Analyzing power measurements for $^3He(\vec{p},p)^3He$ elastic scattering between 20 and 50 MeV

J. Birchall and W. T. H. van Oers
Department of Physics, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2

J. W. Watson
Department of Physics, Kent State University, Kent, Ohio 44242

H. E. Conzett, R. M. Larimer, B. Leemann, E. J. Stephenson,* and P. von Rossen†
Lawrence Berkeley Laboratory, Berkeley, California 94720

Ronald E. Brown
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 27 February 1984)

Analyzing power data $A_y(\theta)$ have been obtained for $\vec{p}+{}^3He$ elastic scattering at 11 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.

I. INTRODUCTION

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, LeMere, and Thompson[2] describes the collision of composite nuclei in terms of the individual nucleon-nucleon interactions, employing totally antisymmetric wave functions 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 antisymmetrization resulted in different potentials for the even and odd l states. Recently, Paez and Landau[4] have constructed a microscopic optical model of p-^{3}He scattering based on antisymmetrized nucleon-nucleon amplitudes. Additionally, there have been substantial efforts in the past few years to develop generalizations 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 characterize any resonant behavior 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 $p+{}^3He$ system in the 20 to 50 MeV range. (Extensive data exist for proton energies below 20 MeV.) In this paper we report analyzing power data $A_y(\theta)$ for $\vec{p}+{}^3He$ scattering at 11 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 polarized $^3\vec{He}$ target.

There are four previous published $\vec{p}+{}^3He$ 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%.

II. EXPERIMENT

The experiment was performed at the 88-inch 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 atm. The windows were of havar 5 μm thick. Beam currents on the target varied between 10 and 100 nA, while the beam polarization 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 up-down pairs of collimators. In the first and second series of runs, the beam was centered 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

