the more usual definition of the reduced width. The reduced width for the transfer of a nucleon between two states is regarded as a product of two factors and is defined as[19]

$$\theta^2 = S\theta_0^2\,. \tag{5}$$

Here S is the spectroscopic factor and θ_0^2 is the single-particle reduced width. It is defined as[19]

$$\theta_0^2 = \tfrac{1}{3} r^3 K^2(r)\,. \tag{6}$$

Since the transfer-reaction cross section is determined by the value of θ^2, rather than just θ_0^2, one must compare $1/\lambda$ with θ^2 rather than directly with θ_0^2. The tunneling theory was derived, however, for the reaction ^{14}N(^{14}N,^{13}N)^{15}N. Therefore, the spectroscopic factors for the nitrogen nuclei are presumably taken into account by the theory. (Macfarlane and French[19] estimate the relevant spectroscopic factor for ^{14}N to be ~ 1.3 and for ^{15}N to be ≥ 1.07 or ≤ 1.25.) If the tunneling theory, when applied to the reaction ^{10}B(^{14}N,^{13}N)^{11}B, does not account for the boron spectroscopic factors then the magnitude of $r^2R^2(r)$ for ^{11}B derived from experiment would have to be reduced by the appropriate value of S. This spectroscopic factor is given as 7/4 by Macfarlane and French.[19]

From the above discussion we note that the uncertainties due to experimental errors and the neglect of spectroscopic factors are on the same order of magnitude as those that enter into the calculated radial wave functions when different combinations of numerical parameters are used. Therefore, while the agreement between the calculated and experimentally determined values of $r^2R^2(r)$ is good, the results shown in Fig. 9 can only be taken to mean that the tunneling theory, when applied to transfers of $1p$ neutrons, yields a reasonable measure of the neutron radial wave function for $r \geq 4$ F.

ACKNOWLEDGMENTS

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^{12}C(γ,n)^{11}C Giant Resonance with Gamma Rays*

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The photonuclear reaction ^{12}C(γ,n)^{11}C was produced in natural carbon by means of the monochromatic gamma rays from T(p,γ)He in the range of $21 < E_\gamma < 26.7$ MeV. The reaction was detected by means of the positron radioactivity of ^{11}C using coincidences of the annihilation gamma radiation from the positrons. The cross section was determined absolutely to an accuracy of 10%. The gamma-ray energy width or resolution varied from about 0.1 MeV at $E_\gamma = 22$ MeV to 0.2 MeV at $E_\gamma = 26$ MeV. The peak cross section is 7.8 mb at both 22.15 and 23.0 MeV, and additional structure is observed at 25.6 MeV. The integrated cross section from 20 to 27 MeV is 36 MeV mb. Comparison is made with other reported measurements and with theoretical calculations. Some agreement is found with the deformed-nucleus calculation of Nilsson, Sawicki, and Glendenning. Also, some indication is observed of transition to excited states of ^{11}C suggesting two-hole–two-particle excitation in ^{12}C.

INTRODUCTION

A GREAT number of measurements[1] have been made of the carbon photoneutron reaction since the first observation of the "giant resonance" by Baldwin and Klaiber.[2] The major source of photons has been bremsstrahlung from energetic and essentially monochromatic electrons accelerated by betatrons and lineacs with gradually improving resolution. The heterogeneity of these photons has made the interpretation of yield curves somewhat difficult, particularly with respect to the so-called "breaks." Annihilation radiation from energetic positrons in flight[3] has recently been applied to this measurement with resolution of about 2%.

Indirect but valuable evidence of the cross-section variation may be obtained from high-resolution neutron-energy measurements using bremsstrahlung[4]

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[4] F. W. K. Firk, K. H. Lokan, and E. M. Bowey, in *Proceedings of the Conference on Direct Interactions and Nuclear Reaction Mechanisms, Padua, 1962* (Gordon & Breach Science Publishers, Inc., New York, 1963), p. 804. F. W. K. Firk and E. M. Bowey, in International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, 1965 (unpublished).

and even more useful information can be secured by step-wise excitation and by comparison with yield curves.

Much of this recent work has been summarized by Hayward.[5] Nevertheless, the importance of detailed and accurate photodisintegration measurements on light nuclei to compare with theoretical calculations led us to apply and extend the technique[6] of monochromatic gamma rays to carbon. Although the gamma-ray intensity is small, the resolution is quite good and the simplicity of interpretation attractive. Such a measurement of $^{12}C(\gamma,n)$ extending over its giant resonance is here described. Preliminary results have already been reported.[7]

EXPERIMENT

As has been described previously,[6] monochromatic gamma rays are produced by bombarding with protons, the tritium absorbed in a thin layer of titanium or zirconium evaporated onto a platinum foil. The University of Pennsylvania Tandem accelerator provided a well-collimated proton beam of 3 to 5 μA at energies above 3.8 MeV. Its half-energy accelerator supplied 5 to 10 μA in the energy range 2.5 to 3.88 MeV. For lower energies we were graciously aided by Professor L. Lidofsky of Columbia University who made available the Columbia Van de Graaff generator. Targets of thickness 428, 1110, and 1543 μg/cm^2 were used. The thickness was specified by the supplier, Oak Ridge National Laboratories. These were directly water-cooled and the beam power limited to 25 W in a spot less than $\frac{1}{2}$ cm in diam.

