[11] A full description of the detector characteristics and circuitry will be given in a separate publication.

[12] J. B. Hastings, J. Appl. Phys. 48, 1576 (1977).

[13] J. A. Bearden, Phys. Rev. B 137, 455 (1965).

[14] W. W. Beeman and H. Friedman, Phys. Rev. 56, 392 (1939), adjusted.

Polarization Analyzing Power $A_y(\theta)$ in pp Elastic Scattering at 643, 787, and 796 MeV

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Data have been obtained for the polarization analyzing power $A_y(\theta)$ in pp elastic scattering from near 30° to 90° (c.m.) at 643, 787, and 796 MeV. Relative uncertainties are typically ± 0.003 with an overall normalization uncertainty of $(^{+1}_{-0.5})\%$. Data are not consistent with existing phase-shift analyses.

Below 400 MeV the proton-proton interaction proceeds essentially through the elastic channel with recent phase-shift analyses[1] indicating that the data are reasonably consistent. In the intermediate energy range from 400 MeV to 1 GeV considerable uncertainty still exists in our knowledge of the phase shifts.[2,3] With the advent of a polarized ion source at the Clinton P. Anderson Meson Physics Facility (LAMPF), a program of experiments is underway to determine uniquely the proton-proton phase shifts at energies in the 400- to 800-MeV range to complement the recent impressive results appearing from TRIUMF.[4] This paper describes measurements of the polarization analyzing power $A_y(\theta)$ in pp elastic scattering that are almost an order of magnitude more precise than earlier data above 500 MeV.

Figure 1 compares our polarization analyzing power measurements at 796 MeV with a calculation made by extrapolating from 750 to 800 MeV the energy-dependent phase-shift solution of MacGregor, Arndt, and Wright, paper XIII[2] (shown as a dashed line) and a calculation with the imaginary part of the $\delta(^1D_2)$ increased by 30° (shown as a solid line). Although the fit is improved by this change, in agreement with what we found in fitting our elastic scattering differential cross sections at this energy reported earlier,[5] this should only be taken as an indication of the large uncertainties in our knowledge of the phase shifts at this energy. Measurements at 643 MeV show a similar shape but the polarization analyzing power at the maximum is increased to 0.55. Figure 2 shows a plot of the polarization analyzing power near its maximum value [about 40° (c.m.)] as a function of proton energy in the intermediate range. Our three data points at 643, 787, and 796 MeV are generally consistent with, but much more precise than, previous data near these energies.

The technique for measuring polarization analyzing power is well known.[7] In this experiment a beam of protons with transverse polarization up to 0.92 was obtained from the LAMPF accelerator and focused (typically 4 mm diam) onto a CH_2 target. Data were taken at three beam energies, two of which were measured by the High Resolution Spectrometer (HRS) to be 796 ± 2 and 787 ± 2 MeV; the third energy was estimated to be 643 ± 4 MeV from accelerator operating param-

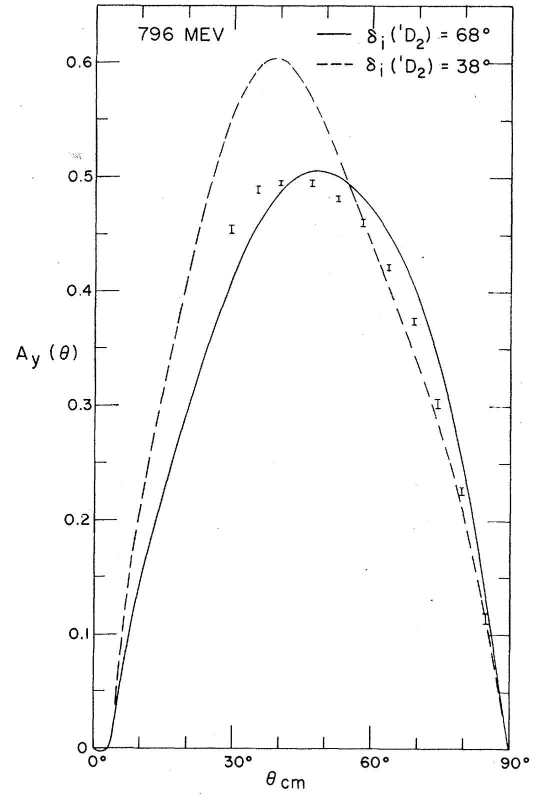

FIG. 1. The measured analyzing power $A_y(\theta)$ for pp elastic scattering near 800 MeV compared with phase-shift predictions extrapolated from MacGregor, Arndt, and Wright, paper VIII (Ref. 2).

eters.

