Resonant Absorption by the 9.17-Mev Level in N^{14}†

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The 9.17-Mev radiation from the reaction $C^{13}(p,\gamma)N^{14}$, $E_p=1.75$ Mev, was used to obtain resonant absorption in the inverse process $N^{14}+\gamma \rightarrow N^{14*}(E_{ex}=9.17$ Mev). The strength of the absorption was measured as a function of absorber thickness. Analysis of the measurements gives $\Gamma=(77\pm12)$ ev and $\omega\Gamma_\gamma=(14.5\pm2)$ ev. The latter value indicates dipole radiation.

IN the important program of determining radiative lifetimes of nuclear energy levels, the phenomenon of resonant absorption or fluorescence provides a powerful method[1] in the region of short lifetimes ($<10^{-10}$ sec). Recently a technique has been used[2,3] in which the resonant absorption is observed by a simple, direct measurement of the transmission through an absorbing sample. The method lends itself especially to the determination of radiative widths of narrow, unbound levels which are otherwise difficult to measure. In this communication we present more detailed observations[2] on the 9.17-Mev level of N^{14} with a more complete analysis of the results.

In the radiative capture of particles having fixed energy and direction of motion, the energy of the radiation varies with the angle of emission but has a definite value at a given angle. The energy of the incident particles may be fixed by selecting a resonant capture process or, if the capture is nonresonant, by using a monoenergetic beam of particles and a thin target. In the present experiment the source of radiation was the reaction $C^{13}(p,\gamma)N^{14}$ at the resonant energy $E_p=1.75$ Mev corresponding to the level at 9.17 Mev in N^{14}. This radiation was then used to study the inverse absorption process $N^{14}+\gamma \rightarrow N^{14*}$ by varying the energy (i.e., angle of emission) of the radiation and observing the change in transmission through a nitrogen absorber. Since an amount of energy $E^2/2Mc^2$ is given to the recoiling nucleus in both the emission and the absorption process, it is necessary to increase the energy of the emitted radiation by an amount E^2/Mc^2 to produce resonance, where E is the energy of the radiation and M the mass of the emitting (or absorbing) nucleus. Since the energy of the emitted radiation varies as $E(v/c)\cos\theta$, where v is the velocity of the radiating nucleus, the resonant angle is obtained from the condition

$$\cos\theta_R=(E/Mc^2)/(v/c)=p_\gamma/p,$$

where p_γ and p are the momenta of the gamma ray and the radiating nucleus, respectively. With $E_p=1.75$ Mev and $E=9.17$ Mev, it follows that $\theta_R=80.8°$.

The experimental arrangement is sketched in Fig. 1. The absorber, slit, and detector were mounted on an arm which could be rotated about the beam spot on the target. Liquid nitrogen, contained in one or more Dewar flasks, was used as the absorber. The slit was formed by two lead bricks with smooth inner faces which were aligned along a radius from the source. In an attempt to improve the resolution, some observations were made with a slit curved to conform approximately to a surface of constant θ. The detector was a NaI crystal 3 in. diameter and 4 in. long. The target was a layer[4] of C^{13}(71%) considerably thicker (as measured in proton energy loss) than the width of the resonance. The target spot was approximately 1 mm wide and for the observations with good resolution the plane of the target was set to coincide nearly (within 10°) with the plane of the slit.

The data are summarized in Table I and several of the runs are illustrated in Figs. 2 and 3. In the observations in Fig. 2 the geometrical width was approximately 0.4° and it is reasonably clear that the observed widths of about 0.8° should be attributed, in part at least, to a natural width of the transmission dip. On the other hand, the total instrumental resolution is not known well enough to provide an accurate analysis by means of line shape as was attempted in our earlier report.[2] Alternatively, the results were anayzed by the

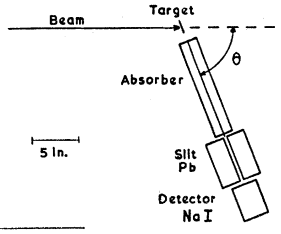

FIG. 1. The experimental arrangement.

