PHYSICAL REVIEW C VOLUME 15, NUMBER 2 FEBRUARY 1977

Analyzing power for ^{4}He$(p,p)^4$He scattering at 11.93 and 17.00 MeV†

R. A. Hardekopf and G. G. Ohlsen
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

(Received 28 June 1976)

An angular distribution of the analyzing power for ^{4}He$(p,p)^4$He elastic scattering was measured at 17.00 MeV to an absolute precision of ±0.01. The normalization uncertainty was verified by measurements at 11.93 MeV, 112° (lab), where A_y is known to reach 1.0. The data are presented in tabular and graphical form along with predictions from published phase shifts.

[NUCLEAR REACTIONS ^{4}He$(p,p)^4$He, $E_p = 11.93$ and 17.00 MeV; measured analyzing power $A_y(\theta)$ at $\theta_{\mathrm{c.m.}} = 119°\text{–}134°$ and $\theta_{\mathrm{c.m.}} = 37\text{–}157°$, respectively.]

I. INTRODUCTION

The data reported here were obtained during the initial test of a new Lamb-shift polarized ion source[1] which was specifically designed for producing a polarized triton beam. This test with hydrogen served to verify, prior to tritium contamination of the source, that performance was as planned. In particular, by using the well known analyzing power of ^{4}He$(\vec{p},p)^4$He elastic scattering near 12 MeV, 112° (lab), it was verified that the quench-ratio method[2] for the determination of the absolute beam polarization was applicable to this particular source (with its various modifications from earlier designs). This paper reports these calibration results and, in addition, presents an angular distribution of the ^{4}He$(\vec{p},p)^4$He analyzing power at 17.00 MeV.

II. POLARIZATION TEST AT 11.93 MeV

The analyzing power A_y is known[3,4] to reach its maximum possible value of 1.0 for ^{4}He$(\vec{p},p)^4$He scattering near 12 MeV, $\theta_{\mathrm{lab}} = 112°$. This reaction has thus become a polarization standard for polarized proton beams. The beam polarization from a Lamb-shift source equipped with a nuclear spin filter may also be routinely determined by an atomic beam technique known as the "quench-ratio" method. This requires only that one alter conditions in the spin filter in such a way that the polarized component of the beam disappears, or is "quenched." The ratio of the normal beam current to the background current remaining during the quenched condition is a measurement of the beam polarization. A complete description of this method and its uncertainties is given in Ref. 2.

To determine the precision of this method for our new polarized source with a redesigned spin filter, we measured left-right asymmetries for several angles near a known maximum in the ^{4}He$(\vec{p},p)^4$He elastic scattering analyzing power. The experiment was performed with a ^{4}He gas target, left-right detectors at symmetric angles, 1.0° full width at half maximum (FWHM) angular resolution, spin-up and spin-down runs, beam position monitoring, and mass identification of the scattered protons. The target was a 2.5-cm-diam cell covered with 25-μm-thick Havar foil and pressurized to 2 atm with ^{4}He gas. The proton energy at the center of the target was 11.93 ± 0.02 MeV with a spread of ±15 keV (FWHM). Other experimental details were essentially identical to those described in Ref. 5.

Figure 1 shows the data obtained in this test. The values plotted for A_y are the left-right asymmetries divided by the beam polarization as determined by the quench-ratio method. The maximum value, measured at $\theta_{\mathrm{lab}} = 112°$, was 0.997 ±0.005. Assuming that A_y actually reaches unity at this point, we thus confirm our beam polarization measurements to an accuracy of 0.5%. We believe, however, that a 1% uncertainty is a more realistic value to apply over the long term, and will adopt that value here. The line through the points represents the calculated values from several sets of p-^{4}He phase shifts.[6–10] These are discussed in Sec. IV. The three data represented by solid squares are from Ref. 2 where the quench-ratio method was first demonstrated on the original LASL polarized source. The agreement is remarkable, considering that different sources and detection apparatus were used for the two experiments.