The disk samples were made from A.G.O.T. reactor-grade graphite of 99.93% purity and were wedge-shaped to subtend a Doppler angle of 11° at the tritium target when placed as shown in Fig. 1.

The gamma-ray energies were calculated assuming the Q value of $T(p,\gamma)$ to be 19.812 MeV.[8] The width, at half maximum, of the gamma-ray energy distribution is calculated from the Doppler angle and the target thickness and varies from about 100 keV at 22 MeV to 200 keV at 26 MeV.

The gamma rays were monitored by a 4.5-in.-diam $\times$6-in.-long NaI(Tl) crystal collimated with a 2-in. hole in a 4-in. lead shield and placed about 2 ft from the target. A typical spectrum is shown in Fig. 2. The forward edge of the peak is extrapolated to the background and three quarters of this energy was taken as the bias in order to eliminate background which piles on the lower part of the response curve. The true-response curve was assumed to be given by extrapolating to zero a curve taken with no pileup and as little background as possible. This extrapolation is substantiated by the observation that very few high-energy pulses emerge from the crystal in coincidence with lower energy pulses in the photo spectrum.[9] The absorption coefficient, 0.116 per cm, used was that measured at 20.48 MeV for a similar Harshaw crystal.[9]

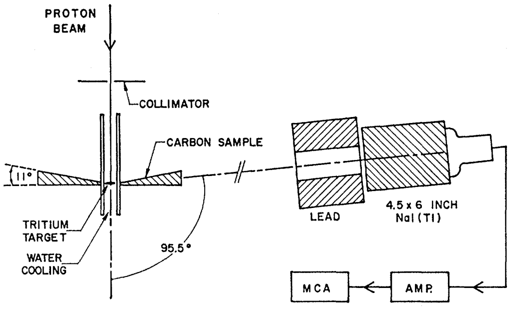

FIG. 1. Schematic experimental arrangement.

The radioactivity of ^{11}C was measured by observing coincidences between converted annihilation photons from the positrons emitted in the sample when it is placed between two 5-in.-diam by 2-in.-thick NaI(Tl) crystals. The detector efficiency was determined by using ^{18}F sources which were counted also in a 2π counter and agreed with our previous similar calibration.[6]

Normally, the samples were irradiated one at a time for 40.8 min (i.e., two half-lives of ^{11}C) at a particular gamma-ray energy and, while that sample was being counted in the positron detector (also for 40.8 min) another sample was irradiated. Several runs were made at every point and the agreements were consistent within the statistical fluctuation expected from the limiting values of the positron detector.

The results are shown in Fig. 3, together with the results previously reported by Del Bianco.[6] The absolute

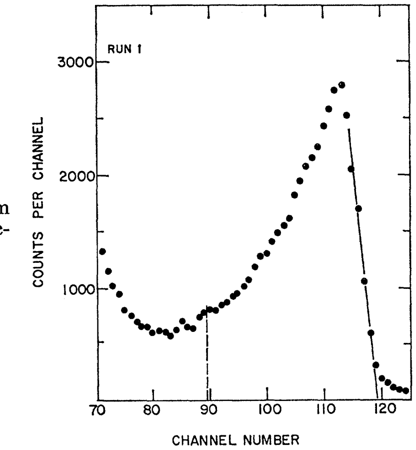

FIG. 2. Sodium iodide crystal response curve.

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[7] W. A. Lochstet and W. E. Stephens, Bull. Am. Phys. Soc. **10**, 94 (1965).

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[9] W. Del Bianco *et al.*, Proceedings of the Symposium on Total Absorption Gamma Ray Spectroscopy, 1960 (unpublished).

accuracy of the cross-section values is estimated to be 10%. This is mostly due to the poor statistics of the positron detector. The uncertainty in the absolute efficiency of the positron detector is estimated to be 5% and that of the gamma-ray monitor, 4%. The relative error of point-to-point is limited mainly by statistics at 5 to 6%.