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[1] W. Kuhn, Phil. Mag. **8**, 625 (1929); Waldman, Collins, Stubblefield, and Goldhaber, Phys. Rev. **55**, 1129 (1939); E. C. Pollard and D. A. Alburger, Phys. Rev. **74**, 926 (1948); P. B. Moon, Proc. Phys. Soc. (London) **A64**, 76 (1951); F. R. Metzger, Phys. Rev. **101**, 286 (1956); C. P. Swann and F. R. Metzger, Phys. Rev. **108**, 982 (1957); G. M. Griffiths, Can. J. Phys. **34**, 339 (1956).

[2] S. S. Hanna and L. Meyer-Schützmeister, Phys. Rev. **108**, 1644 (1957); Bull. Am. Phys. Soc. Ser. II, **2**, 377 (1957); Bull. Am. Phys. Soc. Ser. II, **3**, 188 (1958).

[3] P. B. Smith, in *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 587. P. B. Smith and P. M. Endt, Phys. Rev. **110**, 397 (1958); Phys. Rev. **110**, 1442 (1958).

[4] Supplied by Atomic Energy Research Establishment, Harwell, Berks, England.

area method which has been developed in detail to treat the resonant absorption of slow neutrons.[5] We shall give only the pertinent results of this development which, in almost every respect, is applicable also to the resonant absorption of gamma rays.

The area A above the transmission dip is given in the expression (p. 704 of reference 5).

$$A^2=\pi n\sigma_0\Gamma^2F(n\sigma_0), \tag{1}$$

where n is the number of nuclei per cm^2 of the absorber, σ_0 is the cross section at resonance, Γ is the total width, and F is a function which accounts for the departure from the "thick-sample" value of $\pi n\sigma_0\Gamma^2$. (F is given in Fig. 1 of reference 5.) It is convenient to use the thick-sample approach since, as it turns out, $n\sigma_0\gtrsim 1$. Also, as will appear in the sequel, the Doppler broadening ($\sim$27 ev) of the absorption line may be neglected in the analysis (see Fig. 5 of reference 5).

For two measurements corresponding to two thicknesses of absorber, the ratio of the areas is given by

$$\left(\frac{A_2}{A_1}\right)^2=\frac{n_2}{n_1}\frac{F(n_2\sigma_0)}{F(n_1\sigma_0)}. \tag{2}$$

Since A_2, A_1, n_2, and n_1 are known experimentally, this expression can be used to obtain a value of σ_0. For the circles in Fig. 4, A_1 and n_1 correspond to the thinnest sample used and A_2 and n_2 successively to the three thickest samples. The curve is obtained for $n_1\sigma_0=0.95$. With $n_1=2.4\times10^{23}$ nuclei/cm^2 (7 cm of nitrogen), we find $\sigma_0=4.0$ b. From Eq. (1) it follows that $\Gamma=88$ ev. The crosses in Fig. 4 were obtained with A_1 and n_1 representing values for the 15-cm absorber. The curve shown is for $n_1\sigma_0=3.8$. Hence $\sigma_0=7.2$ b and $\Gamma=66$ ev. It is not practicable to extend the analysis to larger values of $n_1\sigma_0$, because the curves above $n_1\sigma_0=4$ converge rapidly to the limiting case for $n_1\sigma_0=\infty$. We adopt the value $\Gamma=(77\pm12)$ ev.

TABLE I. Summary of the measurements. The orientation of the target is measured with respect to the plane of the slit. The energy scale is obtained from $dE/d\theta=690$ ev/deg.