III. ANGULAR DISTRIBUTION OF A_y AT 17.00 MeV

Using the experimental procedure described above, we obtained ^{4}He$(\vec{p},\mathrm{p})^4$He analyzing power data at a center-of-target proton energy of 17.00 ± 0.02 MeV, with a probable energy spread of ±15 keV (FWHM). The angular range from $\theta_{\mathrm{lab}} = 30°$

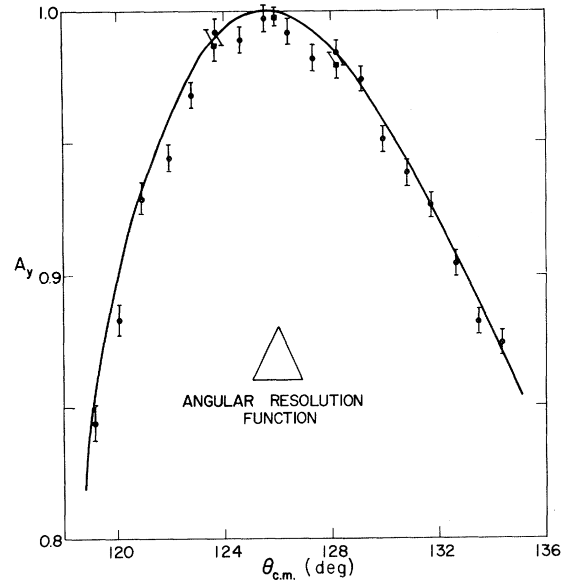

FIG. 1. ^{4}He$(p,p)^4$He analyzing power at 11.93 MeV. The curve represents the calculated values obtained from any of five sets of published phase shifts. The solid rectangles represent data from Ref. 2.

to $\theta_{lab}=160°$ was covered in 5° steps. This energy was chosen because it is near the upper limit of our FN tandem accelerator energy range, and also near the upper energy limit of many of the p-^{4}He phase shift sets published since 1968. The analyzing power predictions from these phase shifts begin to differ significantly near this energy. Because of the importance of this reaction as an analyzer for polarized beams in many laboratories, we felt a comparison of our results to the existing predictions would be useful. Our data are absolute, since the beam polarization is determined as described in the previous section, i.e., without reference to a secondary analyzer.

The results of these measurements are presented in Fig. 2. The various curves result from phase-shift calculations based on several currently available energy-dependent sets, and are further discussed in Sec. V.

IV. ERRORS AND NORMALIZATION

The data are tabulated in Tables I and II with the relative errors resulting primarily from counting statistics. However, when the statistical error was less than ±0.005 we took this value as a lower limit. The limit results from our observation of the maximum *fluctuation* in quench-ratio determinations of the beam polarization (caused by beam instability and measurement technique), and from the errors in the asymmetry measurement which arise from beam instability, small background effects, etc.

We have not unfolded the angular resolution from our data (see Fig. 1). The effect is small (maximum correction of 0.001) and should not significantly affect our results or conclusions. In a precision analysis, there may be some merit to angular smearing of the fit near the regions of large curvature of the data.

The absolute normalization of our data is of considerable importance for the accurate determination of the p-^{4}He phase shifts in this energy range. Most of the existing analyzing power data are normalized by measuring the beam polarization via an auxiliary scattering reaction in a polarimeter. The most commonly used reaction for this purpose has been ^{4}He$(p,p)^4$He elastic scattering itself, for which an absolute normalization is impossible without reliance on existing phase phase shifts. Self-consistency is usually obtained by allowing the normalization to be a free parameter in the phase-shift searches.

Other p-^{4}He data have been normalized with a carbon polarimeter which in turn was normalized in a double-scattering experiment. Although such techniques can lead to absolute normalizations, it is well known that high levels of accuracy are not easily obtained. Corrections to the quench-ratio method can also result in a normalization uncertainty, but we feel that such corrections are much

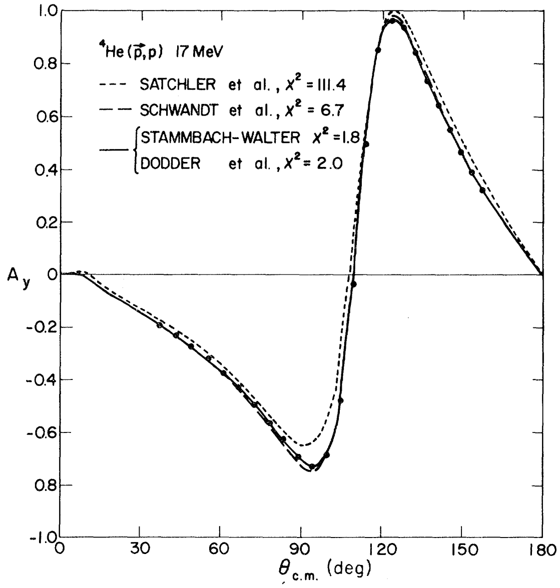

FIG. 2. ^{4}He$(p,p)^4$He analyzing power at 17.00 MeV. The curves represent calculated values from various published phase-shift sets. The errors on the data points are of the order of the size of the points. The χ^2 per degree of freedom associated with the various parametrizations are included.

