shown) are worse fits than solution one. The χ^2 values for solutions 3M, 4M, A-M, and 3 (the closest bad fit) are 2.5, 5.8, 3.6, and 15.6, respectively. The expected value for a reasonable fit is five, the number of data points.

Solutions 3M, 4M, and A-M also give quite acceptable fits to the polarization measurements reported in the following paper.[2] Since our R_t and P data were *not* used as input for any of the phase-shift searches, the good agreement suggests that 3M, 4M, and A-M are fairly close to the true solutions near 203 MeV, and further changes in them in this energy region will be small.

ACKNOWLEDGMENTS

We wish to thank Dr. R. Wright, Professor G. Breit, and Professor P. Signell for helpful communications concerning phase-shift analyses. We are grateful to Professor Alan Cromer for discussions about our impulse-approximation calculation, and for numerical evaluations of the needed coefficients. P. Koehler and L. Moyer assisted with various aspects of the experiment. S. Chadwick, D. Harmon, and M. Eipper helped with data reduction. The experiment depended heavily upon the various support groups of the 130-Inch Cyclotron Laboratory: cyclotron operating crew, mechanical design group, machine shop, and electronics shop.

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Asymmetry in the (p,n) Reaction on Deuterium and Carbon at 215 MeV*†

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A double-scattering experiment was performed on targets of deuterium and carbon, using 215-MeV, 85% polarized protons as incident particles. The asymmetry of recoil neutrons was measured at laboratory angles between 10° and 35°, using a neutron counter consisting of a polyethylene converter and multi-element scintillation telescope. The deuterium measurements are related to the free n-p polarization parameter by an impulse-approximation calculation. The deuterium results are in good agreement with the predictions of Yale phase-shift solutions 3, 3M, and 4M and the new Livermore solution, and are incompatible with Yale solutions 0, 1, 2, 2M. The asymmetries from carbon agree with free-n-p scattering except at laboratory angles of 10° and 35°, where they are greater in absolute value. The asymmetry from carbon showed the greatest dependence on neutron energy at these angles.

I. INTRODUCTION

We have measured the asymmetry parameter P in the (p,n) reaction on deuterium and carbon targets.

The p-d scattering can be related to free nucleon-nucleon scattering by making the impulse approximation. A calculation appropriate to the final state occurring in the present measurements is described in the preceding paper.[1] Using this calculation, we can compare the predictions of various phase-shift solutions against our measurements.

We have studied the (p,n) reactions on carbon principally to allow use of the charge-symmetric (n,p) reaction in neutron-spin analysis. For example, in Ref. 1 neutron spin was analyzed by hydrogen associated with considerable carbon contaminant. The similarity of asymmetry parameters for carbon and hydrogen (demonstrated in this experiment) makes a carbon subtraction unnecessary. A similar experiment has been performed by Carpenter and Wilson[2] at 143 MeV.

The experiment itself is standard in design. Plan and elevation views are shown in Fig. 1. A transversely polarized proton beam is directed onto the target, and neutrons recoiling in a plane perpendicular to the incident polarization are detected in a scintillation telescope. Under these conditions the measured asymmetry e is related to the beam polarization P_b and the reaction asymmetry P by the relation $e=PP_b$. As P_b and e are measured, P can be found.

II. APPARATUS AND PROCEDURE

The Beam

The polarized proton beam of the Rochester synchrocyclotron was stochastically accelerated[3] with a duty cycle of approximately 30%. Mean energy, polarization, and other beam parameters are listed in Table I. After

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† Submitted by one of us (D. Spalding) in partial fulfillment of the requirements for the Ph. D. degree in physics at the University of Rochester, Rochester, New York.

[1] N. W. Reay, E. H. Thorndike, D. Spalding, and A. R. Thomas, preceding paper, Phys. Rev. **150**, 801 (1966).

[2] S. G. Carpenter and R. Wilson, Phys. Rev. **113**, 650 (1959).

[3] E. Nordberg, IEEE Trans. Nucl. Sci. **NS-12**, 973 (1965).

TABLE I. Proton-beam parameters. The first three columns give the average beam energy, energy spread, and beam polarization to be quoted for the experiment. The beam was nearly a Gaussian peak with some low-energy tail. The peak is parametrized in the fourth and fifth columns, where its center energy and full width at half-maximum (FWHM) are given. The last columns describe the tail. Listed are the ratio of the tail intensity to peak intensity in percent, and the cutoff energy below which there is zero beam intensity.

