of counting statistics and uncertainties in the extraction of peak areas. As a result, 0.004 has been added in quadrature with the statistical errors of the analyzing power results.

When the data of Fig. 1 are compared with older data,[10-13] the most notable differences, apart from the greater statistical accuracy of the present results, are in the magnitudes of the analyzing powers in the vicinity of the backward angle maximum at $\Theta_{CM} \sim 135°$. The analyzing powers from the present work have a back angle maximum typically 0.15 to 0.20 larger than reported in refs. 10 to 13. This is in an angular region where the differential cross-section is varying rapidly[8] (the minimum occurs near the points where the analyzing power goes through zero at $\Theta_{CM} \sim 120°$). The smaller analyzing powers reported in refs. 10 to 13 resulted presumably from the effects of finite geometry which, as noted, are very small for the present work.

4. DISCUSSION

The restrictions imposed by invariance under rotations and reflections of the coordinate system as well as time reversal invariance lead to a p + ^{3}He scattering matrix which may be written as the sum of six 4 x 4 matrices with coefficients (amplitudes) a, b, c, d, e, f, which are functions of energy and scattering angle[16].

$$M(\vec{k}_f, \vec{k}_i) = \tfrac{1}{2} [(a + b) + (a - b)(\vec{\sigma}_1 \cdot \vec{n})(\vec{\sigma}_2 \cdot \vec{n})$$

$$+ (c + d)(\vec{\sigma}_1 \cdot \vec{m})(\vec{\sigma}_2 \cdot \vec{m}) + (c - d)(\vec{\sigma}_1 \cdot \vec{l})(\vec{\sigma}_2 \cdot \vec{l})$$

$$+ e(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{n} + f(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{n}],$$

where $\vec{l}$, $\vec{m}$ and $\vec{n}$ are orthogonal unit vectors defined by

$$\vec{l} = \frac{\vec{k}_f + \vec{k}_i}{|\vec{k}_f + \vec{k}_i|} \quad , \quad \vec{m} = \frac{\vec{k}_f - \vec{k}_i}{|\vec{k}_f - \vec{k}_i|} \quad , \quad \vec{n} = \frac{\vec{k}_i \times \vec{k}_f}{|\vec{k}_i \times \vec{k}_f|} \quad ,$$

and $\vec{k}_i$ and $\vec{k}_f$ are unit vectors in the directions of the initial and scattered particle momenta in the centre of mass. $\vec{\sigma}_1$ and $\vec{\sigma}_2$ are the Pauli spin matrices, acting on the spin space of the proton and the ^{3}He, respectively. Each amplitude is complex, so that measurements of eleven different observables are needed at each incident energy and scattering angle to specify the p + ^{3}He system completely (a common phase can be removed from the six amplitudes). Differential cross-section data or differential cross-section plus proton analyzing power data alone do not suffice to determine all of the parameters unambiguously. For example, the

spin triplet-singlet (phase shift) mixing parameters appear in the partial-
wave expression for the singlet-triplet transition amplitude, if $/\sqrt{2}$.
Consequently, the measurement of an observable or a combination of
observables that is most sensitive to f is required for best determination
of these mixing parameters. The simplest experimental combination that
satisfies this criterion is the difference between the proton and ^{3}He
analyzing powers, ΔA, since [16],

$$\Delta A = \frac{2}{\sigma_o} \ Re \ (b^* f),$$

where σ_o is the differential cross-section for the scattering of
unpolarised protons from ^{3}He. As a result accurate data for as many
observables as possible is essential and logically the next step to the
measurement of the proton analyzing powers is the measurement of the $^3\vec{\text{He}}$
analyzing powers.

The $\vec{p} + {}^3$He analyzing power data presented here have been used
along with the total reaction cross-section,[7] differential cross-
section,[8] preliminary p + $^3\vec{\text{He}}$ analyzing power data of Ref. 9 and those
at 25.0 MeV (Ref. 17) and at 26.8 MeV (Ref. 18) and the spin correlation
data of Ref. 19 as input for a single energy phase-shift analysis[20].
The results of the fits obtained are plotted as solid lines in Fig. 1.
Details of the formalism of the phase-shift analysis can be found in
ref. 18.