TABLE I. $^4\text{He}(\vec{p},p)^4\text{He}$ analyzing power at 11.93 MeV.

$\theta_{\text{c.m.}}$	A_y	ΔA_y
119.18	0.844	0.007
120.11	0.883	0.006
121.03	0.929	0.005
121.95	0.944	0.005
122.87	0.968	0.005
123.78	0.992	0.005
124.69	0.989	0.005
125.60	0.997	0.005
126.50	0.992	0.005
127.39	0.982	0.005
128.28	0.984	0.005
129.17	0.974	0.005
130.05	0.951	0.005
130.93	0.938	0.005
131.81	0.926	0.005
132.68	0.904	0.005
133.55	0.882	0.005
134.41	0.874	0.005

TABLE II. $^4\text{He}(\vec{p},p)^4\text{He}$ analyzing power at 17.00 MeV.

$\theta_{\text{c.m.}}$	A_y	ΔA_y
37.3	−0.181	0.005
43.4	−0.229	0.005
49.4	−0.273	0.005
55.4	−0.320	0.005
61.3	−0.376	0.005
67.1	−0.432	0.005
72.8	−0.497	0.005
78.4	−0.564	0.005
83.8	−0.626	0.005
89.2	−0.694	0.005
94.5	−0.733	0.005
99.7	−0.686	0.006
104.7	−0.482	0.008
109.7	−0.035	0.010
114.5	0.495	0.010
119.2	0.849	0.007
123.8	0.957	0.006
128.3	0.935	0.005
132.7	0.839	0.005
137.0	0.734	0.005
141.2	0.640	0.005
145.4	0.550	0.005
149.4	0.463	0.005
153.4	0.387	0.005
157.3	0.320	0.005

smaller than can be easily obtained with other techniques.

V. COMPARISON WITH PHASE-SHIFT CALCULATIONS

We list in Table III the results of calculations with phase shifts from the energy-dependent analyses currently available.[6–10] The various columns give the phase shifts at 11.93 MeV and comparisons of the calculations to our 11.93-MeV data as indicated by the χ^2 per point. The next-to-last column gives the best normalization as calculated by the computer program; i.e., the normalization of our data that would minimize χ^2. It is seen that all of the analyses are consistent at 11.93 MeV, giving equally good representations of the data. One may also observe that each of the analyses gives a best fit to the data if a normalization factor of about 1.005 is applied. This normalization is consistent with our measurement at the $A_y = 1$ point at $\theta_{\text{c.m.}} = 125.6°$ for which we obtained a value of 0.997 ± 0.005. This is well within the normalization uncertainty of one percent which we normally assign. The χ^2 per degree of freedom values in the last column are those obtained with a normalization of 1.005 applied to our data.

The results at 17.00 MeV are given in Table IV. At this energy, near the upper end of most of the analyses, the differences become apparent. The optical model analysis of Satchler[6] is clearly inferior, but one also observes that there are significant differences between the other analyses. The best parametrizations at this energy appear to be those of Stammbach and Walter[9] and Dodder *et al.*[10] It should be pointed out that the present data were included in the analyses of Dodder *et al.*[10] at a late stage, resulting in a fine adjustment to their solution. The normalization factors for the better phase-shift solutions are consistent with those at 11.93 MeV and are again within our 1% uncertainty.

If we take the 11.93-MeV data as a calibration of the quench-ratio method and therefore apply a normalization factor of 1.005 to the 17.00 MeV, the χ^2 per degree of freedom results presented in the last column of Table IV are obtained. The con-

TABLE III. Phase shifts and fits to polarization data at 11.93 MeV.

Phase-shift set	$s_{1/2}$	$p_{3/2}$	$p_{1/2}$	$d_{5/2}$	$d_{3/2}$	$f_{7/2}$	$f_{5/2}$	χ^2	Norm	$\chi^2(1.005)$
Satchler *et al.* (1968)	109.89	104.50	59.08	2.97	1.79	0.10	0.07	2.7	1.007	1.2
Arndt *et al.* (1971)	110.09	103.66	56.99	0.73	0.28	0.20	0.14	2.6	1.005	1.6
Schwandt *et al.* (1971)	110.34	105.08	59.15	2.19	1.50	0.46	0.35	2.0	1.005	1.1
Stammbach and Walter (1972)	110.11	104.24	58.30	1.72	1.09	0.46	0.33	2.6	1.005	1.9
Dodder *et al.* (1976)	110.75	104.52	58.34	1.57	0.83	0.69	0.52	2.2	1.005	1.3

TABLE IV. Phase shifts and fits to polarization data at 17.00 MeV.

