Scattering of Fast Neutrons from C^{12} and F^{19}†

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High-resolution total cross-section measurements were made in the vicinity of the neutron scattering resonance occurring in C^{12} at (2.076 ± 0.008)-Mev bombarding energy with a total width of 7 kev. These data, coupled with differential cross-section measurements in the same energy range, lead to the assignment of $D_{5/2}$ to this state in C^{13}. Angular distributions of neutrons scattered from C^{12} measured between 1.45 and 4.10 Mev were analyzed in terms of partial waves. The resulting phase shifts indicate that the $D_{3/2}$ state occurring at 2.95 Mev has a width of 90 kev, while the $D_{3/2}$ state at 3.67 Mev has a width of 1.69 Mev.

Total cross-section measurements for fluorine, having resolutions of 20 and 70 kev, indicate the presence of resonances at 1.10 and 2.25 Mev, as well as some structure above 3 Mev not previously reported. Angular distributions were measured between 0.66 and 2.92 Mev.

INTRODUCTION

STUDIES of the $C^{12}+n$ system have revealed considerable information on states of the C^{13} nucleus.[1] Elastic scattering is the dominant mode of interaction for neutron bombarding energies less than 4.8 Mev, the threshold for inelastic scattering. Furthermore, the ground state spin of C^{12} is 0^+, which makes the analysis of the results reasonably straightforward and unambiguous.

Total cross-section measurements have been made for carbon by several groups.[2–7] Bockelman *et al.*[2] observed a narrow resonance occurring at a neutron energy of 2.08 Mev. The resolution of their work indicated that this level has a width less than 11 kev and a spin of 3/2, or greater. In addition, they[2] report another level at 2.95 Mev of width 120 kev and spin 3/2. A broad level at 3.6 Mev has been observed by the Minnesota group[3] and Ricamo and Zunti.[4] The only other resonance reported below 4.8 Mev is that at 4.2 Mev measured by Hafner *et al.*[5] Angular distribution data[8–10] have shown that the lower 3 resonances are due to *d*-waves. Other groups have also measured differential elastic scattering cross sections in the energy range below 4.8 Mev.[11–14]

A re-examination of the narrow level with better energy resolution, and additional data on the angular distributions was felt worthwhile in order to determine the detailed properties of these levels in C^{13}. Recent work on the mirror reaction $C^{12}+p$ has been extended to higher energies[15] making a direct comparison of the $N^{13}-C^{13}$ excited states possible.

The interaction of fast neutrons with F^{19} has also been studied in the past.[7,16–18] This present work includes the total cross section from 0.4 to 5 Mev, as well as five elastic scattering angular distributions.

EXPERIMENTAL METHODS

The $Li^7(p,n)Be^7$ and $T(p,n)He^3$ reactions served as neutron sources in these measurements. Thin metallic layers of normal lithium were evaporated, in place, onto a rotating backing plate of tantalum, 10 mils thick. A gas target for the tritium consisted of a 3-cm cell, lined with gold and sealed with 0.05- or 0.1-mil nickel foils from the accelerator vacuum system. Pressures up to one atmosphere could be held over an aperture of $\frac{3}{16}$-inch diameter. Suitable collimating slits were used to insure reliable measurement of the charge collected at the target. Analyzed protons for the reactions were obtained from the ORNL 5.5-Mev Van de Graaff accelerator.[19]

Neutrons were detected by propane recoil counters (1 in. diameter, 4 in. sensitive length, 1 atmosphere pressure) and a xylene-terphenyl liquid scintillator (1-in. diameter, 2 in. long). Since this scintillation counter was also sensitive to gamma radiation, it was useful only

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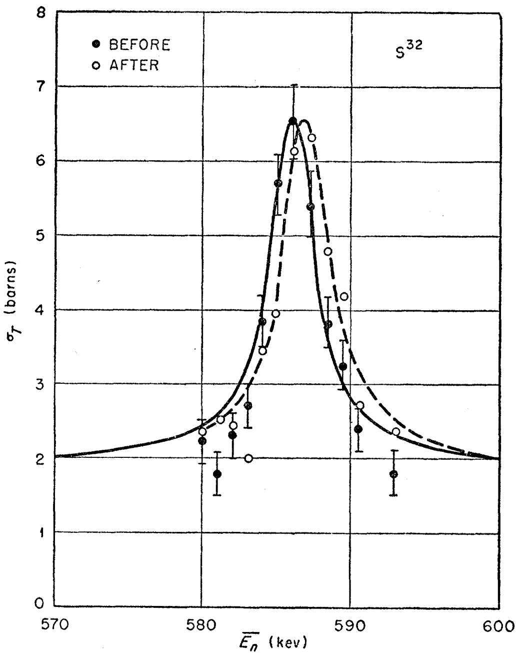

FIG. 1. Total cross section of S^{32} measured before and after the total cross section of C^{12} as a check on the over-all resolution.

for neutron energies greater than 2.5 Mev, where the discrimination became favorable.