For comparison, the predictions of an energy-dependent phase shift
analysis[21] using the Los Alamos code, EDA[22] are also shown. The

energy parameterisation of EDA is that of the R-matrix formalism.   The

energy dependent phase shift analysis had as data base the total reaction

cross section[7] and differential cross section[8] and the proton

analyzing power data at 21.4, 24.8, 27.3 and 30.1 MeV.   Clearly, with

increasing energy the discrepancies between these predictions and the

measured proton analyzing power data increase significantly pointing out

the importance of spin-dependent data for such analyses.

We have measured $\vec{p}$ + ^{3}He analyzing powers at eleven energies

between 21.4 and 49.6 MeV for scattering angles between 20° and 150°c.m.

The statistical uncertainties of all but a few points are less than 0.03

and the scale uncertainties are $\leq 3\%$ at all energies.   These data plus

recent total reaction cross-section, differential cross-section and p +

$^3\vec{\text{He}}$ analyzing power data for the same energy range have been used in a

single energy phase-shift analysis which will be reported in another paper.

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FIGURE CAPTION

Fig. 1 (a,b,c)

Analyzing power A_y for $^3\text{He}(\vec{p},p)^3\text{He}$ elastic scattering between 20 and 50 MeV. The solid curves are the results of single-energy phase-shift analysis fits to the data, while the dashed curves correspond to predictions from an energy dependent phase shift analysis based upon a subset of the data.
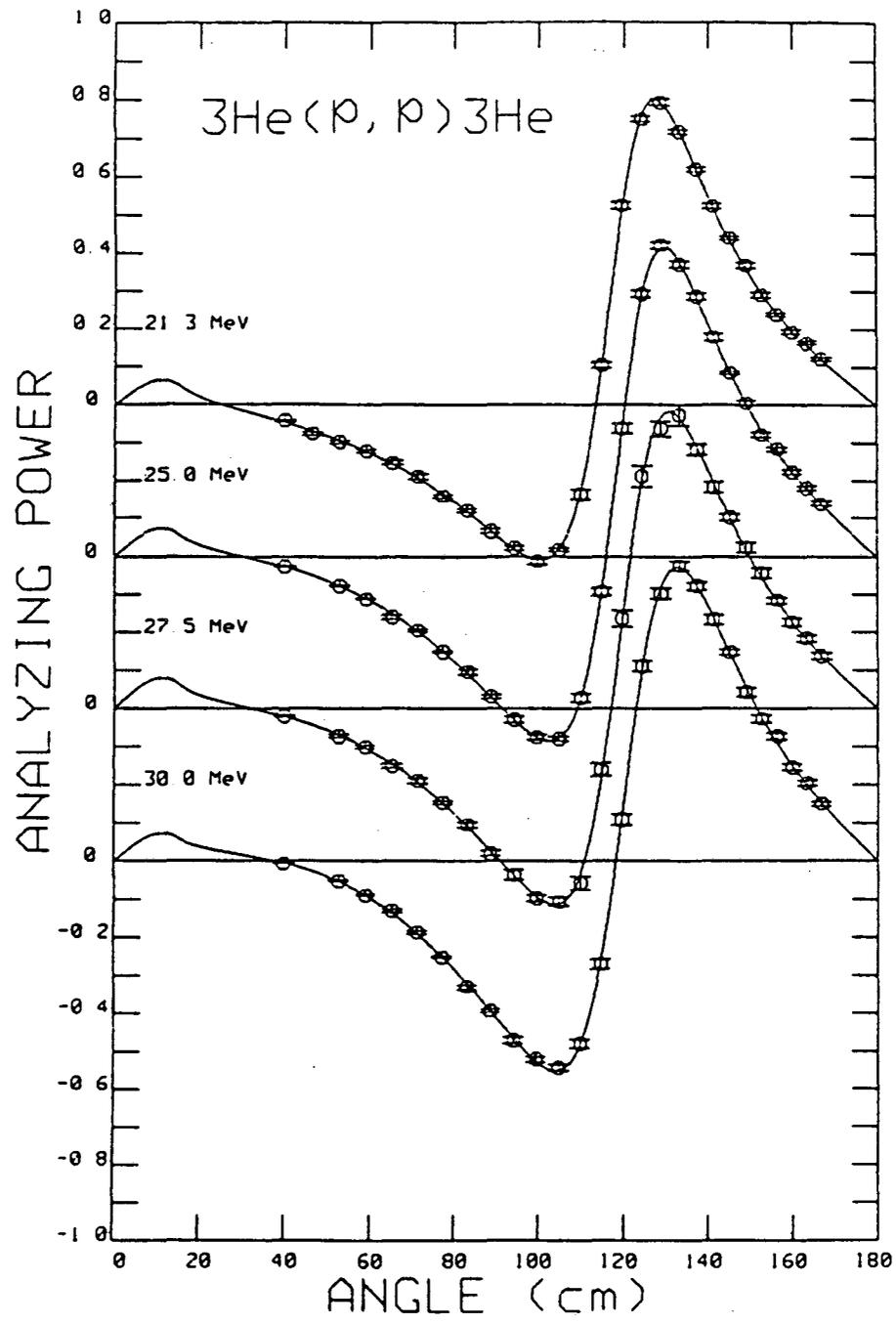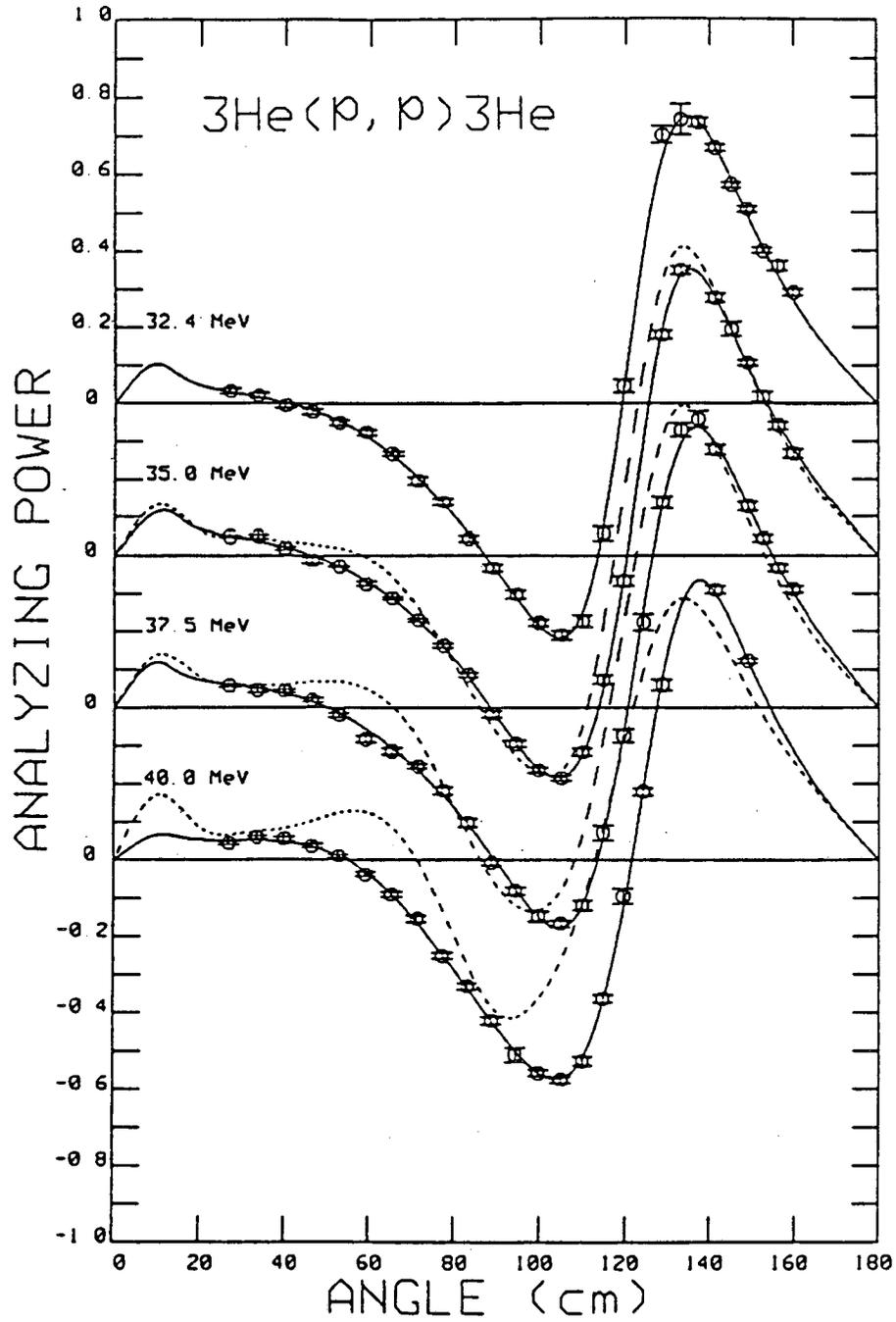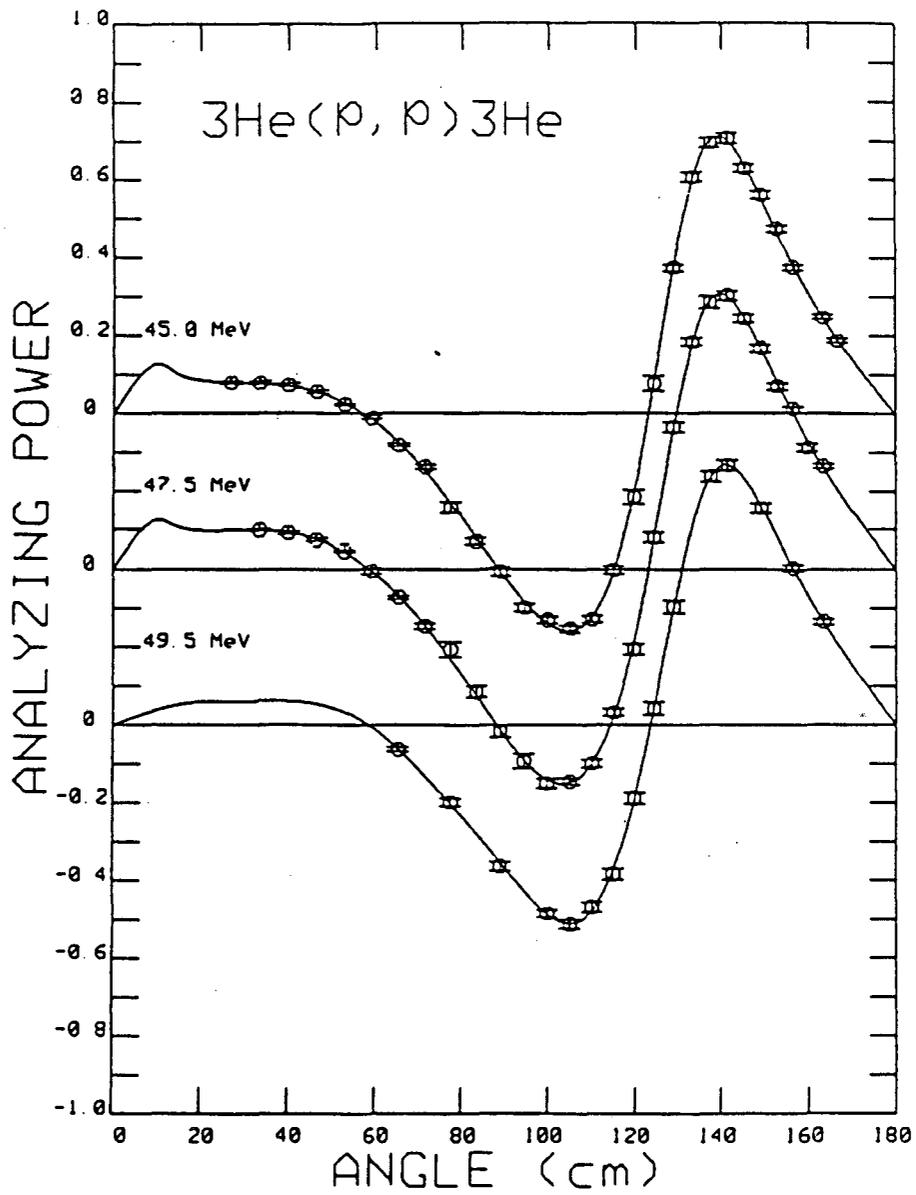
Fig. 1 (a)

$3He(p,p)3He$

Fig. 1. (b)

Fig. 1 (c)