DISCUSSION

The cross-section curve of Fig. 3 displays the uneven giant resonance which has been the characteristic feature of the photonuclear experiments on carbon with improved resolution. The recent betatron experiment of Min and Whitehead[10] agrees within its limited statistics and $\frac{1}{2}$-MeV resolution. The, as yet unpublished, results of Cook and his colleagues[11] at Iowa State using bremsstrahlung with much finer energy control and more sophisticated analysis is generally in good agreement with Fig. 3. Around 23.5 MeV, Cook's cross section is somewhat larger than the present data, but elsewhere the agreement seems to be within the experimental uncertainties. A recent unpublished measurement of ${}^{12}\mathrm{C}(\gamma,n){}^{11}\mathrm{C}$ by Fultz[12] and his colleagues in Lawrence Radiation Laboratory at Livermore using annihilation photons agrees well in general shape with our results but the cross section is slightly lower, especially at the higher photon energies. Spicer[13] has summarized a large number of previous photoneutron cross-section measurements and applied corrections in an attempt to reconcile the results from different laboratories. A comparison of his corrected values for carbon with the present results confirms Spicer's suggestion that the energy scale of many previous results is not reliable, at least above 19 MeV. Since energy resolution affects the peak cross section, it should be more worthwhile to compare integrated cross sections. Our cross section, integrated from 20 to 27 MeV, is 36 MeV mb. Previous results on carbon are generally smaller, ranging from 25 to 29 MeV mb.

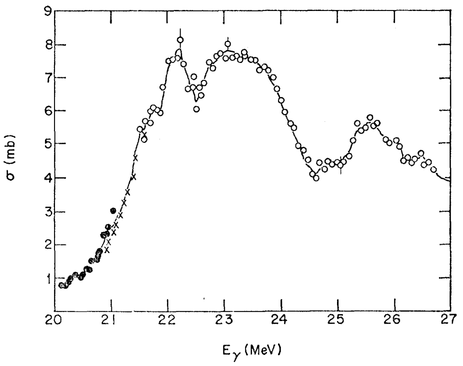

FIG. 3. ${}^{12}\mathrm{C}(\gamma,n){}^{11}\mathrm{C}$ activation cross-section curve as a function of photon energy.

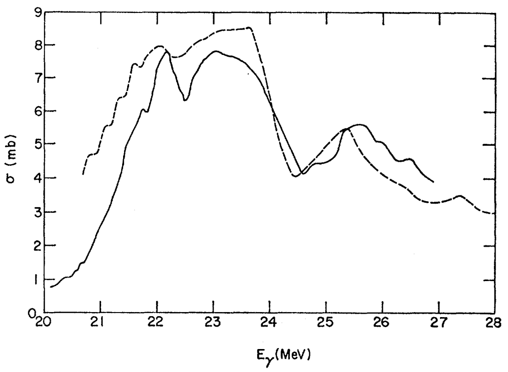

FIG. 4. Comparison of time-of-flight neutron-energy curve (dashed line) of Firk and Bowey with ${}^{12}\mathrm{C}(\gamma,n){}^{11}\mathrm{C}$ activation curve of present experiment (solid line).

It is interesting to compare our ${}^{12}\mathrm{C}(\gamma,n){}^{11}\mathrm{C}$ activation curve with the results by Firk, Lokan, and Bowey[4] (using bremsstrahlung and neutron time-of-flight technique) shown in Fig. 4. Since Firk has not given absolute magnitudes of the cross sections, his curve has been normalized to our results as shown. The general agreement in shape suggests that ${}^{11}\mathrm{C}$ is usually left in its ground state. However, there appears to be additional yield in Firk's curve in the region of 2–3-MeV neutron energy over our curve. This can be interpreted as indication of emission of photoneutrons of 2–3-MeV energy leaving the ${}^{11}\mathrm{C}$ nucleus in an excited state. However, Firk's curve was taken at only one angle and so the magnitude and energy of this excited-state transition is hard to estimate. Another recent time-of-flight measurement[14] suggests somewhat less structure and is several millibarns lower in cross section than our results although, perhaps, not outside the relative uncertainties.

A comparison of the (γ,n) cross section with the (γ,p) cross section should indicate something of the charge dependence of the nuclear interactions. The phase space and Coulomb-barrier factor give a factor[15] of 1.3 for σ_p/σ_n in the giant-resonance region. The observed ratio [compared with the inverse ${}^{11}\mathrm{B}(p,\gamma_0)$[16] as shown in Fig. 5] is greater than 3 at 20.5 MeV, dropping to about 1 at 25.5 MeV. In the giant-resonance region, 22 to 23.5 MeV, the ratio varies from 1.15 to 1.6. The large ratio on the low-energy side of the giant resonance can be interpreted[15] as the effects of admixtures of states of other parity. These isotopic-spin impurity effects seem also to vary from one state to the next in the giant-resonance region, although the amounts of admixture need only be of the order of a few percent.[15]

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[11] B. C. Cook (private communication).