Total cross-section measurements employed standard techniques in which neutron intensities were obtained with and without the sample placed midway between the source and the detector. Samples were cylinders of 1.125-in. diameter and the proper length to give approximately 60% transmission. Pure samples of graphite and Teflon $(CF_2)^n$ were used. The fluorine cross sections were obtained by experimentally subtracting the effects of the carbon. Good geometry limited the in-scattering corrections to less than 3% in all cases. These corrections were made on the basis of measured angular distributions and also those calculated from final spin and parity assignments of the levels, when possible. Care was taken to assure that the counter and sample were properly aligned. The background of neutrons not originating directly at the target, as well as those scattered from equipment, walls, and floors, was subtracted from the observed intensities. Machine background, obtained with a clean piece of tantalum in place of the target, was quite small and considered only in the case of high-resolution work. In the study of the 2.08-Mev resonance of C^{12} where a 2.3-kev lithium target was the source, this background was 2.4% of the direct beam. Scattered background was measured by placing a 12-in. long Lucite shadow cone between the target and the detector. This background was always less than 2.2% of the direct beam.

The experimental arrangement for the measurement of the differential cross sections has been previously described.[12] All distributions below neutron energies of 2.5 Mev were obtained with the propane detector shielded by a paraffin wedge. Above 2.5 Mev both the propane and the scintillation counters were employed. A lead shield was used with the latter detector to reduce the gamma-ray background from hydrogenous materials. Scattering samples were cylinders of 3-in. heights and diameters such as to give a minimum transmission of 65%. The fluorine data were taken by interchanging Teflon $(CF_2)^n$ and carbon samples of proper thickness.

Corrections were made for energy dependence of the counter sensitivity,[12] multiple scattering[20,21] in the sample, and the finite angular resolution.[22] All differential cross sections were then transformed to the center-of-mass system. The neutron energies quoted, however,

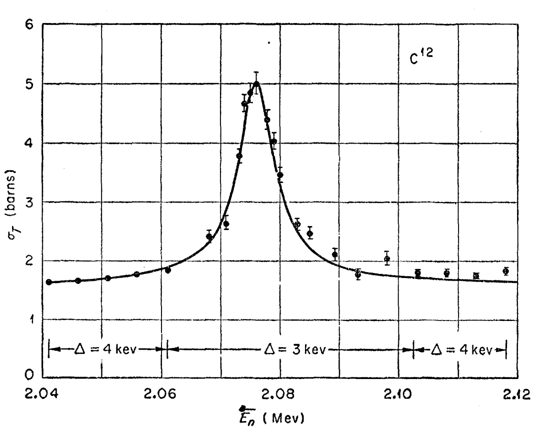

FIG. 2. Total cross section of C^{12} in the vicinity of the 2076-kev resonance. The solid curve is calculated for a $D_{5/2}$ resonance and corrected for energy resolution and the low-energy group of neutrons from $Li^7(p,n)Be^{7*}$. The natural width assumed was 7.0 kev.

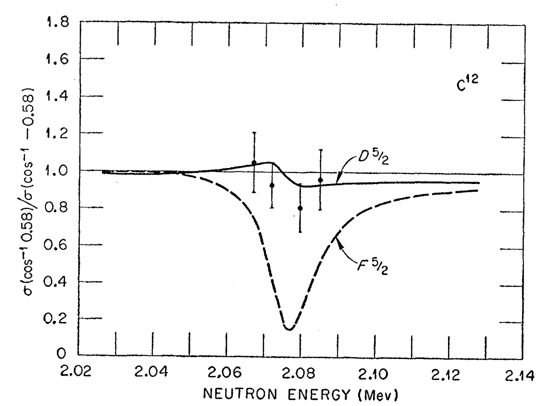

FIG. 3. The ratio of differential cross sections of neutrons scattered elastically by C^{12} for $\cos\phi = 0.58$ to $\cos\phi = -0.58$ in the center-of-mass system. The solid curve was calculated for a $D_{5/2}$ resonance, while the dotted curve represents the energy dependence of an $F_{5/2}$ resonance, both of 7.0-kev natural width.

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remain in the laboratory system, unless otherwise stated. Errors shown are statistical only, the over-all error in the cross section is estimated to be about 1.5 times this.

