Total Cross Section for *n-p* Scattering at 20 Mev*

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(Received November 3, 1958)

The total scattering cross section for neutrons incident on protons has been measured in a good-geometry transmission experiment. The scatterer was hydrogen gas contained in a pressure vessel one meter long, at a pressure of 4000 psi. The resulting cross section is $\sigma_t=0.494_2\pm0.0025$ barn at a laboratory neutron energy of 19.665 ± 0.026 Mev.

I. INTRODUCTION

THERE are at least two important reasons for measuring carefully the total cross section for the scattering of neutrons incident on hydrogen. First, this cross section contributes information on the "two-body" problem, long an important concern of nuclear physics. Second, it serves as the basis for the measurement of neutron flux in several instruments in which recoil protons are produced and counted. Since 1949 many accurate total cross sections of *n-p* scattering have been measured throughout a wide range of neutron energy.[1] The present experiment at 20 Mev was undertaken because of the gap in precise information existing between 14 and 40 Mev. Preliminary results of this work were published some time ago.[2]

Nearly all previous experiments were complicated somewhat by the fact that the hydrogen total cross section was deduced from the difference between the cross sections for a hydrocarbon and carbon. Here, however, the hydrogen cross section σ was obtained from the transmission T of hydrogen gas for 20-Mev neutrons by means of the usual relation

$$T=e^{-n\sigma l},$$

where n is the density of hydrogen nuclei and l is the length of the scattering volume. Furthermore, the method used here made the determination of n and the analysis for possible impurities in the scattering sample much easier than usual.

II. EXPERIMENTAL TECHNIQUE

The total cross section of hydrogen was measured in a good-geometry transmission experiment. Monoenergetic neutrons from the $T(d,n)He^4$ reaction were detected by a biased stilbene scintillation counter, placed 160 cm from the neutron source. The scattering sample was hydrogen gas contained at 4000 psi in a stainless steel cylinder, 2.2 cm i.d. by 1 meter long.[3,4] The neutron flux attenuated lengthwise through this cylinder was compared with the direct flux transmitted through an identical, evacuated cylinder, the hydrogen transmission being about 0.57. The length of the cylinder was known to 0.01% and the hydrogen pressure was measured to 0.1%. The statistical accuracy of the counting data, combined with measured and calculated backgrounds, produced a transmission accurate to 0.25% and hence a total cross section accurate to ±0.5%. Pertinent experimental details are given below.

a. Physical Arrangement

The 20-Mev neutrons were produced by bombarding a tritium gas target with 3-Mev deuterons accelerated by the large electrostatic generator at Los Alamos. The targets were 6 cm long and 1 cm in diameter, and were filled to a pressure of 55 cm of Hg. The target chamber was constructed of stainless steel 0.025 cm thick with an end cap of gold, also 0.025 cm thick, to stop the deuteron beam. The beam-entrance foil was of 1.25-micron nickel.

The transmission cell and detector were fixed rigidly in space by means of a light wire suspension. The detector was placed 160 cm from the end of the gas target at 0° to the deuteron beam, and the transmission cell was placed on this beam axis with its near end 25 cm from the center of the tritium target. Peep sights could be inserted in the mounting fixtures to permit visual alignment of the tritium target, transmission cell, and detector within 0.025 cm of collinearity. Furthermore, the mounting was such that the hydrogen and vacuum transmission cells could be easily replaced in their correct positions with a reproducibility better than 0.025 cm.

The fraction of neutrons scattered by the air and walls of the room was measured with the aid of a copper shadow bar, which was 61 cm long and 2.2 cm in diameter. A third stainless steel tube held the shadow bar and located it at the position normally occupied by the transmission cell. Although room scattering was the

* Work performed under the auspices of the U. S. Atomic Energy Commission.

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[1] A summary of accurate values of the total *n-p* scattering cross section has been given in the Appendix of a paper by Bame, Haddad, Perry, and Smith, Rev. Sci. Instr. **28**, 997 (1957). See also W. N. Hess, University of California Radiation Laboratory UCRL-4639, 1956 (unpublished). An excellent discussion of the method of measuring total cross sections is given by E. M. Hafner *et al.*, Phys. Rev. **89**, 204 (1953).

[2] Day, Mills, Perry, and Scherb, Phys. Rev. **98**, 279(A) (1955).