Absorber thickness (cm)	Target orientation (degrees)	Geometrical width of slit (degrees)	Observed width (degrees)	Area of dip (ev)
46.0	10	1.6	1.7	385±30
34.3	55	1.2	1.5	330±40
27.3	55	1.1	1.5	280±40
27.3	55	1.1	1.3	290±30
27.3	55	0.7	1.4	320±40
27.3	10	0.38	0.85	260±30
27.3				Av=285±20
15.3	10	1.6	1.7	210±30
15.3	10	0.33	0.75	210±40
15.3				Av=210±20
7.0	55	1.1	1.5	120±30
7.0	10	1.5	1.5	85±30
7.0	10			110±30
7.0				Av=105±20

[5] Melkonian, Havens, and Rainwater, Phys. Rev. **92**, 702 (1953).

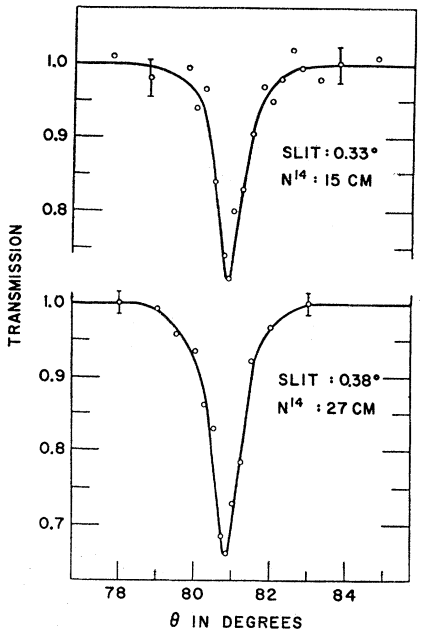

FIG. 2. Transmission curves obtained with a narrow slit for two thicknesses of absorber. The energy scale may be obtained from $dE/d\theta=690$ ev/degree.

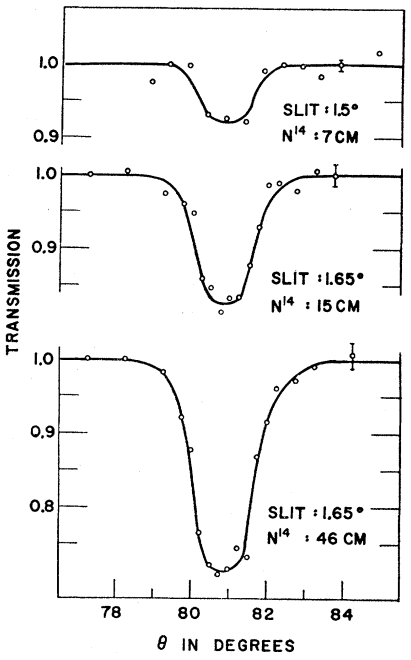

FIG. 3. Transmission curves obtained with a wide slit for three thicknesses of absorber. The energy scale may be obtained from $dE/d\theta=690$ ev/degree.

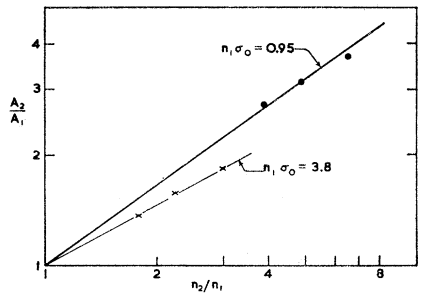

FIG. 4. The ratio method for obtaining σ_0. The area A_1 and thickness n_1 refer to a given absorber, and A_2 and n_2 to one or more thicker absorbers.

The absorption cross section at resonance may be obtained from the one-level formula

$$\sigma_0 = 2\pi\lambda\!\!\!^{-2}\omega\Gamma_\gamma/\Gamma, \tag{3}$$

where $\lambda\!\!\!^{-}$ is $1/(2\pi)$ times the wavelength of the radiation, Γ_γ is the radiation width, and ω is the statistical factor $(2J_r+1)/(2J_g+1)$, in which J_r and J_g are the spins of the upper and lower states; the statistical weight 2 for the gamma ray has been absorbed in the numerical constant in Eq. (3). Combining Eqs. (1) and (3), we obtain

$$A^2 = 2\pi^2\lambda\!\!\!^{-2}n\omega\Gamma_\gamma\Gamma F(n\sigma_0). \tag{4}$$