RESULTS FOR $C^{12}+n$

Before the total cross section in the region of the 2.08-Mev resonance can be analyzed, the following points must be considered. The high-resolution work requires the use of lithium as a source, but this (p,n) reaction is not monoenergetic for neutrons above 650-kev energy.[1] At 3.75-Mev bombarding proton energy where this resonance occurs, the transition to the first excited state of Be^7 is about 10% of the ground state.[23] This "second group" of neutrons has an energy of 1.61 Mev where the total cross section of C^{12} is smoothly varying and about 2 barns.[2] Thus, the experimentally observed cross section at this resonance will be reduced by 0.25 barn if the spin is 3/2, and 0.40 barn if it is $J=5/2$. The nonresonant cross section will be raised by 0.04 barn. These calculations assume the detector sensitivity is the same for both groups of neutrons, as was the case for the bias setting employed.

If the energy resolution used is comparable to the observed width of a level, the total cross section at resonance will, of course, be reduced. The experimental resolution was taken to be the rms value of machine energy resolution, target thickness, and neutron energy

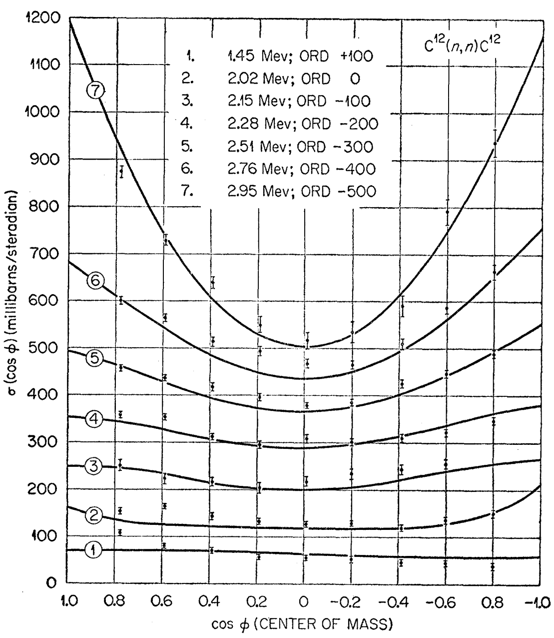

FIG. 4. Center-of-mass differential cross sections of neutrons scattered elastically by C^{12} for bombarding energies of 1.45, 2.02, 2.15, 2.28, 2.51, 2.76, and 2.95 Mev. Solid curves were calculated from the phase shifts of Table II, correction being made for energy resolution. The experimental points were corrected for multiple scattering and angular resolution. Note the shifts of zero ordinates.

[23] L. Cranberg, Los Alamos Scientific Laboratory Report LA-1654, 1954 (unpublished).

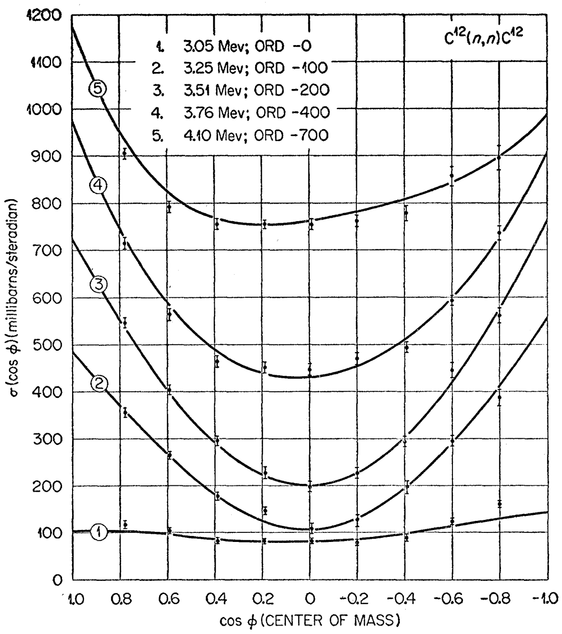

FIG. 5. Center-of-mass differential cross sections of neutrons scattered elastically by C^{12} for bombarding energies of 3.05, 3.25, 3.51, 3.76, and 4.10 Mev. Solid curves were calculated from the phase shifts of Table II, correction being made for energy resolu- The experimental points were corrected for multiple scattering and angular resolution. Note the shifts of zero ordinates.

variation with angle. Machine resolution was checked by observing the narrow (p,γ) resonances in Al^{27} at 933.3 kev[24] and C^{13} at 1746.9 kev,[25] giving a value of 0.06%, or 2.3 kev at 3.75 Mev. The target thickness was first obtained from the geometric peak at the threshold of the $Li^7(p,n)Be^7$ reaction. However, for thin targets (≤ 5 kev) this method is not reliable and a check on the over-all resolution was obtained by measuring the narrow resonance in the total neutron cross section of S^{32} of 585 kev.[26,27] Figure 1 shows these data, before and after the run on C^{12}, with the thinnest target used. The observed level width of 3.6 kev corresponded to a target thickness of 3.1 kev at this bombarding proton energy. Accordingly, the thickness at $E_p=3.75$ Mev was about 2.3 kev, the neutron angular energy variation was 0.2 kev, and hence the rms resolution was 3.3 kev.