Target	$\bar{E}$ (MeV)	Entire beam ΔE rms (MeV)	$P(\bar{E})$ %	Peak E_0 (MeV)	Peak FWHM (MeV)	Tail % of peak	Tail MeV cutoff
D_2	211	16	0.83 ± 0.036	217	16	19	145
C	217	7	0.86 ± 0.036	217	19	3	190

the extraction, beam polarization was rotated into a horizontal plane by means of a solenoid magnet. The sign of the beam polarization could be changed by reversing the current direction through the solenoid. The two possibilities, "normal" and "reverse" are designated N and R. During the experiment the beam position was determined frequently, with particular attention being paid to any beam motion caused by reversing the solenoid current.

Targets

The carbon target was 8.7 g/cm^2 thick. The liquid-deuterium cup was a horizontal cylinder 5-in. long $\times 5$ in. in diameter, with 0.003-in. Be-Cu walls. The orientation of its axis horizontal and transverse to the proton beam is shown in Fig. 1.

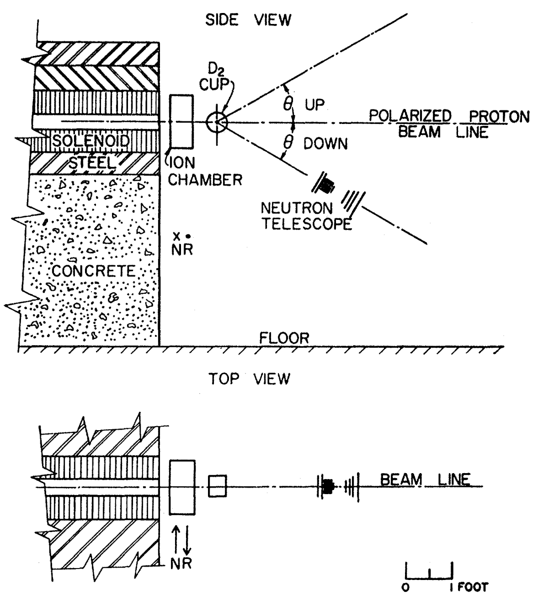

FIG. 1. Views of the second scattering. Shown are the steel and concrete neutron shielding and the ion-chamber beam monitor. Polarization directions of the beam at the solenoid exit, labeled N and R, are indicated in the views.

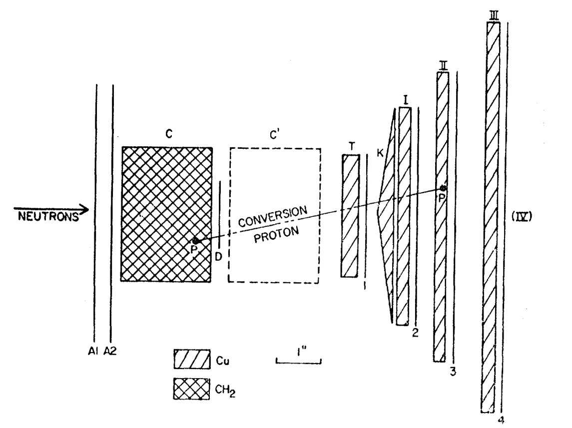

FIG. 2. Neutron detector. All counters are plastic scintillators viewed by phototubes. A typical path PP for a conversion proton is shown. Absorber K is a partial compensator for kinematic spread in the conversion protons, while absorber T sets the lower threshold on neutron energy. Conversion protons, giving counts in differential bins I, II, and III, stop in absorbers I, II, and III, respectively, and proton counts in differential bin IV go through all counters into the region labeled IV. A1 and A2 are independent veto counters, needed to exclude counts from protons entering the converter C, while D is the first defining counter for conversion protons. Counters 1–4 are used in logic for bins I–IV. Position C′ is reserved for the converter when converter "out" counts are taken.