Elastic pp scattering was distinguished from background by detecting in coincidence both final-state protons in multiwire proportional chambers (MWPC)[8] and requiring the precise angular correlation for two-body kinematics. The background was typically 0.5%, consisting mostly of quasielastic C(p, 2p) with a small contribution from random coincidences. Background curves were generated either by scattering from carbon, or by a Monte Carlo simulation, and subtracted by normalizing in the wings. No difference was observed between these two methods. The contribution from background subtraction to the uncertainty in the asymmetry is estimated to be about 0.02%.

Protons were detected simultaneously scattering both to the left and right while flipping the beam spin (up and down) every 3 min. If the left-right asymmetry is defined as $\epsilon = (L - R)/(L + R)$, where L and R are each the geometric mean of two of the four yields, it has been shown that false asymmetries disappear to a high order.[7]

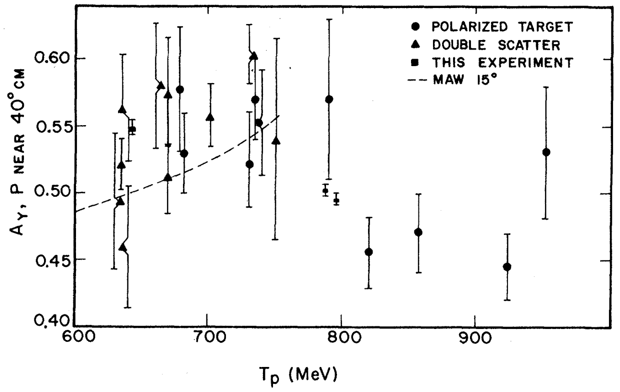

FIG. 2. Maximum values of analyzing power $A_y(\theta = 40°(\text{c.m.}), E)$ for pp elastic scattering from 600 to 1000 MeV. The phase-shift solution is from MacGregor, Arndt, and Wright, paper VIII (Ref. 2). The data are from the compilation of Bystricky *et al.* (Ref. 6).

Small residual false asymmetries that might remain were monitored and found to be insignificant at all angles. Deadtime was monitored, for example, and its false asymmetry was found to be $(1 \pm 1) \times 10^{-4}$. Events with more than one track in the wire chambers (mostly δ rays) were discarded, leading to a possible false asymmetry of $(1 \pm 2) \times 10^{-4}$. No corrections were made for these possible false asymmetries. The only significant contribution to the uncertainty in the measurement of the left-right asymmetry ϵ was from counting statistics.

The polarization analyzing power is obtained from the quotient of the left-right symmetry and the beam polarization $A_y(\theta) = \epsilon/P$. The beam polarization was monitored by a polarimeter consisting of four pairs of scintillation detectors placed to detect pp elastic scattering from CH_2 near the maximum of the analyzing power [17° (lab)] in each of four directions: left and right, up and down. The up-down asymmetry was zero so long as the polarization vector was correctly vertical, while the left-right asymmetry monitored the beam polarization. A constant background from C(p, 2p) gave a polarimeter asymmetry 2% lower than pp elastic scattering at 643 MeV and 3% lower near 800 MeV. After subtraction of random coincidences ($< 10^{-3}$) it was found that the uncertainty in the beam polarization was dominated by counting statistics in the polarimeter (≈ MWPC values) and by the absolute calibration.

Absolute calibration of the beam polarization is usually the most difficult part of a polarization experiment. The usual methods have been double-scattering and NMR measurements from polarized targets, which have both been limited in accuracy to (3–5)% at energies above 500 MeV. At LAMPF a third technique is available which takes advantage of the atomic physics of the polarized source. This technique, known as the "quench ratio," was developed and tested at the Los Alamos Van de Graaff accelerator, and is unique to Lamb-shift ion sources with a spin filter. The principles have been examined in detail[9] and cross checked against p-^{4}He scattering at Van de Graaff accelerator energies to an accuracy of ± 0.4%.[10] The behavior of the LAMPF polarized ion source has been observed to be very similar to that of the Van de Graaff accelerator. The only significant difference appears to be the possibility of depolarization of the beam after it leaves the ion source, a possibility which would lead to a systematic error since the quench-ratio technique measures the polarization as it existed in the ion source.