Figure 2 shows the total cross section of C^{12} with only the in-scattering correction applied to the data points. The observed width is 7.7 kev, hence the natural width is 7.0 kev. Since the peak value is higher than the predicted value of 4.54 barns for a spin $J=3/2$ level, the corrections for $J=5/2$ were applied, giving a maximum cross section of 6.1 ± 0.1 barns at resonance, 2.076 ± 0.008 Mev. This is in excellent agreement with the expected value of

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[26] Peterson, Barschall, and Bockelman, Phys. Rev. **79**, 593 (1950).
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TABLE I. $\sigma(\cos\phi)$ center-of-mass differential cross section (millibarns/steradian) for the $C^{12}(n,n)C^{12}$ reaction.

$\bar{E}_n$ Incident neutron energy in Mev \ $\cos\phi$	0.78	0.59	0.39	0.19	−0.01	−0.20	−0.41	−0.60	−0.80
1.45	209±6	182±6	172±6	154±7	154±8	151±8	145±8	145±8	137±13
2.02	155±6	166±6	147±7	135±7	128±7	131±7	120±7	138±8	150±8
2.15	150±13	122±10	118±11	104±12	119±10	137±11	147±11	159±12	...
2.28	159±6	155±6	114±7	99±7	110±7	104±7	110±7	121±8	147±8
2.51	155±6	137±6	116±6	98±6	79±6	89±6	125±7	147±8	188±8
2.76	200±8	164±9	115±9	95±10	68±11	67±11	111±13	189±14	263±17
2.95	370±15	227±16	139±16	52±18	16±20	36±22	91±26	291±28	438±30
3.05	118±6	103±6	84±6	80±6	81±6	80±6	90±7	124±8	164±8
3.25	254±10	163±10	77±11	48±11	9±12	26±13	97±14	197±15	285±18
3.51	346±11	201±13	95±11	28±13	−3±12	26±13	94±13	245±18	359±16
3.76	315±11	161±11	63±11	51±13	47±13	70±13	91±14	192±15	339±17
4.10	201±6	89±6	53±6	56±6	56±6	61±7	78±8	158±9	195±9

6.01 barns for a spin 5/2 level. This conclusion differs from a preliminary result published earlier,[28] where all the above corrections were not properly considered.

The parity of this level can be checked by differential measurements only. These were taken with 5-kev resolution at center-of-mass angles $\phi=\cos^{-1}(\pm 0.58)$, the zeros of the second Legendre polynomial. This ratio is shown in Fig. 3. The solid curve shows the predicted asymmetry for a $D_{5/2}$ resonance interfering with the s-, p-, and d-wave nonresonant phase shifts, while the dotted curve shows the energy dependence for an $F_{5/2}$ level. It is concluded from the accumulated evidence that this level is indeed $D_{5/2}$.

Center-of-mass angular distributions between 1.45 and 4.10 Mev for neutrons scattered elastically by C^{12} are shown in Figs. 4 and 5. The data above 2.5 Mev are the averages of runs with both propane and scintillation detection (which agreed well with each other). The energy resolution was less than 50 kev for all measurements except those at 1.45 and 2.02 Mev where the resolution was about 100 kev. Table I summarizes these data.

Solid curves shown in Figs. 4 and 5 were calculated from the phase shifts listed in Table II and plotted in Fig. 6. Corrections for energy resolution were made at 2.95 and 3.05 Mev. These phase angles were fitted to the data by the usual phase-shift analysis. Explicit formulas for spin-zero nuclei appear in the paper by Meier, Scherrer, and Trumpy,[9] while the generalization can be found in Blatt and Biedenharn.[29] In the fitting of the data it was assumed that the phase shifts vary smoothly with energy, except in the region of resonances where the dependence is predicted by a Breit-Wigner type two-level expression, allowing in the usual manner for barrier penetration and level shift.[30] It was not necessary to include f waves to obtain reasonable fits. Changes in the phase angles by more than 3° gave significantly poorer agreement with the data. The center-of-mass cross sections are obtained from the expansion $\sigma(\cos\phi)=\sum_{L=0}^{4} B_L P_L(\cos\phi)$. The B_L coefficients calculated[9] from the phase shifts appear in Table III.