Neutron Counter

Figure 2 shows the neutron counter in detail. It is a differential-range telescope arranged to have four energy bins whose position and size can be adjusted by varying the thicknesses of copper absorber at places T, I, II, and III in the figure. The data from the detector may be sorted into energy bins labeled "integral" or "differential". Integral bins include all recoil protons with an energy greater than a threshold value for that bin. Differential bins I, II, and III include only particles which stop in the absorber between two given counters and have rates computed by taking the difference of rates in two adjacent integral bins; e.g., integral bin II includes all $\bar{A}$D12 counted, whereas differential bin II includes $\bar{A}$D12 minus $\bar{A}$D123. Differential bin IV is defined to be the same as integral bin IV. Each bin has assigned a nominal energy for the detected neutron, obtained by using computed efficiency information. A *differential* bin energy is assigned as follows: This energy is that for which detection efficiency for neutron counts placed in that bin was a maximum. The nominal energy was assumed smeared to neutron energies for which the efficiency was half maximum. Thus, for the deuterium data, efficiency for neutron counts in differential bin II was highest for 152-MeV neutrons incident on the detector. For 129-MeV or 175-MeV (i.e. 152 ± 23-MeV) incident-neutron energy, efficiency was near half maximum. Hence, counts in this differential bin were assigned the nominal energy 152 ± 23 MeV. One notes that *integral* bins include all neutron counts above a threshold energy. It is convenient to assign as the

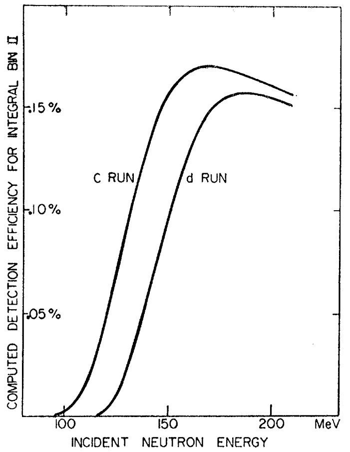

FIG. 3. Computed detection efficiency for integral bin-II neutrons. The difference in the C and d runs is due to use of different Cu absorber settings. These curves determine the effective energy threshold (see Sec. II).

threshold that energy for which detection efficiency is half maximum. Smear in this threshold is half the difference in the neutron energies for which efficiency is 90% maximum and 10% maximum (see Fig. 3).

Other features of the counter include a conical absorber placed at I to partially correct for kinematic energy spread of conversion protons, and a back (C′) position for the converter to allow acquisition of converter "out" data with proper range requirement. As shown in Fig. 1, the counter has "up" and "down" positions (U and D) above or below the beam line. Computed efficiency curves for integral bin-II neutrons are shown in Fig. 3. The counter was positioned to an angular accuracy of $\pm\frac{1}{2}°$. At 15°–35°, root-mean-square angular resolution was ±2.9°, while at 10° it was ±2.5° for deuterium and ±2.1° for carbon.

Procedures

For each scattering angle, data were collected for both solenoid-current conditions (N and R), neutron-counter positions (U and D), and both neutron-converter positions (forward and back), with target both in (or full) and out (or empty). Random-coincidence rates were measured simultaneously. Converter back counts were subtracted from converter forward, thereby removing charged particles that the anticoincidence requirements failed to eliminate. U, D, N, and R data were combined to give the asymmetry, as in Eq. (4) of Ref. 1.

For differential bins II, III, and IV, and integral bin II, backgrounds generally varied between 4% and 16% with the lowest percentages occurring at the largest angles and the highest energies. A typical background for differential bin I was 50%. Target-associated converter back counts (which include neutrons converting in the first defining counter) were ≈5%, while random counts were 1% at the most.

For the carbon measurement at 25°, a CH_2-C converter subtraction was performed to give effectively a pure hydrogen converter. Elsewhere, only a CH_2 converter was used.

Carbon and deuterium data were taken during experimental runs separated by several months. During each run, the beam energy and beam polarization were measured. The beam energy was determined from a range curve[4] taken with a separate proton telescope. The beam polarization was found by using the neutron detector to observe protons scattered from carbon at a laboratory angle of 15°, thereby obtaining proton asymmetry as a function of scattered-proton range. The polarization of the primary beam was then unfolded from this function with the help of a computer program. Input data for the program included the primary beam distribution in range and published values of the p-C elastic and inelastic $d^2\sigma/d\Omega dE$ and asymmetry parameters.[5–7] Uncertainty in the effect of inelastic p-C scattering was the largest source of error in the value assigned the beam polarization, contributing 0.030 to the total root-mean-square error of 0.036.