For thick samples ($n\sigma_0 > 1$), F is a slowly varying function so that A^2 is nearly linear in n. The quantity $\omega\Gamma_\gamma\Gamma$ is therefore determined with good accuracy as illustrated in Fig. 5. The best agreement is obtained with $\omega\Gamma_\gamma\Gamma = 1120$ ev^2. Actually, in obtaining this fit the function $F(n\sigma_0)$ is treated as a parameter. The final value selected gives a measure of σ_0, but this determination is equivalent to the analysis in Fig. 4. With $\omega\Gamma_\gamma\Gamma = (1120\pm100)$ ev^2 and $\Gamma = (77\pm12)$ ev we obtain $\omega\Gamma_\gamma = (14.5\pm2)$ ev.

Another approach to the data is obtained from Eq. (4) if, for each absorber, $\omega\Gamma_\gamma$ is plotted against Γ. The intersection of the curves thus obtained provides a solution giving $\omega\Gamma_\gamma$ and Γ. This technique is illustrated in Fig. 6 for three of the absorbers. The failure of the three curves to intersect in a common point is, of course, indicative of the errors in the measurements. In general, the values of $\omega\Gamma_\gamma$ and Γ are not obtained with as great an accuracy as the product $\omega\Gamma_\gamma\Gamma$.

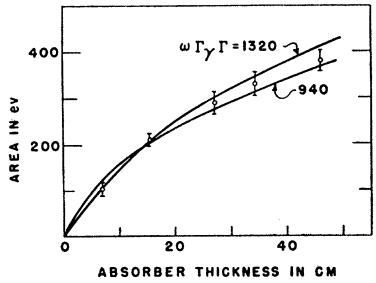

FIG. 5. Method of obtaining the product $\omega\Gamma_\gamma\Gamma$. For the curve with $\omega\Gamma_\gamma\Gamma = 1320$ ev^2, a value of $\omega\Gamma_\gamma = 13$ ev is assumed in obtaining $F(n\sigma_0)$; for the curve with $\omega\Gamma_\gamma\Gamma = 940$ ev^2, $\omega\Gamma_\gamma = 20$ ev is used.

The value found for $\omega\Gamma_\gamma$ strongly indicates dipole radiation. A width $\Gamma_\gamma \approx 14$ is about 0.03 Weisskopf unit for $E1$ radiation, about 0.8 Weisskopf unit for $M1$ radiation, and about 140 Weisskopf units for $E2$ radiation. The dipole values are very acceptable, but the quadrupole value is unreasonably large.[6] Spin zero is ruled out for the excited state because of the anisotropy[7] of the radiation in the capture process $C^{13}(p,\gamma)N^{14}$. Moreover, the polarization of the capture radiation indicates even parity,[8] so that the only remaining possibilities are 1^+ and 2^+, which give $\Gamma_\gamma = (14.5\pm2.5)$ ev and (8.7 ± 1.5) ev, respectively. The second value is equivalent to 0.5 Weisskopf units. The angular distribution[7] of the 9.17-Mev gamma ray can also be fitted with an assignment of either 1^+ or 2^+. Recently however the presence of a small term in $\cos^4\theta$ was reported,[8] which would require the presence of some $E2$ radiation and the assignment 2^+ to the excited state.

The level parameters obtained from the resonant absorption may be used to compute the cross section or

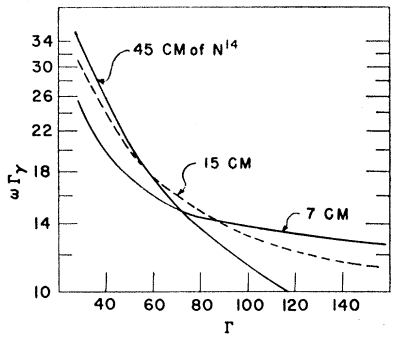

FIG. 6. Method of intersecting curves. The quantity $\omega\Gamma_\gamma$ is plotted against Γ for an absorber [see Eq. (4)]. The intersection of two such curves gives a solution for the two corresponding absorbers.