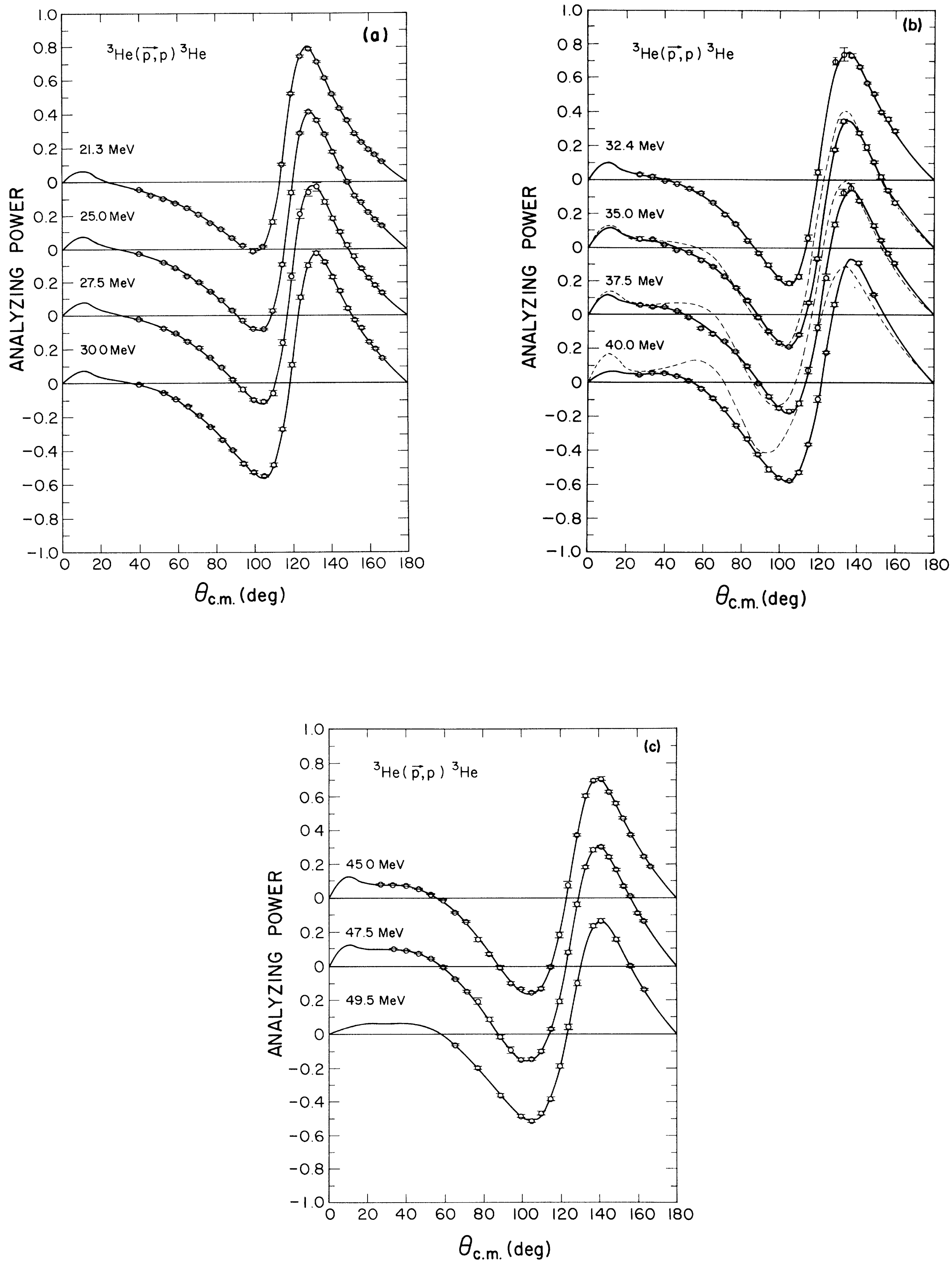

FIG. 1. Analyzing power A_y for ^{3}He($\vec{p}$,p)^{3}He elastic scattering between 20 and 50 MeV. The solid curves are the results of single-energy phase-shift analysis fits to the data, while the dashed curves correspond to predictions from an energy dependent phase shift analysis based upon a subset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

detector systems was 1.5° FWHM in each case. Pulse-height spectra were recorded in a pulse-height analyzer and 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%.

The beam was collected in a Faraday cup at the exit of the polarimeter. The polarization of the beam was reversed manually after approximately 30 min in series I. In series II and III the polarization 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.

III. 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 $\lesssim 3\%$. 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:

$$\Omega=(L^+R^+/L^-R^-)^{1/2} ,$$

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:

$$\epsilon_L=(L^+-L^-)/(L^++L^-) ,$$
$$\epsilon_R=(R^--R^+)/(R^-+R^+) .$$

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 magnitude of the analyzing powers in the vicinity of the backward angle maximum at $\theta_{\mathrm{c.m.}}\sim 135°$. The analyzing powers from this work have a back angle maximum typically 0.15 to 0.20 larger than reported in Refs. 10—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 $\theta_{\mathrm{c.m.}}\sim 120°$). The smaller analyzing powers reported in Refs. 10—13 resulted presumably from the effects of finite geometry which, as noted, are very small for this work.

IV. 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 4×4 matrices with coefficients (amplitudes) a, b, c, d, e, and f, which are functions of energy and scattering angle.[16]

$$\begin{aligned}M(\vec{k}_f,\vec{k}_i)=\tfrac{1}{2}[&(a+b)+(a-b)(\vec{\sigma}_1\cdot\vec{n})(\vec{\sigma}_2\cdot\vec{n})\\&+(c+d)(\vec{\sigma}_1\cdot\vec{m})(\vec{\sigma}_2\cdot\vec{m})\\&+(c-d)(\vec{\sigma}_1\cdot\vec{l})(\vec{\sigma}_2\cdot\vec{l})\\&+e(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\vec{n}+f(\vec{\sigma}_1-\vec{\sigma}_2)\cdot\vec{n}] ,\end{aligned}$$

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

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

and $\vec{k}_i$ and $\vec{k}_f$ are unit vectors in the directions of the initial and scattered particle momenta in the center 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 11 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 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]

$$\Delta A = \frac{2}{\sigma_0} \mathrm{Re}(b^* f) ,$$

where σ_0 is the differential cross section for the scattering of unpolarized 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 $^3\vec{\mathrm{He}}$ 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 $p+{}^3\vec{\mathrm{He}}$ analyzing power data of Ref. 9 and those at 25.0 MeV (Ref. 17) and 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 (Ref. 22) are also shown. The energy parametrization 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] 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 11 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 $\lesssim 3\%$ at all energies. These data, plus recent total reaction cross section, differential cross section, and $p+{}^3\vec{\mathrm{He}}$ 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.

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada and the United States Department of Energy.

---

*Present address: Indiana University Cyclotron Facility, Bloomington, IN 47405.