The $s_{1/2}$ phase shift is everywhere negative and varies smoothly with energy. It is larger than expected from hard-sphere potential scattering, but the known[1] bound $s_{1/2}$ level certainly adds its contribution. A static potential well with a diffuse boundary used by Fowler and Cohn,[31,32] not only gives good agreement with the experimental data, but correctly predicts the location

TABLE II. Phase shifts for $C^{12}(n,n)C^{12}$.

$\bar{E}_n$ (Mev)	$\delta_{0\frac{1}{2}}$	$\delta_{1\frac{1}{2}}$	$\delta_{1\frac{3}{2}}$	$\delta_{2\frac{3}{2}}$	$\delta_{2\frac{5}{2}}$
1.451	−80°	−4°	−2°	3°	0°
2.015	−92°	−6°	−3°	10°	4°
2.150	−94°	−6°	−3°	13°	176°
2.283	−95°	−6.5°	−3.5°	16°	177°
2.505	−99°	−6.5°	−3.5°	23°	178°
2.758	−103°	−7°	−3.5°	34°	178°
2.946	−105°	−7.5°	−3.5°	90°	178°
3.052	−106°	−8.0°	−4.0°	190°	177°
3.254	−108°	−8.5°	−4.0°	230°	176°
3.505	−111°	−9.0°	−5.0°	252°	175°
3.762	−114°	−10.0°	−8.0°	277°	174°
4.100	−118°	−12.0°	−12.0°	300°	173°

TABLE III. Legendre coefficients for $C^{12}(n,n)C^{12}$.

$\sigma(\cos\phi)=\sum_{L=0}^{4} B_L P_L(\cos\phi)$. ($B_L$ in millibarns/steradian.)

$\bar{E}_n$	B_0	B_1	B_2	B_3	B_4
1.451	164.7	7.8	−1.1	−2.3	0.0
2.015	131.9	−10.3	37.9	−14.9	16.5
2.150	127.8	−7.7	43.3	−2.3	−16.0
2.283	124.7	−10.9	56.3	−4.8	−13.8
2.505	126.6	−18.6	109.9	−11.9	−12.3
2.758	141.4	−24.4	193.8	−14.1	−14.1
2.946	244.8	0.3	473.9	5.3	1.3
3.052	81.5	−13.4	26.2	−1.9	−6.7
3.254	159.2	−25.3	284.3	−10.6	−23.3
3.505	190.4	−14.1	366.8	−1.1	−12.0
3.762	188.2	7.6	331.2	28.2	17.3
4.100	145.8	27.7	196.6	67.7	41.1

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[29] J. M. Blatt and L. C. Biedenharn, Revs. Modern Phys. **24**, 258 (1952).

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[32] J. L. Fowler and H. O. Cohn, Phys. Rev. **109**, 89 (1958).

TABLE IV. Properties of excited states in C^{13} and N^{13}.

Compound nucleus	C^{13}			N^{13}		
Bombarding energy (Mev)	2.076	2.95	3.67	4.803	5.37	5.9
Excitation energy (Mev)	6.86	7.67	8.33	6.38	6.90	7.4
J^π (spin and parity)	$5/2^+$	$3/2^+$	$3/2^+$	$5/2^+$	$3/2^+$	...
Reduced width γ^2 (Mev-cm)	0.088×10^{-13}	0.548×10^{-13}	7.27×10^{-13}	0.044×10^{-13}	0.17×10^{-13}	...
$\gamma^2/(3\hbar^2/2\mu R)$[a]	0.006	0.038	0.51	0.003	0.012	...

[a] μ is the reduced mass of the system.

of the bound $2s$ state about -2 Mev. Using their constants for the well,

$$V=-48.8 \text{ Mev for } r<2.67\times10^{-13} \text{ cm},$$
$$V=-48.8 \exp[-(r-2.67)/0.75] \text{ Mev for } r>2.67\times10^{-13} \text{ cm},$$

the solid curve in Fig. 6 for the $s_{1/2}$ phase shift was obtained.

The $p_{1/2}$ and $p_{3/2}$ phase shifts are negative, small, and vary smoothly with energy. No p-wave resonances are observed up to 4 Mev, and the effect of the $p_{1/2}$ resonance at 4.2 Mev is not large.

The $d_{3/2}$ phase shift shows a resonance behavior which can be fitted quite well assuming that the levels at 2.95 and 3.67 Mev have widths of 90 kev and 1.69 Mev, respectively. A nuclear interaction distance R of 4.61×10^{-13} cm $[1.40(A^{1/3}+1)]$ was used in the calculation of the barrier penetration and level shift factors, and the tangents of the phase shifts of the two individual resonances were added to give the tangent of the resultant $d_{3/2}$ phase shift, which appears as a solid curve in Fig. 6.