yield for the inverse capture process. In this process the cross section at resonance is

$$\sigma_R = 4\pi\lambda\!\!\!^{-}{}_p^2\omega_1\Gamma_p\Gamma_\gamma/\Gamma^2, \tag{5}$$

where $\lambda\!\!\!^{-}{}_p$ is $1/(2\pi)$ times the wavelength of the proton and ω_1 is the statistical factor equal to $(2J_r+1)/(2s+1)(2i+1)$, in which s and i are the spins of the initial particles. Putting in the numerical values, we find $\sigma_R = (200\pm40)$ mb. (Note that the result is rather insensitive to the value of J_r.) For the thick-target yield we have[9]

$$Y = \tfrac{1}{2}\pi\sigma_R\Gamma/\epsilon, \tag{6}$$

where ϵ is the stopping power of the target for the

[6] D. H. Wilkinson in *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 175.
[7] Woodbury, Day, and Tollestrup, Phys. Rev. **92**, 1199 (1953).
[8] Strassenburg, Hubert, Krone, and Prosser, Bull. Am. Phys. Soc. Ser. II, **3**, 372 (1958).
[9] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948).

incident beam. Using the value[10] $\epsilon=3.1\times10^{-15}$ ev-cm^2, we find $Y=(7.7\pm1.5)\times10^{-9}$ gamma rays (9.17 Mev)/proton.

The thick target yield of radiation was measured by use of a NaI crystal 3 in. in diameter and 4 in. long, and also one 3.5 in. in diameter and 3.5 in. long. The results for the two crystals agreed satisfactorily. Measurements were made at an angle of 0° and at distances of 6 in. and 11.5 in. from the target. The efficiencies of the crystals were obtained from the computation of Miller, Reynolds, and Snow.[11] In obtaining the total yield, the angular distribution of the radiation and the isotopic composition of the target were taken into account. The value obtained was $Y=(7.4\pm3)\times10^{-9}$ gamma ray (9.17 Mev)/proton, which may be compared with the value above and with the value of 11.5×10^{-9} obtained previously by Seagrave.[12] In the latter result, however, no correction[7] has been made for the 10% branch to the level at 6.44 Mev.

[10] W. Whaling, *Handbuch der Physik* (Springer-Verlag, Berlin, 1958), Vol. 34, p. 193.

[11] Miller, Reynolds, and Snow, Rev. Sci. Instr. **28**, 717 (1957).
[12] J. D. Seagrave, Phys. Rev. **85**, 197 (1952).

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Absolute Activation Cross Sections for Reactions of Bismuth, Copper, Titanium, and Aluminum with 14.8-Mev Neutrons*

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Absolute neutron activation cross sections at 14.8 Mev have been measured for bismuth, copper, titanium, and aluminum based on comparison with the $Cu^{63}(n,2n)Cu^{62}$ reaction (556 millibarns) which served as a standard for monitoring the flux. The reactions studied, measured half-lives, and cross sections are: $Bi^{209}(n,\alpha)Tl^{206}$, 4.29±0.05 min, 1.1±0.3 mb; $Bi^{209}(n,p)Pb^{209}$, 3.31±0.03 hours, 0.83±0.40 mb; $Bi^{209}(n,\gamma)Bi^{210}$, ≤1.7 mb; $Cu^{65}(n,2n)Cu^{64}$, 12.85±0.05 hours, 954±130 mb; $Cu^{65}(n,p)Ni^{65}$, 2.56±0.20 hours, 27±11 mb; $Ti^{50}(n,p)Sc^{50}$, 1.8±0.2 min, 27±6 mb; $Ti^{50}(n,p)Sc^{50}$, 22±3 min, 48±15 mb; $Ti^{50}(n,\gamma)Ti^{51}$, ≤9 mb; $Ti^{49}(n,p)Sc^{49}$, 58±2 min, 29±5 mb; $Ti^{48}(n,p)Sc^{48}$, 44.0±0.9 hours, 58±8 mb; $Ti^{47}(n,p)Sc^{47}$, 3.45±0.06 days, 230±40 mb; $Ti^{46}(n,2n)Ti^{45}$, 3.06±0.08 hours, 50.4±8.0 mb; $Ti^{46}(n,p)Sc^{46}$, 85±2 days, ~520 mb; $Al^{27}(n,\alpha)Na^{24}$, 15.00±0.06 hours, 114±7 mb; $Al^{27}(n,p)Mg^{27}$, 9.46±0.02 min, 53±5 mb.