[3] The transmission cell was designed and tested in 1951 by Mills, Edeskuty, and Sesonsky of this Laboratory, at the request of J. H. Coon. A description of the cell appears in J. D. Seagrave and R. L. Henkel, Phys. Rev. **98**, 666 (1955), Appendix I.

[4] Coon, Bondelid, and Phillips [quoted in Coon, Graves, and Barschall, Phys. Rev. **88**, 562 (1952)] used the same cell for an accurate hydrogen total cross-section measurement at 14 Mev.

largest background encountered in the experiment, it amounted to only 0.6 percent of the direct neutron flux.

The detector was a stilbene crystal 1.9 cm in diameter and 3.8 cm long, mounted on a DuMont 6467 photomultiplier. Pulses from the photomultiplier were amplified by two Los Alamos Model 250 preamplifiers and amplifiers[5] in parallel and counted by a total of three discriminator-scalers (two on the output of one amplifier, and one on the other). The discriminators were biased to detect neutrons with energies >10 Mev. Except for the photomultipliers and preamplifiers all the electronic apparatus was mounted in a temperature-controlled rack for stability of operation.

Individual counting runs were controlled by a beam-current integrator that terminated each run after 180 microcoulombs were collected at the target (corresponding to about 10 000 neutrons counted in the direct beam). A second stilbene scintillation counter, placed 1 meter from the target at an angle of 45° to the deuteron beam, served as a monitor of the neutron flux. In addition to checking on the operation of the current integrator the monitor also showed whether the neutron flux was changing because of beam heating effects or loss of tritium from the target.

b. Transmission Cell

The transmission cell and the accurate determination of its length and volume have been described in detail previously.[3] The cell consisted of a stainless steel cylinder, nominally 1 meter long inside, with an inside diameter of 2.2 cm and a wall thickness of 0.15 cm. The end caps were flat and had a thickness of 0.25 cm. A steel capillary filling line 120 cm long was soldered in the side of the cell, with its far end closed by two high-pressure valves. At the working pressure and temperature of this experiment, the length and volume of the cell were determined to be 100.084±0.010 cm and 384.64±0.10 cm^3, respectively. The evacuated cell whose transmission was compared with the hydrogen-filled cell was essentially identical to the latter.

c. Filling of Cell

After determination of its empty weight, the cell was placed in a carefully thermostated water bath. Electrolytic tank hydrogen, boosted to about 5000 psi by a compression cylinder, was passed slowly through a high-pressure filter and then through a charcoal trap maintained at liquid nitrogen temperature. The purified gas was admitted to the cell, and when the cell was half filled a gas sample was withdrawn for mass spectrometer analysis. At completion of the filling, when the gas had reached temperature equilibrium with the water bath, a final pressure was read on a Heise laboratory gauge which had been calibrated previously with a free piston gauge. The result was $p=274.29\pm0.25$ atmos. The bath temperature was determined to be 303.06±0.01°K from an average of 8 local temperatures read throughout the bath with a calibrated micro-Beckman thermometer. The cell content, 3.621±0.004 moles, was computed from a curvilinear interpolation of tabulated PVT data for hydrogen.[6]

The full cell was reweighed and the mass increase was found to be 7.319±0.005 g. Mass-spectrometric analysis of the gas sample withdrawn during filling gave the following composition in mole percent: $(99.95_{-0.00}^{+0.05})$ H_2 and $(0.05_{-0.05}^{+0.00})$ N_2, with all intermediate masses below the sensitivity limit of the instrument. When the cell was emptied at the completion of the cross-section measurements, the mass decrease was measured as 7.314±0.005 g, which indicated that no significant amount of gas was lost during the course of the experiment.

It is believed that the gas in the cell was pure hydrogen and that the apparent indication of nitrogen was either a spurious and variable background in the mass spectrometer or a result of the sampling technique used. One cc of activated charcoal at liquid nitrogen temperature will adsorb 100 cc of nitrogen gas. At this temperature, one cc of charcoal will adsorb completely the nitrogen from a one-percent nitrogen-in-hydrogen gas mixture at a flow rate of one liter of gas mixture per minute.[7] The filling rate used in the present experiment was 5 liters per minute and the trap contained about 100 cc of charcoal.