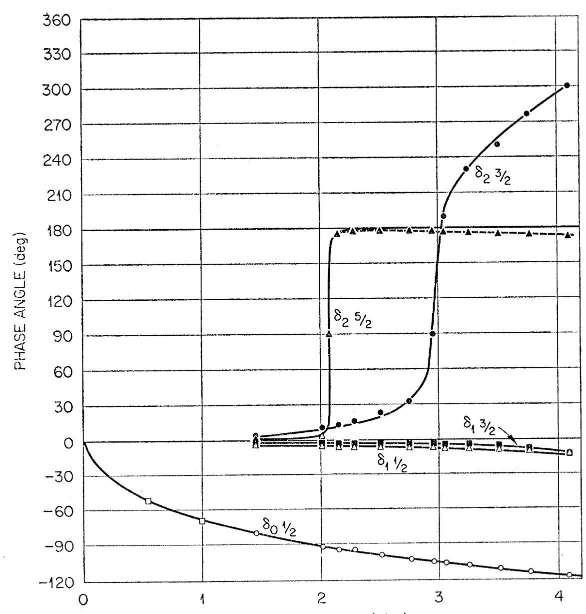

FIG. 6. Phase shifts for neutrons scattered elastically by C^{12}. For a detailed explanation see text.

The $d_{5/2}$ phase shift is due almost entirely to the 2.076-Mev level, although the deviation from resonance behavior, shown as a dotted curve in Fig. 6, is probably due to potential d-wave scattering.

Agreement of the experimental data with that of Meier, Scherrer, and Trumpy at common energies is quite good. However, their phase-shift analysis decreases the $s_{1/2}$ contribution and increases the $d_{3/2}$, relative to the present results. Neither set is unique, but it is felt that the smaller d-wave contribution is necessary to fit the measured angular distributions below 2 Mev, where the interaction is dominantly s wave.

Pertinent properties of these observed D states in C^{13} are summarized in Table IV together with those of the mirror levels in N^{13}. Reasonable correspondence exists. It should be pointed out that levels in C^{13} at 5.51- and 6.10-Mev excitation have been observed[33] in the $B^{11}(He^2,p)C^{13}$ reaction. These states should appear at 0.61- and 1.25-Mev bombarding neutron energy. Similarly the $C^{12}(d,p)$ reaction has revealed[34] levels at 7.47- and 7.53-Mev excitation in C^{13}, corresponding to 2.73- and 2.80-Mev bombarding neutron energy. The nonobservance of resonances at these energies in the total cross section of C^{12} indicates the states must be formed by high angular momentum with very narrow

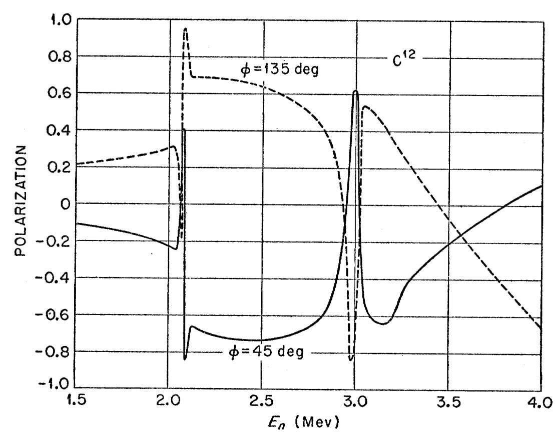

FIG. 7. Calculated values of the polarization of neutrons scattered elastically by C^{12} for center-of-mass angles $\phi=45°$ and $135°$. The phase shifts of Table II were used.

[33] C. D. Moak *et al.* (to be published).
[34] McGruer, Warburton, and Bender, Phys. Rev. **100**, 235 (1955).