III. CORRECTIONS AND ERRORS

Due to the solenoid use, the only significant first-order error in the asymmetry data which was not expected to cancel was that due to beam motion caused by solenoid current reversal. Good alignment kept such beam movements small, but, in the case of carbon, it still was necessary to apply systematic corrections to the asymmetry, ranging in absolute value between 0.002 and 0.008. In all corrections of this variety, random errors, due to uncertainty in knowledge of the proton-beam position, ranged between ±0.002 and ±0.008.

Upper limits on second-order errors were estimated as follows: If one defines $U=(U,N)+(U,R)$, $D=(D,N)+(D,R)$, $N=(U,N)+(D,N)$, and $R=(U,R)+(D,R)$ then, for an ideal experiment with no spurious asymmetries, $e_{UD}=(U-D)/(U+D)$ and $e_{NR}=(N-R)/(N+R)$ should vanish. These values actually were $e_{UD}\leqslant 0.03$ and $e_{NR}\leqslant 0.03$. Taking the square of either of these as a measure of the size of a typical second-order error, one gets ≈0.0009. Assuming there may be ten such second-order errors adding in quadrature, one gets less than 0.003, or ≈2% of the asymmetry for all second-order effects. For each angle this number was added in with statistical and first-order errors to constitute the total error in the measured asymmetry.

Because of the energy spread in the beam, the asymmetry measured may not equal one found using a monoenergetic beam of energy $\bar{E}$. (See Table I.) Of the two experimental runs, the deuterium run had the poorer quality beam. It was estimated that the effect of energy spread caused the measured deuterium asym-

[4] The beam energy information was found using range-energy tables in M. Rich and R. Madey, University of California Radiation Laboratory Report No. UCRL-2301 (unpublished).
[5] E. M. Hafner, Phys. Rev. 111, 297 (1958).
[6] H. Tyren and Th. A. J. Maris, Nucl. Phys. 4, 637 (1957).
[7] P. Hillman, A. Johansson, and H. Tyren, Nucl. Phys. 4, 648 (1957).

TABLE II. Experimental and theoretical deuterium data. On the left side of the table are absolute values of measured asymmetries normalized to values at a 100% polarized incident beam. Also listed is the difference between differential bin-IV and -II values, used in the text in discussing dependence on neutron energy. Above the asymmetries are two lines giving, respectively, the bin and nominal neutron energy associated with the asymmetries. On the right-hand side of the table are theoretical quantities correct for integral bin-II neutrons. Listed is the theoretical correction which will yield the absolute value of free-n-p asymmetry when added to the integral bin quantities tabulated here. The "correction" column is an average of values derived from the acceptable phase sets 3, 3M, 4M, and A-M. A given phase set would yield corrections which typically differ from the average by ±0.002. The last column lists the ratio of "free" to "charge-exchange scattering" used to derive the corrections. [Cf. Eq. (2) of Ref. 1, replacing R there by P.]

	Experimental data						Theoretical quantities	
	Asymmetries for a 211-MeV 100% polarized beam							
Bin:	Diff I	Diff II	Diff III	Diff IV	Int II	Diff IV−	Correction	$aI_0^{np}/$
θ_{lab} MeV:	141±21	152±23	167±24	$E>177\pm25$	$E>145\pm22$	Diff II	$P_{np}-e_d$	$2bI_0^s$
10°	0.139±0.092	0.077±0.052	0.091±0.051	0.109±0.021	0.099±0.020	+0.032±0.056	−0.013	1.22
15°	0.116±0.050	0.105±0.035	0.102±0.033	0.143±0.019	0.126±0.017	+0.038±0.040	−0.010	2.85
20°	0.141±0.051	0.145±0.039	0.131±0.036	0.086±0.023	0.112±0.019	−0.059±0.045	−0.006	4.88
25°	0.232±0.039	0.170±0.025	0.163±0.025	0.134±0.024	0.154±0.017	−0.036±0.035	−0.002	7.33
30°	0.177±0.043	0.156±0.031	0.175±0.033	0.080±0.042	0.146±0.022	−0.076±0.052	−0.001	5.25

metry to be in error of the order of 3%. As the estimate was not precise and the 3% error was small compared to the statistical error ≈10%; no corrections for this effect were made to any of the data.