The molar content of the cell was computed as the average of values obtained from the PVT measurement (3.621±0.004 moles) and from the mean mass change ($7.316_5\pm0.010$ grams ÷2.0160 grams $mole^{-1}=3.629$ ±0.005 moles). Experimental errors in the two independent measurements gave values of the cell content which barely overlap. Therefore, the error of the average was increased, and the cell content was considered to be 3.625±0.006 moles of pure, normal hydrogen.

d. Treatment of Data

The primary data, from which the hydrogen transmission was largely determined, were obtained by measuring the counting rate in cycles of the form: sample out, sample in, shadow bar, sample in, sample out. ("Sample in" and "sample out" merely mean hydrogen cell in place and evacuated cell in place, respectively.) This procedure should have cancelled out the effects of small changes in equipment behavior providing these changes were linear in time. (Examples of possible troubles are drifts in amplifier gain, discrimination level, or photomultiplier gain, and gradual loss of tritium gas from the neutron source.) In addition, the magnitude of the deuteron beam and its focal

[5] C. W. Johnstone, Los Alamos Report LA-1878 (unpublished).

[6] Wooley, Scott, and Brickwedde, J. Research Natl. Bur. Standards (U. S.) 41, 379 (1948). Values obtained from these tables appear to be accurate to 0.01%. It should be noted that at the operating pressure and temperature hydrogen fails to obey the ideal gas law by about 17%.

[7] E. R. Grilly (unpublished measurements).

TABLE I. Summary of counting data and transmission results for 20-Mev n-p scattering. One cycle of data determined an individual experimental value of transmission. The numbers of counts per cycle are indicated in Cols. 3 and 4. Columns 6 and 7 contain standard deviations (S.D.) of individual transmissions, calculated from observed results (6) and from counting statistics (7). The standard error (S.E.) of the mean transmission, shown in Col. 8, is based on the larger of the two S.D.'s. The relative weight of the mean transmission is proportional to $(\text{S.E.})^{-2}$.

1	2	3	4	5	6	7	8	9	10
Data series	Number of cycles	"Sample in" count	"Sample out" count	Mean trans.	S.D. of indiv. trans. values, observed	S.D. of indiv. trans. values, statistical	S.E. of mean trans.	Rel. wt. of mean trans.	Monitor counter used
A	8	40000	43000	0.5690	±0.46%	±0.70%	±0.25%	16	No
B	11	19500	17000	0.5688	±1.4 %	±1.15%	±0.44%	5	Yes

conditions were kept as nearly constant as possible throughout a cycle in order to avoid variations in accelerator-induced background and in neutron yield caused by beam heating effects in the tritium target.

Secondary data pertaining to effects of accelerator-induced backgrounds were taken with the tritium target evacuated. Again sample in, sample out, and shadow bar counting rates were measured. However, since these background components were only about 0.1% of the direct primary counting rates, no cyclical order was necessary in recording these data. Runs to obtain the secondary data were interspersed with those on the primary data in order to insure that the accelerator-induced background did not change significantly.

By use of all of the above data the primary "sample in" and "sample out" readings were corrected in first approximation for room scattering and accelerator background. For a particular cycle the ratio of these corrected readings was the observed hydrogen transmission for that cycle.

Nineteen individual transmissions were measured. Table I summarizes the data and indicates the spread found in transmission values. Use of the monitor counter was somewhat arbitrary: in Series *A* (Table I) where the standard deviation of the individual transmissions was less than that expected from the counting statistics, the monitor record was not used; whereas in Series *B*, use of the monitor reduced the observed standard deviation from 1.7% to 1.4%. In computing the standard error of the mean transmission for each series, the larger of the two standard deviations (observed *vs* statistical) was used. It may be noted in passing that 96% of all data taken was used. The remaining 4% was rejected because, during a short period on the first day of data taking, the counter sensitivity was somewhat erratic.

The weighted mean observed transmission of the hydrogen filling was 0.5689, with a statistical standard error of ±0.22%. It should be noted that this is a fairly good first approximation to the true transmission of an ideal experiment. The additional small corrections required in this experiment are discussed in Sec. III below.

e. Neutron Energy Measurement

The determination of the mean neutron energy for the experiment depends on the mean deuteron energy in the tritium target, and the Q of the $T(d,n)He^4$ reaction. An enumeration of the pertinent steps, with their uncertainties, is given below.