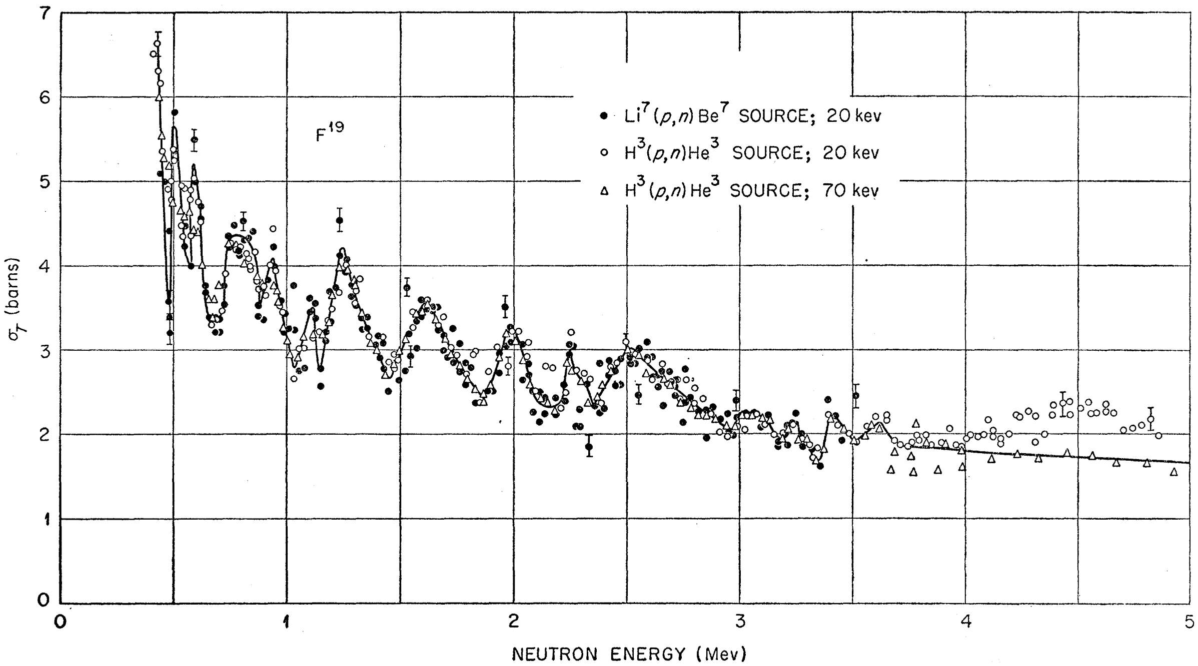

FIG. 8. Total cross section of F[19] from 0.5 to 5 Mev.

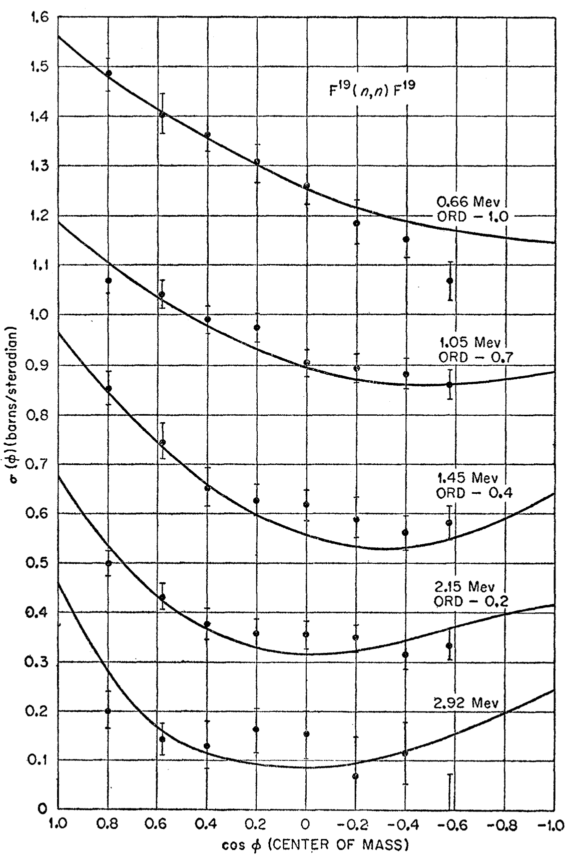

FIG. 9. Center-of-mass of neutrons scattered elastically by F[19] at 0.66-, 1.05-, 1.45-, 2.15-, and 2.92-Mev bombarding energy. The solid curves were calculated from the phase shifts of Table V. Note the shifts of zero ordinates.

widths. High-resolution work in this region may reveal such states.

This reaction has been used frequently as a neutron polarization analyzer.[8,9,35,36] Utilizing the phase shifts listed in Table II, the predicted polarization for neutrons scattered through 45° and 135° in the center-of-mass system was calculated as a function of neutron energy. Explicit formulas appear in Meier, Scherrer, and Trumpy[9] while the general polarization calculation is given by Simon and Welton.[37] Our results are shown in Fig. 7. It should be pointed out to those wishing to make further use of this as an analyzer, that the results are extremely sensitive to the phase shifts. There are large differences at some energies between the results of Meier *et al.* and the present work, due mainly to the larger $s_{1/2}$ phase shift found here. Conversely, accurate measurements with known sources of polarized neutrons would resolve these differences.

TABLE V. Phase shifts for $F^{19}(n,n)F^{19}$.

$\bar{E}_n$ (Mev)	δ_0	δ_1	δ_2
0.66	−60°	−10°	0°
1.05	−77°	−15°	0°
1.45	−91°	−24°	0°
2.15	−110°	−30°	−3°
2.92	−120°	−40°	−6°

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[36] W. Haeberli and W. W. Rolland, Bull. Am. Phys. Soc. Ser. II, 2, 234 (1957).
[37] A. Simon and T. A. Welton, Phys. Rev. **90**, 1036 (1953).