Phase-shift set	$s_{1/2}$	$p_{3/2}$	$p_{1/2}$	$d_{5/2}$	$d_{3/2}$	$f_{7/2}$	$f_{5/2}$	χ^2	Norm	$\chi^2(1.005)$
Satchler *et al.* (1968)	97.59	95.21	54.17	5.77	2.90	0.26	0.15	111.4	1.014	110.0
Arndt *et al.* (1971)	98.11	95.62	54.87	2.41	1.21	0.72	0.52	8.9	1.026	6.0
Schwandt *et al.* (1971)	99.14	98.57	58.40	4.79	3.10	1.37	1.01	6.7	1.022	4.4
Stammbach and Walter (1972)	96.60	95.91	55.29	4.47	2.97	1.45	1.01	1.8	1.003	1.8
Dodder *et al.* (1976)	100.84	98.37	58.17	4.70	3.16	2.06	1.55	2.0	1.010	1.1

clusions remain the same, except that now the phase shifts of Dodder *et al.*[10] are now decidedly superior to the others. It must be pointed out, however, that this was the only analysis which included the present data and thus will naturally be biased in its favor. A complete description of their fits to all p-^{4}He scattering data is in preparation by these authors.

A recent paper by Brandan, Plattner, and Haeberli[11] has compared the various phase shift sets for ^{4}He$(p,p)^4$He scattering in the energy range 2–9 MeV. It is interesting to note that in this range, the phase shifts of Arndt and of Stammbach appear to be the best, while at 12 MeV we find the results of Schwandt to be best. (The analysis of Dodder *et al.* was not available to these authors.)

VI. CONCLUSIONS

Analyzing power data have been presented at 11.93 and 17.00 MeV with uncertainties smaller than those on previously available data. An absolute uncertainty better than 0.01 has been demonstrated at 11.93 MeV and the extension of the technique to the 17.00-MeV data provides a criterion for selecting phase-shift solutions in this energy range. We conclude that the analyses of Stammbach and Walter[9] and Dodder *et al.*[10] are preferred near 17 MeV. Analyzing powers near the minimum and maximum calculated with the other available phase shifts differ from these results by at least 0.015 to as much as 0.08. These conclusions may be of value to experimenters using helium polarimeters for accurate beam polarization monitoring.

[†] Work done under the auspices of the U. S. Energy Research and Development Administration.

[1] R. A. Hardekopf, in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions, Zurich, 1975* (Birkhauser-Verlag, Basel und Stuttgart, 1976).

[2] G. G. Ohlsen, J. L. McKibben, G. P. Lawrence, P. W. Keaton, Jr., and D. D. Armstrong, Phys. Rev. Lett. 27, 599 (1971).

[3] G. R. Plattner and A. D. Bacher, Phys. Lett. 36B, 211 (1971).

[4] P. W. Keaton, Jr., D. D. Armstrong, R. A. Hardekopf, P. M. Kurjan, and Y. K. Lee, Phys. Rev. Lett. 29, 880 (1972).

[5] R. A. Hardekopf, G. G. Ohlsen, R. V. Poore, and N. Jarmie, Los Alamos Scientific Laboratory Report No. LA-6188 (unpublished).

[6] G. R. Satchler, L. W. Owen, A. J. Elwyn, G. L. Morgan, and R. L. Walter, Nucl. Phys. A112, 1 (1968).

[7] R. A. Arndt, L. D. Roper, and R. L. Shotwell, Phys. Rev. C 3, 2100 (1971).

[8] P. Schwandt, T. B. Clegg, and W. Haeberli, Nucl. Phys. A16, 432 (1971).

[9] Th. Stammbach and R. L. Walter, Nucl. Phys. A180, 225 (1972).

[10] D. C. Dodder, G. M. Hale, N. Jarmie, J. H. Jett, P. W. Keaton, Jr., R. A. Nisley, and K. Witte, Los Alamos Scientific Laboratory Report No. LA-6389-MS (unpublished); following paper, Phys. Rev. C 15, 518 (1977).

[11] M. E. Brandan, G. R. Plattner, and W. Haeberli, Nucl. Phys. A263, 189 (1976).