1. *Accelerator energy scale: ±8 kev.*—The beam analyzer magnet was calibrated to ±0.1% in energy by means of the $C^{13}(p,n)N^{13}$ threshold[8] (3.236 Mev) and an $Al^{27}(p,\gamma)Si^{28}$ resonance[9] (0.9933 Mev), and was monitored by a proton-moment device. However, recent work[10] has thrown some doubt on the energy scale used as a standard, and we have, therefore, increased the error to include this uncertainty.

2. *Magnet entrance slits: ±6.5 kev.*—The analyzer entrance slits were operated at about ±0.2% energy resolution. However, in practice no energy discrepancies this large were observed.

3. *Magnet hysteresis: ±2 kev.*—Recent measurements of the apparent variation of the $Li^7(p,n)Be^7$ threshold have indicated a possible uncertainty of ±2 kev due to inconsistencies in recycling the magnet current.[11]

4. *Accelerator deuteron energy: 3253±10.5 kev.*—The error here was compounded from the above values.

5. *Energy loss in nickel target foil: 102±15 kev.*—This energy loss was based on the measured areal density of the foil and theoretical values of dE/dx for protons in nickel.[12] This method of determining the energy loss has been checked by measuring the position of the first $C^{12}(n,n)C^{12}$ scattering resonance. Since the value obtained for the resonance (2.079 Mev) was slightly lower than the average of the best values[13] that have been measured, the areal density is based on this new value.

6. *Mean energy loss in tritium: 84±5 kev.*—This figure represents half the energy loss of deuterons traversing the entire target length. It is based on target length and pressure, and on theoretical values of dE/dx for protons in hydrogen.[12] (Calculated[12] and measured[14] values of this stopping cross section agree to 1%.)

[8] Richards, Smith, and Brown, Phys. Rev. **80**, 524 (1950).
[9] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).
[10] Bumiller, Staub, and Weaver, Helv. Phys. Acta **29**, 83 (1956).
[11] E. Haddad and J. E. Perry (private communication, 1957).
[12] M. C. Walske (private communication, 1952).
[13] Fields, Becker, and Adair, Phys. Rev. **94**, 389 (1954), obtained $E_n=2.087\pm0.0035$ Mev, while H. B. Willard *et al.* (private communication, 1957) obtained 2.076±0.008 Mev.
[14] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. **25**, 779 (1953).

Reduction of tritium gas density in the region of the deuteron beam was taken into account.

7. Mean deuteron energy: 3.067±0.020 Mev.—The uncertainty shown here was compounded quadratically from the above values, and is believed to be an rms error. The spread in deuteron energy in the target was ±84 kev.

8. Mean neutron energy: 19.665±0.026 Mev.—This value was obtained from Wapstra's masses[15] of the reaction particles. The uncertainty derives from two sources: (a) ±25 kev from the kinematical fact that $\partial E_n/\partial E_d = 1.25$, and (b) ±7 kev from uncertainties in the reaction Q due to quoted uncertainties in particle masses. The spread of neutron energy is ±105 kev about the mean. Throughout all calculations appropriate relativistic equations have been used.

III. SMALL CORRECTIONS TO CELL TRANSMISSION

Subsequent to the experiment a study was made to determine the extent of possible systematic errors. Of the several possible sources of error, only two required corrections to the transmission and four resulted in significant uncertainties in the transmission. The various considerations are outlined below.

1. Target scattering.—Although the cylinder which held the tritium gas target had quite thin walls (Sec. IIa), calculations showed that scattering of the source neutrons by these walls contributed a flux of degraded-energy neutrons at the detector equal to 0.5% of the unscattered neutron flux. While the energy distribution of the scattered neutrons extended down to about 10 Mev, the number of neutrons was appreciable only above 19 Mev, and this number was insufficient to entail correction to the hydrogen transmission or to the mean neutron energy. Calculation also showed that the effect of low-energy neutrons from T(d,d)T scattering followed by T(d,n)He^4 reactions in the target was negligible.