Comparisons of the experimental cross sections with values estimated according to the continuum theory of the compound nucleus outlined by Blatt and Weisskopf are in agreement within an order of magnitude, except in the case of the bismuth results which exhibit large discrepancies.

From irradiations of natural titanium and highly enriched Ti^{50}, a new activity was observed having a half-life of 22±3 minutes. This activity is not produced from enriched Ti^{47} or Ti^{49} samples, and it is therefore assigned tentatively to an isomer of Sc^{50}. Further work on this activity is in progress.

INTRODUCTION

NEUTRON activation cross sections of bismuth, copper, titanium, and aluminum have been measured at 14.8 Mev as part of a systematic study being carried out for comparison with nuclear reaction theory. Monoenergetic neutrons of 14.8±0.9 Mev energy (taken at 0° to the beam axis) are produced by the $H^3(d,n)He^4$ reaction in thin zirconium-tritium targets giving total yields ranging from 10^9 to more than 10^{11} neutrons/second on the University of Arkansas 400-kv Cockcroft-Walton accelerator.[1]

EXPERIMENTAL

The samples were in the form of solid metallic foils 1.7 to 2.1 cm in diameter having surface densities in mg/cm^2 as follows: copper, 3 to 6; aluminum, 3; natural titanium, 8; and bismuth, 34 to 56. Enriched samples of titanium[2] were in the form of TiO_2 powder. All target materials were of reagent-grade purity. Irradiations were carried out for periods ranging from 10 to 60 minutes, the samples being placed in contact with the back of the target plate. In the experiments in which limits were obtained for the (n,γ) cross sections at 14.8 Mev of titanium and bismuth, the samples were wrapped in cadmium sheet in order to eliminate any possible contribution from slow neutrons. The flux passing through the samples generally was of the order

* Supported in part by the U. S. Atomic Energy Commission.
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[1] Bronner, Ehlers, Eukel, Gordon, Marker, Voelker, and Fink, Nucleonics **17**, No. 1, 94 (1959); R. W. Fink, Atomic Energy Commission Report ORO-172, 1958 (unpublished). Detailed information on the neutrons produced in the *DD* and *DT* reactions is contained in the report by J. D. Seagrave, Atomic Energy Commission Report LAMS-2162, 1958 (unpublished), J. H. Coon, in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (to be published), Chap. IV. D; and by J. Benveniste and J. Zenger, Atomic Energy Commission Report UCRL-4266, 1954 (unpublished).

[2] The enriched samples of titanium had the following mass analyses, as supplied by Oak Ridge National Laboratory: Ti^{47}, 85.6±0.3% (with 1.7±0.1% Ti^{46}, 11.3±0.2% Ti^{48}, 0.8±0.1% Ti^{49}, and 0.6±0.1% Ti^{50} as isotopic impurities); Ti^{49}, 81.5±0.2% (with 1.3±0.1% Ti^{46}, 1.3±0.1% Ti^{47}, 14.5±0.1% Ti^{48}, and 1.4±0.1% Ti^{50} as isotopic impurities); Ti^{50}, 84.69±0.04% (with 1.25±0.01% Ti^{46}, 1.23±0.04% Ti^{47}, 10.99±0.07% Ti^{48}, and 1.84±0.03% Ti^{49} as isotopic impurities.)