The beam polarization was assigned ≈4% error. The value quoted is the value at the beam energy $\bar{E}$ and is the effective polarization. As statistical errors are all ≈10%, the beam polarization error, as well as all the errors cited above, are small or negligible in comparison.

IV. DEUTERIUM DATA

Part of the data from deuterium, and various phase shift predictions are shown[8] in Fig. 4. Table II lists all the deuterium data. Also included in Table II are theoretical corrections to convert p-d data to free-n-p data, and the ratio of "free" to "singlet" scattering (see Ref. 1) used in arriving at these corrections.

The integral bin-II data have been compared with predictions of the Yale phase-shift solutions 0, 1, 2, 2M, 3, 3M, and 4M, and the new solution of Arndt and MacGregor (here labeled A-M).[9-11] Table III lists the χ^2 for these solutions. Ruled out are 0, 1, 2, and 2M, while 3, 3M, 4M, and A-M are acceptable. If the data from this paper are considered together with that of the previous one (Ref. 1), then only 3M, 4M and A-M are acceptable. It should be noted that the Yale group considered fits 3M and 4M as preferable to their others.[9,11]

TABLE III. χ^2 from the comparison of the deuterium data and theoretical predictions. As explained in Sec. I, the predictions are made using an impulse approximation and several sets of phase shifts for free scattering. The names of these sets are listed in the first line of the table. For five data points, the list of χ^2 values breaks into two groups. The left four values correspond to probability $p<1\%$, while the right four have $p>10\%$.

	Phase shift set							
	2	1	2M	0	4M	3	3M	A-M
χ^2	72	42	41	22	8.7	5.9	5.3	3.1

Considering differential data, the differences of asymmetry for bin IV and II (listed in Table II) indicate that the asymmetry increases with neutron energy at the larger angles and decreases at the smaller angles. However, the trend is not well outside of statistical errors.

Figure 4 includes quasi-free $d(p,n)2p$ data taken by Tinlot and Warner[12] at 217 MeV. There is agreement of their results and ours where there is overlap in angles used.

V. CARBON DATA

All final data are displayed[8] in Table IV. Differential bin-I data are not used because of high backgrounds for this bin in the carbon run. Also shown is the difference

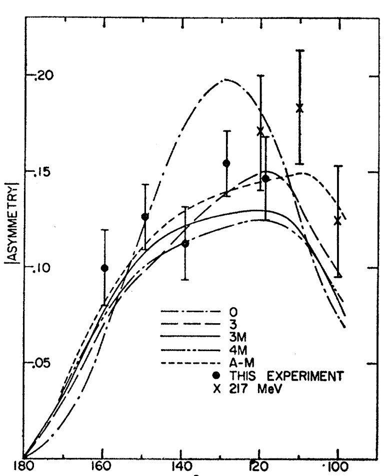

FIG. 4. Integral bin-II deuterium data compared with predictions made using the impulse approximation of Ref. 1 and phase shift sets 3, 3M, 4M, A-M, and 0 of Refs. 5–7. (Set 0 is the best of the sets incompatible with the data.) Also shown are data of Tinlot and Warner at 217 MeV (Ref. 12).

[8] All asymmetries measured in this experiment had the same sign, which was the same as for free p-n scattering in this angular region. For convenience, we take this sign to be *positive*.

[9] M. Hull, K. Lassila, H. Ruppel, F. McDonald, and G. Breit, Phys. Rev. **122**, 1606 (1961).

[10] R. A. Arndt and M. MacGregor, Phys. Rev. **141**, 873 (1966).

[11] G. Breit, R. E. Seamon, and R. D. Haracz (private communication).

[12] J. Tinlot and R. E. Warner, Phys. Rev. **124**, 890 (1961).

TABLE IV. Experimental carbon data. Listed are absolute values of measured asymmetries normalized to values at a 100% polarized incident beam. Also shown is the difference between differential bin-IV and -II values, used in the text in discussing dependence on neutron energy. Above the asymmetries are two lines giving, respectively, the bin and nominal neutron energy associated with the asymmetries. All data, except the last line (with asterisk), were taken using a CH_2 converter. The last line is data taken by CH_2-C subtraction.