2. Air scattering.—Although the background produced by air scattering was supposed to be taken into account by the shadow-bar readings, some of the air-scattered neutrons that would have been detected by the scintillation counter were absorbed by the shadow bar. A fraction of these passed through the entire length of the transmission cell, and therefore underwent the same attenuation as the primary neutron flux. The effect of the remaining air scattering on the observed transmission of the hydrogen has been calculated and found to be negligible.[16]

3. Shadow-bar transmission.—In order to measure the air- and room-scattering properly one would have preferred a shadow bar that was completely "black" to 20-Mev neutrons. The shadow bar used here was shown to be satisfactory as follows: First, it was assumed that all neutrons undergoing nonelastic collisions were effectively absorbed. The transmission of the bar was calculated to be 0.05% from the known nonelastic cross section for copper. Second, when the elastic scattering was considered as well, it was shown by means of simple arguments based on single and multiple scattering that an upper limit to the transmission for the geometry used here was 0.01%. This was sufficiently small that the shadow bar could be considered black, and no correction was required. Furthermore, a calculation showed that a negligible number of gamma rays produced by inelastic scattering in the bar could have been counted by the detector.

4. Cell inscattering.—With the evacuated cell in place, the detector saw the direct source flux plus a small spurious flux caused by inscattering from the cylindrical steel wall of the cell. With the hydrogen-filled cell, the detector count derived from (a) the properly attenuated direct flux, (b) a somewhat improperly attenuated steel-inscattered flux, and (c) a hydrogen-inscattered flux. Single-scattering calculations of these effects agreed with a Monte Carlo calculation[17] and indicated that the true transmission was 0.25% larger than that observed. In connnection with this calculation and that of item 5, below, an auxiliary good-geometry transmission experiment was performed to obtain the attenuation coefficient for stainless steel. The shape of the elastic scattering angular distribution, needed for the inscattering calculations, was calculated from the complex potential model. Since only the small-angle scattering was important here, the model is quite satisfactory for this purpose. Incidentally, it was not necessary to make a correction for inscattering by the steel ends of the transmission cells since the neutrons thus scattered had the same attenuation in the hydrogen as the direct neutron flux.

5. Cell end attenuation.—Uncertainties in the thickness of the end caps of the transmission cells (0.25 cm ±0.0025 cm) led to uncertainties of ±0.1% in the observed transmission.

6. Scattering from detector housing.—The diameter of the transmission cell was not quite large enough to shadow completely the outer part of the photomultiplier and its light-tight housing. Therefore, neutrons that were scattered into the crystal by these parts would not have undergone the proper hydrogen attenuation. The magnitude of this effect was calculated and found to have a negligible effect on the observed transmission.

7. Hydrogen gas impurities.—A +0.005% correction to the observed transmission was made for deuterium assumed present in the cell in its customary isotopic abundance so that the final transmission would be characteristic of the proton component of the gas.

8. Counting rate effects.—All the transmission meas-

[15] A. H. Wapstra, Physica **21**, 378 (1955).

[16] We are indebted to Max Goldstein of Los Alamos Scientific Laboratory Group T-1 for supervising part of these calculations.

[17] Herman Kahn of the Rand Corporation performed the multiple-scattering Monte Carlo calculation of cell inscattering.

urements were made with a constant neutron flux; thus the counting rates with the transmission cell in and out differed by a factor of approximately two. Since it seemed possible that the response of the detector and electronic equipment might depend somewhat on the counting rate, a separate experiment was undertaken to determine the magnitude of such an effect. The experiment was performed by measuring the counting rates from each of two gamma-ray sources separately and from the two sources simultaneously. The deviation of the sum of the two separate counting rates from the combined rate was then a measure of any effective shift of gain or bias in the detecting system. The use of gamma-ray sources was appropriate since the shape of the pulse-height spectrum was nearly the same for gamma rays as for protons with the stilbene scintillation counter used here. Measurements were made for several gamma-ray sources and with various voltages on the photomultiplier, such that the range of output pulse heights overlapped those produced in the n-p scattering experiment. At the counting rates used in the transmission measurements the effect of counting rate shifts in the detector response was found to be very small. In every case the effect was small enough to cause an error in the transmission of less than 0.1%. No transmission correction was made for this effect, but the transmission was considered uncertain by 0.1%.

Table II contains a summary of corrections to, and uncertainties in, the transmission. The final value of hydrogen-one (proton) transmission was 0.57035 $\pm$0.00015 (i.e., $\pm$0.27%).