†Present address: Institut für Kernphysik, Kernforschungsanlage, Jülich, Federal Republic of Germany.

[1]P. P. Szydlik, Phys. Rev. C 1, 146 (1970); P. P. Szydlik, J. R. Borowisz, and R. F. Wagner, *ibid.* 6, 1902 (1972).

[2]Y. C. Tang, M. LeMere, and D. R. Thompson, Phys. Rep. 47, 167 (1978).

[3]H. S. Sherif, Phys. Rev. C 19, 1649 (1979).

[4]M. J. Paez and R. H. Landau, Bull. Am. Phys. Soc. 27, 695 (1982); R. H. Landau, in *Proceedings of the Tenth International Conference on Few Body Problems in Physics, Karlsruhe, 1983,* edited by B. Zeitwitz, p. 194.

[5]M. Sawicki and J. M. Namyslowski, Phys. Lett. 60B, 331 (1976); M. Sawicki, *ibid.* 68B, 43 (1977).

[6]R. Perne and W. Sandhas, Phys. Rev. Lett. 39, 788 (1977).

[7]A. M. Sourkes, A. Houdayer, W. T. H. van Oers, R. F. Carlson, and R. E. Brown, Phys. Rev. C 13, 451 (1976).

[8]B. T. Murdoch, D. K. Hasell, A. M. Sourkes, W. T. H. van Oers, P. J. T. Verheijen, and R. E. Brown Phys. Rev. C 29, 2001 (1984), the preceding paper.

[9]R. H. McCamis, P. J. T. Verheijen, G. R. Maughan, N. T. Okumusoglu, W. T. H. van Oers, J. M. Daniels, and A. D. May, in *Polarization Phenomena in Nuclear Physics—1980* (Fifth International Symposium, Santa Fé), Proceedings of the Fifth International Symposium on Polarization Phenomena in Nuclear Physics, AIP Conf. Proc. No. 69, edited by G. G. Ohlsen, R. E. Brown, N. Jarmie, M. W. McNaughton, and G. M. Hale (AIP, New York, 1981), p. 1266.

[10]W. F. Tivol, Ph.D. thesis, University of California Radiation Laboratory Report No. UCRL-18137, 1968.

[11]S. A. Harbison, F. G. Kingston, R. J. Griffiths, A. R. Johnston, and J. H. P. C. Megaw, Nucl. Phys. A112, 137 (1968).

[12]R. Darves-Blanc, Nguyen Van Sen, J. Arvieux, J. C. Gondrand, A. Fiore, and G. Perrin, Nucl. Phys. A191, 353 (1972).

[13]S. A. Harbison, R. J. Griffiths, N. M. Stewart, and G. T. A. Squier, Nucl. Phys. A150, 570 (1970).

[14]A. D. Bacher, G. R. Plattner, H. E. Conzett, D. J. Clark, H. Grunder, and W. F. Tivol, Phys. Rev. C 5, 1147 (1972).

[15]S. Kato, K. Okada, M. Kondo, A. Shimizu, K. Hosono, T. Saito, N. Matsuoka, S. Nagamuchi, K. Nisimura, N. Tamura, K. Imai, K. Egawa, M. Nakamura, T. Noro, H. Shimizu, K. Ogino, and Y. Kadota, Nucl. Instrum. Methods 169, 589 (1980).

[16]P. La France, C. Lechanoine, F. Lehar, F. Perrot, L. Vinet, and P. Winternitz, Nuovo Cimento A64, 179 (1981).

[17]D. Muller, R. Beckmann, and U. Holm, Nucl. Phys. A311, 1 (1978).

[18]R. H. Ware, W. R. Smythe, and P. D. Ingalls, Nucl. Phys. A242, 309 (1975).

[19]S. D. Baker, T. A. Cahill, P. Catillon, J. M. Durand, and D. Garreta, Nucl. Phys. A160, 428 (1971).

[20]P. J. T. Verheijen, Ph.D. thesis, University of Manitoba, 1983; P. J. T. Verheijen, R. H. McCamis, and W. T. H. van Oers (unpublished).

[21]R. E. Brown, B. T. Murdoch, D. K. Hasell, A. M. Sourkes, and W. T. H. van Oers, in *Proceedings of the Eighth International Conference on Few Body Systems and Nuclear Forces I,* edited by H. Zingl, M. Haftel, and H. Zankel (Springer, Berlin, 1978), p. 292.

[22]G. M. Hale and D. C. Dodder (private communication).