A calculation[11] indicates that depolarization of the beam after acceleration through the LAMPF accelerator should be about 0.1%; our investigations are consistent with this estimate. The calculation shows that depolarization is a function of beam phase space. Extensive comparison of different phase-space components over many months and a wide variety of conditions shows no change (to 0.5%) in the polarimeter calibration. Further possibilities for depolarization within the ion source exist[8] which have also been checked and found to be less than about 0.5%.

An independent check of the polarimeter calibration is obtained from results obtained with a polarized proton target at LAMPF in 1977.[12] Preliminary results from 28 pairs of runs, with NMR calibrations obtained under a wide variety of conditions, give an absolute measurement of the beam polarization of 1.01 ± 0.01 times that given by the quench-ratio calibration.

TABLE I. Measured values of analyzing power $A_y(\theta)$. The overall normalization uncertainty of $(^{+1}_{-0.5})\%$ applies equally to all data and has *not* been included in the uncertainties.

Energy (MeV)	θ_{lab} (deg)	$\theta_{\text{c.m.}}$ (deg)	$A_y(\theta)$	$\Delta A_y(\theta)$
643	12.31	28.38	.5030	.0043
	15.02	34.54	.5475	.0054
	17.44	40.00	.5480	.0035
	19.98	45.69	.5438	.0040
787	14.87	35.11	.4878	.0019
	16.87	39.73	.5011	.0017
	19.87	46.59	.4949	.0033
	27.36	63.31	.4250	.0036
	32.36	74.10	.3120	.0031
	34.90	79.46	.2243	.0027
796	12.37	29.33	.4541	.0031
	14.87	35.16	.4886	.0029
	16.87	39.79	.4946	.0018
	19.87	46.66	.4940	.0027
	22.36	52.29	.4805	.0025
	24.85	57.86	.4598	.0028
	27.36	63.39	.4216	.0025
	29.86	68.83	.3749	.0024
	32.36	74.19	.3021	.0038
	34.90	79.56	.2258	.0035
	37.38	84.71	.1146	.0048

We conclude that possible depolarization results in a calibration uncertainty of less than 1%. If depolarization occurred, then the true analyzing power would be larger than that reported here. In the other direction, the estimated uncertainty results from accelerator noise which limits our ability to measure the required ratio of beam intensities. In conclusion, we estimate a normalization uncertainty, which applies equally to all data at any one energy, of $(^{+1}_{-0.5})\%$. This uncertainty has *not* been included in Table I where the data for 643, 787, and 796 MeV are summarized. The uncertainty in the mean angle is about 0.1° (c.m.). Corrections for the finite angular acceptance of the MWPC's (3.3°) have been made, increasing the values of A_y by up to 0.0015 over those quoted earlier.[13]

These data, with greatly improved absolute accuracy as well as relative precision, based on the unique ability of LAMPF to determine the polarization of the beam so well, should provide an important step in further constraining phase-shift parameters at energies above the threshold for pion production.

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[1] R. A. Arndt, R. H. Hackman, and L. David Roper, Phys. Rev. C 9, 555 (1974), and 15, 1002 (1977).

[2] Malcolm H. MacGregor, Richard A. Arndt, and Robert M. Wright, Phys. Rev. 169, 1149 (1968) (this is paper VIII in a series), and 173, 1272 (1968), and 182, 1714 (1969).

[3] J. Bystricky *et al.*, Nucl. Phys. A285, 469 (1977).

[4] C. Amsler *et al.*, Nucl. Instrum. 144, 401 (1977);

C. Amsler *et al.*, Phys. Lett. 69B, 419 (1977); D. Axen *et al.*, Lett. Nuovo Cimento 20, 151 (1977); D. V. Bugg *et al.*, Rutherford Laboratory Report No. RL77-146/B, 1977 (unpublished).

[5] H. B. Willard *et al.*, Phys. Rev. C 14, 1545 (1976).

[6] J. Bystricky *et al.*, Centre d'Etudes Nucléaires de Saclay Report No. CEA-N-1547, 1972 (unpublished).