As a partial check on the accuracy of the calculations of air scattering and cell inscattering (items 2 and 4 above) the "transmission" of an open-ended dummy cell was measured and compared with the calculated value. Calculations showed that the cell inscattering should be 0.76$\pm$0.04% of the direct flux,[17] that air scattering from the regions of air affected by the presence of the cell should be about 0.2% of the direct flux, and that specifically the ratio "dummy cell in" to "no cell" should be 1.006. The measured value, 1.007 $\pm$0.0035, was considered to show that no gross errors existed in the calculations. The uncertainties of $\pm$0.05% in the hydrogen transmission shown in Table II for these two items were based on estimates of the accuracy of the calculated correction terms. These uncertainties appear to be both liberal and reasonable in view of the following facts: (a) one uncertainty represents 25% of the possible air scattering, (b) the other is somewhat larger than the accuracy of the cell inscattering calculation, and (c) correction terms for each item appear in both numerator and denominator of the expression for hydrogen transmission, so that errors tend to cancel.

TABLE II. Corrections to the observed transmission and uncertainties in the transmission. Numbers correspond to the numbered items of Sec. III.

No.	Item	Correction to observed transmission (%)	Uncertainty (%)
···	Counting statistics	···	±0.22
1	Target scattering	···	±0.01
2	Air scattering	···	±0.05
3	Shadow-bar transmission	···	±0.01
4	Cell inscattering	+0.25	±0.05
5	Cell end attenuation	···	±0.10
6	Scattering from crystal housing	···	±0.01
7	Hydrogen gas impurities	+0.005	±0.01
8	Counting rate effect	···	±0.10
	Total values	+0.255	±0.56
	Root-mean-square uncertainty	···	±0.27

TABLE III. Uncertainties in the n-p scattering cross section at $E_n = 19.665$ Mev.

Item	Uncertainty (%)	Cross-section uncertainty (%)
Transmission	±0.27	±0.48
Cell molar content	±0.17	±0.17
Cell volume	±0.026	±0.026
Cell length	±0.01	±0.01
	Total cross-section uncertainty	±0.69%
	Rms uncertainty	±0.51%

IV. CROSS SECTION AND ITS ACCURACY

The final value of the total cross section for neutron-proton scattering is 0.4942$\pm$0.0025 barn at a laboratory neutron energy of 19.665$\pm$0.026 Mev. Components of the cross-section uncertainty are listed in Table III. It is felt that both of the above uncertainties are of the nature of root-mean-square errors.

V. DISCUSSION

Several accurate values of the total cross section for n-p scattering have been measured in the neutron energy range from thermal to 42 Mev. Using these cross sections and effective-range theory, Gammel has obtained a semiempirical expression for the n-p total cross section as a function of neutron energy.[18] The agreement of this expression with the measured values is $\pm$0.2% (average deviation) for all of the carefully determined cross sections. The result of the present experiment was used in Gammel's work and subsequently agreed with his formula to 0.1%.

One could analyze this experiment, after making correction for higher partial waves, in terms of S-wave effective-range theory. It seems superfluous to do so at this time, since detailed analyses of all nucleon-nucleon interactions have recently appeared.[19,20] These

[18] Gammel's semiempirical expressions for n-p scattering have appeared in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 4, p. 251, and appear in somewhat more detail in the first item of reference 1.

[19] Gammel, Christian, and Thaler, Phys. Rev. **105**, 311 (1957); also J. L. Gammel and R. M. Thaler, Phys. Rev. **107**, 291 (1957) and Phys. Rev. **107**, 1337 (1957).

[20] P. S. Signell and R. E. Marshak, Phys. Rev. **109**, 1229 (1958).

analyses explain fairly successfully all nucleon-nucleon interactions up to several hundred Mev in terms of central, tensor, and spin-orbit forces that are derived from potentials with a Yukawa shape and a hard central core[19] or from the Gartenhaus potential plus a spin-orbit potential.[20]

ACKNOWLEDGMENTS

We are indebted to F. J. Edeskuty for assistance in the weight determinations of the cell, to Max Goldstein for supervising some of the air-scattering calculations, to Herman Kahn of the Rand Corporation for the Monte Carlo calculation of cell inscattering, and to James H. Coon for the use of his transmission cells.