Bin: MeV: θ_{lab}	Diff II 136±21	Diff III 154±23	Diff IV $E>162\pm23$	Int II $E>129\pm20$	Diff IV− Diff II
10°	0.058±0.053	0.208±0.051	0.169±0.045	0.125±0.020	+0.111±0.070
15°	0.139±0.026	0.144±0.028	0.119±0.029	0.137±0.016	−0.020±0.039
20°	0.108±0.019	0.115±0.020	0.121±0.022	0.113±0.013	+0.013±0.029
25°	0.148±0.019	0.120±0.022	0.177±0.026	0.137±0.014	+0.029±0.032
30°	0.125±0.033	0.148±0.033	0.193±0.038	0.154±0.019	+0.068±0.050
35°	0.143±0.030	0.132±0.040	0.288±0.055	0.191±0.019	+0.145±0.063
*25°	0.166±0.028	0.126±0.028	0.196±0.030	0.152±0.017	···

between differential bins IV and II. This difference, averaged over all angles, is 0.058±0.020, indicating that the higher energy neutrons systematically have an asymmetry significantly larger in magnitude than the lower energy ones. This increase of asymmetry with energy is also found in Ref. 2 (cf. Fig. 3 there). The energy dependence is smallest in the region between 15° and 25°, being of the order of 0.5% MeV^{-1}.

In Fig. 5 are compared integral bin-II data and the Yale 3M phase-shift prediction for *free–n-p* scattering (the 3M solution is one of the ones found acceptable in Sec. IV). There is fair agreement between the data and free scattering, except at the extremes of the angular range examined. The number of standard deviations between the 3M free scattering and the data is 2.8 at 10° and 4.2 at 35°. The behavior at the larger angles is similar to that found in Ref. 2 at 143-MeV incident energy. At 25°, the analyzing angle used in Ref. 1, the difference between the data and the 3M prediction for free scattering is 0.009±0.014. This near-zero difference and the relatively slow energy dependence of asymmetry in this region are fortunate results, for, as noted in the introduction, they make acceptable carbon admixtures in hydrogen analyzers for triple-scattering experiments.

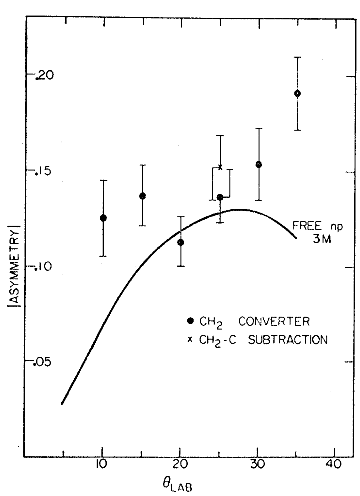

FIG. 5. Integral bin-II carbon data compared with a prediction for free–*n-p* scattering made with one of the four sets of phase shifts found acceptable in Sec. IV. (Yale set 3M.)

Finally, one notes that the CH_2-C subtracted data at 25° in Table IV are in agreement with the data taken with a CH_2 converter.

VI. CONCLUSIONS

When combined with the data of the preceding paper (Ref. 1), the integral bin-II data are consistent with the predictions of Yale phase shift sets 3M, 4M, and the new set of Arndt and MacGregor. The integral bin-II asymmetries from carbon agree with free–*n-p* scattering between laboratory angles of 15° and 25°, but tend to larger magnitudes at 10° and 35°. For a carbon target, the higher energy neutrons systematically have higher asymmetries. This energy dependence and the behavior at 35° is similar to that found in Ref. 2 for carbon at the lower incident-proton energy of 143 MeV.

ACKNOWLEDGMENTS

We wish to thank Dr. R. Wright, Professor G. Breit, and Professor P. Signell for helpful communications concerning phase-shift analyses. We are grateful to Professor Alan Cromer for discussions about our impulse-approximation calculation, and for numerical evaluations of the needed coefficients. P. Koehler, L. Moyer, and I-Hung Chiang assisted with various aspects of the experiment. S. Chadwick and M. Eipper helped with data reduction. The experiment depended heavily upon the various support groups of the 130-Inch Cyclotron Laboratory: cyclotron operating crew, mechanical design group, machine shop, and electronics shop.