[7] G. G. Ohlsen and P. W. Keaton, Nucl. Instrum. 109, 41 (1973).

[8] P. R. Bevington and R. A. Leskovec, Nucl. Instrum. 147, 431 (1977).

[9] G. G. Ohlsen, Los Alamos Scientific Laboratory Report No. LA-4451, 1970 (unpublished).

[10] G. G. Ohlsen *et al.*, Phys. Rev. Lett. 27, 559 (1971).

[11] R. M. Mobley, Brookhaven National Laboratory Report No. BNL-50120, 1968 (unpublished), p. 430.

[12] M. W. McNaughton *et al.*, Bull. Am. Phys. Soc. 23, 625 (1978).

[13] M. A. Schardt *et al.*, Bull. Am. Phys. Soc. 23, 625 (1978).

Collective Resonances in Pion-Nucleus Scattering

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Pion-nucleus scattering is described by the excitation of bound nucleons into the Δ resonance leading to isobaric resonances of the whole nucleus. A few broad collective resonances of different multipolarity are shown to dominate elastic and inelastic π-^{12}C scattering. From the qualitatively good agreement with the data, we conclude that those giant isobaric resonances are a general feature of the nuclear excitation spectrum in the Δ(3, 3) energy range.

It is well known that pion-nucleon scattering at intermediate energies is dominated by the Δ(3, 3) resonance. From the large elementary cross section of $\sigma_{\pi^+p} \sim 200$ mb at the resonance energy, it is to be expected that a conventional multiple-scattering approach to pion-nucleus scattering converges slowly. A natural way of introducing many-body effects resulting from the strong pion-nucleon interaction is the explicit inclusion of the isobar degrees of freedom of bound nucleons. For such a description various related models have been developed during the last few years: the isobar doorway model of Kisslinger and Wang,[1] the collective model of Dillig and Huber,[2] and the multiple-scattering approach of Lenz and co-workers[3]; related aspects have been discussed by Brown and Weise.[4]

In this paper we adopt the approach of Ref. 2 to describe elastic and inelastic pion-^{12}C scattering: We assume that the incoming pion excites a bound nucleon into the Δ(3, 3) resonance, thereby creating an isobaric particle-hole ($\Delta\bar{N}$) configuration. Since the Δ interacts strongly with the surrounding nucleons the various ($\Delta\bar{N}$) configurations of the same quantum numbers are coupled, thus leading to new eigenmodes of the whole nucleus. Those nuclear excitations, $|A_\nu^{*J^\pi}\rangle$, can decay emitting a pion thereby leaving the target nucleus in its ground or one of its excited states, respectively. The corresponding T matrix for pion-nucleus scattering then is given by

$$T(\vec{k}, \vec{k}', \omega) = \sum_{J^\pi, M, \nu} \frac{\langle \vec{k}', f | \mathcal{L}^\dagger | A_\nu{}^{*J^\pi, M}\rangle \langle A_\nu{}^{*J^\pi, M} | \mathcal{L} | \vec{k}, i\rangle}{\omega - \mathcal{E}_\nu{}^{J^\pi}}. \tag{1}$$

Here $|i, \vec{k}\rangle$ and $|f, \vec{k}'\rangle$ denote the initial and final states, $\mathcal{E}_\nu{}^{J^\pi}$ is the complex eigenenergy of the A^* resonances, $\mathcal{L}$ is the usual $\pi N\Delta$ transition operator,[4] and ω is the pion energy in the π-nucleus c.m. system.

For the actual calculations the Δ particle and the nucleons are assumed bound in a common harmonic oscillator potential, h_{ext} ($\hbar\omega = 41A^{-1/3}$). Accordingly, the resonance energies $\mathcal{E}_\nu{}^{J^\pi}$ of Eq. (1) are obtained as the (complex) eigenvalues of the many-body Hamiltonian

$$H = \sum_{i=1}^{A} [h_{\text{ext}}(i) + h_{\text{int}}(i)] + \frac{1}{2} \sum_{i \neq k} V_{\Delta N}(i, k). \tag{2}$$

Here h_{int} describes the internal degrees of freedom of the baryons. For $V_{N\Delta}$ we used a one-boson-exchange (OBE) interaction taking into account explicitly π and ρ exchange.[5-7] The π-exchange part is dominating and describes the coup-