PHYSICAL REVIEW VOLUME 114, NUMBER 1 APRIL 1, 1959

$C^{13}(p,\gamma)N^{14}$ 1.47- and 2.11-Mev Resonances and the Odd-Parity Levels of Mass 14*

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(Received November 11, 1958)

A study has been made of the γ rays emitted by the 8.9- and 9.5-Mev levels of N^{14} using the $C^{13}(p,\gamma)N^{14}$ reaction at the 1.47- and 2.11-Mev resonances. The decay schemes of these levels were reinvestigated using a three-crystal pair spectrometer, NaI(Tl) single-crystal measurements, and standard $\gamma-\gamma$ coincidence techniques. The anisotropies relative to the bombarding beam of most of the observed γ transitions were measured using the three-crystal pair spectrometer. The angular distributions of some of the γ transitions were measured using a single NaI(Tl) crystal. Measurements were made of the Doppler shifts of the ground state decay of the N^{14} 5.10-Mev level and the cascade from the N^{14} 5.83-Mev level to the N^{14} 5.10-Mev level. From these Doppler shift measurements the mean lifetime of the N^{14} 5.83-Mev level was found to be in the range $(5\text{-}65)\times10^{-14}$ sec; while an upper limit of 3×10^{-13} sec was set on the mean life of the N^{14} 5.10-Mev level. The results of the study of the γ decay of the N^{14} 9.5- and 8.9-Mev levels combined with the results of earlier measurements give conclusive assignments of 2^-, 3^-, 3, and 2 for the N^{14} levels at 9.50, 8.90, 5.83, and 5.10 Mev. The 5.83-Mev level most probably has odd parity. A tentative assignment of $J=2$ is given to the N^{14} 7.02-Mev level. Evidence is presented, from this and previous investigations, that indicates the N^{14} 8.06-, 8.70-, 8.90-, and 9.50-Mev levels arise from the s^4p^92s and s^4p^9d configurations with the largest contribution being from the $(p_{1/2}2s_{1/2})$ configuration for the 8.06- and 8.70-Mev levels and from the $(p_{1/2}d_{5/2})$ configuration for the 8.90- and 9.50-Mev levels. The analogs of these $T=1$ levels in C^{14} are almost certainly the C^{14} 6.09-, 6.89-, 6.72-, and 7.35-Mev levels, respectively. The $T=0$, s^4p^92s and s^4p^9d states of N^{14} are also discussed. It is proposed that the 4.91-, 5.69-, 5.10-, and 5.83-Mev levels of N^{14} are 0^- and 1^-, $s^4p^92s_{1/2}$ and 2^- and 3^-, $s^4p^9d_{5/2}$ states, respectively.

I. INTRODUCTION

THE experimental work which will be described in this paper consists of a detailed investigation of the γ transitions from the resonances in the $C^{13}(p,\gamma)N^{14}$ reaction at proton energies of 1.47 and 2.1 Mev. These resonances, which correspond to N^{14} levels at excitations of 8.9 and 9.5 Mev, have been previously investigated by the $C^{13}(p,p)C^{13}$ reaction[1–3] and the $C^{13}(p,\gamma)N^{14}$ reaction.[4,5] The proton scattering data of Milne[1] for the 1.47-Mev resonance and of Zipoy *et al.*[2] for the 2.1-Mev resonance showed that these resonances are formed by even-wave protons. The Wigner sum-rule limit rules out capture of protons with orbital angular momentum greater than three, and the complexity of the angular distributions of the elastically scattered protons rules out pure *s*-wave proton formation.[1,2] Therefore, the 1.47-Mev and 2.1-Mev resonances are formed at least partially by *d*-wave protons. Since the C^{13} ground state has[6] $J^\pi=\frac{1}{2}^-$, the possible spin-parity assignments for the N^{14} 8.9-Mev and 9.5-Mev levels are $J^\pi=1^-$, 2^-, or 3^-. The scattering analysis gives a most probable assignment of $J^\pi=3^-$, with 2^- more likely than 1^-, for the 8.9-Mev level,[1] and a most probable assignment of $J^\pi=2^-$, with 3^- more likely than 1^-, for the 9.5-Mev level.[3,7]

The N^{14} 8.9-Mev and 9.5-Mev levels were first investigated by Seagrave[4] who observed the 1.47-Mev and 2.1-Mev resonances in a general investigation of the $C^{13}(p,\gamma)N^{14}$ reaction. Seagrave measured the

* Work performed under the auspices of the U. S. Atomic Energy Commission.

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