RESULTS FOR $F^{19}+n$

Measured values of the total cross section of fluorine are shown in Fig. 8. The discrepancy between the high- and low-resolution measurements above 4 Mev was attributed to the presence of lower energy neutrons in the beam arising from improper beam collimation in the high-resolution measurements.

The rise in cross section at 800 kev appears to be due to a group of unresolved levels. Those at 1.1 and 2.25 Mev, as well as the structure above 3 Mev, have not been previously reported.[16–18]

Angular distributions of the scattered neutrons were measured at energies between the resonances in an attempt to obtain information concerning the magnitude of the potential-scattering phase shifts. Those results are shown in Fig. 9. Interference between neighboring levels was undoubtedly present, but the phase shifts extracted from the data should be more suitable for describing the scattering than those calculated from nuclear models. These phase shifts are listed in Table V.

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Fierz Interference of the Fermi Interactions in Beta Decay*

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The coupling constant combinations $(|C_S|^2+|C_S'|^2+|C_V|^2+|C_V'|^2)$ and $\mathrm{Re}(C_SC_V^*+C_S'C_V'^*)$ are evaluated for the beta-decay interaction by an analysis of data for $0\to0$ (no) transitions.

I. INTRODUCTION

The theoretical expression for the electron energy spectrum for allowed beta transitions is

$$N(W)dW = (2\pi^3)^{-1}pW(W_0-W)^2F(Z,W)\xi(1+b/W)dW, \quad (1)$$

where, in the case of pure Fermi transitions ($0\to0$, no),

$$\xi=\left|\int 1\right|^2[k^{-2}(|C_S|^2+|C_S'|^2)+(|C_V|^2+|C_V'|^2)], \quad (2)$$

$$\xi b=\pm2\gamma\left|\int 1\right|^2 \mathrm{Re}[k^{-1}(C_SC_V^*+C_S'C_V'^*)], \quad (3)$$

$$k=\int 1\bigg/\int\beta. \quad (4)$$

The notation is that of Rose[1] with the modifications introduced by Lee and Yang[2] which allow for noninvariance under the parity transformation, charge conjugation, and time reversal. The parameter k, which does not appear in references 1 and 2, is introduced here because the scalar matrix element $\int\beta$ and the vector matrix element $\int 1$ are equal only in the approximation of nonrelativistic nucleon motion.[3] In Eq. (3) the upper sign applies for electron emission, the lower for positron emission. The term containing b is the Fierz interference term.

Upon integrating Eq. (1) over the range of electron energies, the ft value is obtained:

$$2\pi^3(ft)^{-1}\ln2=\xi+\xi b\langle W^{-1}\rangle, \quad (5)$$

where

$$f=\int_1^{W_0}F(Z,W)pW(W_0-W)^2dW, \quad (6)$$

$$\langle W^{-1}\rangle=f^{-1}\int_1^{W_0}F(Z,W)p(W_0-W)^2dW. \quad (7)$$

$\langle W^{-1}\rangle$ is the average of W^{-1} over the allowed spectrum.

If the Fierz constant b is not zero, the electron spectrum will deviate from the allowed shape; also, the ft values for allowed transitions will depend on endpoint energy. A similar Fierz interference effect occurs for the K capture to positron ratio.[4] The general linearity of Kurie plots has long been known and indicates that $\xi b\ll\xi$. Accurate determinations of the coupling constant combinations contained in b from spectral shape studies, however, have been restricted by the stringent instrumental requirements necessary if the weak W dependence of the Kurie plot is to be detected unambiguously. Such determinations have been made recently for the interference of Gamow-Teller interactions by several groups,[5] but no similar

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[1] M. E. Rose, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), pp. 273–291.

[2] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[3] S. R. DeGroot and H. A. Tolhoek, Physica **16**, 456 (1950). The notation introduced here is the same as that of Porter *et al.* (reference 5) except for a change of sign.

[4] This effect is discussed by R. Sherr and R. H. Miller, Phys. Rev. **93**, 1076 (1954). These authors find $b_{\mathrm{GT}}=-0.01\pm0.02$.

[5] Pohm, Waddell, and Jensen, Phys. Rev. **101**, 1315 (1956); Schwarzchild, Rustad, and Wu, Bull. Am. Phys. Soc. Ser. II, **1**, 336 (1956); Porter, Wagner, and Freedman, Phys. Rev. **107**, 135 (1957). These authors place somewhat different limits on the magnitude of b_{GT}. Their various results fall in the range $-0.15\leqslant b_{\mathrm{GT}}\leqslant0.093$.