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[15] F. C. Barker and A. K. Mann, Phil. Mag. **2**, 5 (1957).

[16] R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, and R. E. Segel, Nucl. Phys. **58**, 122 (1964). R. C. Morrison (private communication). See also W. R. Dodge and W. C. Barber, Phys. Rev. **127**, 1746 (1962); Y. M. Shin and W. E. Stephens, *ibid.* **136**, B660 (1964).

TABLE I. ^{12}C energy levels (in MeV). Italicized values correspond to giant-resonance peaks.

This expt.	Firk[a] (γ,n)	Dodge[b] (e,p)	Allas[b] $^{11}B(p,\gamma)$	^{12}C level[c]	^{12}B analog[c]	Nilsson[d]	Gillet[e]	Vinh-Mau[f]	Mikeska[g]	Mihailovic[h]
(26.5)						26.3				
(26.0)				25.95						
		25.7								25.4
25.6	25.5		25.5							
				25.24						
					25.1				25	
				24.93			24.9			
(24.9)		24.8								
				24.42						*24.6*
							24.2			
				23.87				23.9		
	23.8	23.8				23.74				
23.7			23.6							
				23.51			23.5			23.6
					23.3					
		23.2					23.2			
	23.1									
23.0				23.04	22.9	22.97				
							22.7			
			22.6	22.63						
		22.5								
22.2	22.1		22.14			*22.21*		*22.2*		
							21.9			21.9
(21.75)	21.65				21.7				*21.7*	
			21.5	21.48						
							21.3			

[a] See Ref. 4.
[b] See Ref. 16.
[c] See Ref. 17.
[d] See Ref. 19.
[e] See Ref. 21.
[f] See Ref. 18.
[g] See Ref. 20.
[h] See Ref. 22.

If the irregularities in cross section are considered as indicative of resonances in ^{12}C, then our results would suggest states in ^{12}C at (21.75), *22.2*, *23.0*, ~23.7, (24.9), 25.6, (26.0), and (26.5). The italics indicate the giant-resonance region. The parentheses indicate the less obvious bumps.

States of spin greater than zero[17] in ^{12}B at 6.6, 7.77, 8.23, and 9.95 MeV should be reflected in analog states in ^{12}C at energies 15.11 MeV higher (since the first $1^+T=1$ state in ^{12}C at 15.11 MeV is regarded as the isotopic analog of the ground state of ^{12}B). Consequently, $T=1$ states of possible spin one in ^{12}C would be expected to occur at 21.7, 22.9, 23.3, and 25.1 MeV. While agreement is not exact, possible rough correspondence exists.

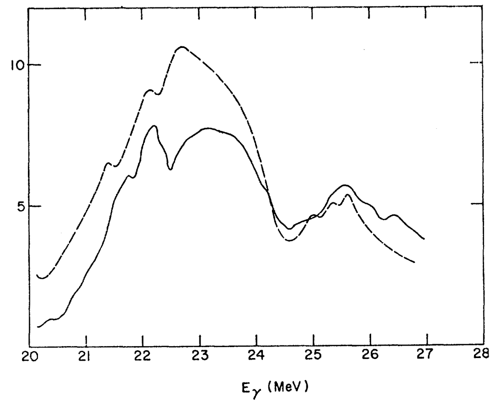

FIG. 5. Comparison of $^{12}C(\gamma,p_0)$ (dashed line) from the inverse $^{11}B(p,\gamma_0)$ with the $^{12}C(\gamma,n)^{11}C$ activation curve of the present experiment (solid line).

Several shell-model calculations have been made to predict the characteristics of the excited states of ^{12}C. Vinh-Mau and Brown[18] carried out such a calculation in the approximation of zero-range forces, both with and without ground-state correlations. With ground-state correlations, the calculated $T=1$, 1^- states in the energy region of this experiment include a level at 22.2 MeV with 75% of the dipole strength arising from the $(1p_{3/2})^{-1}(1d_{5/2})$ configuration and another level at 23.9 MeV with 0.5% of the dipole strength arising from the $(1p_{3/2})^{-1}(1d_{3/2})$ configuration. In addition, two other levels were calculated outside the range of this experiment, one at 18.7 MeV of 6.5% dipole strength arising from the $(1p_{3/2})^{-1}(2s_{1/2})$ configuration and the other at 34.3 MeV of 18% dipole strength arising from the $(1s_{1/2})^{-1}(1p_{1/2})$ configuration.

Assuming a deformed nuclear potential, Nilsson, Sawicki, and Glendenning[19] calculated the energies and strengths of the states which contribute to the giant $E1$ resonance. They neglected ground-state correlation effects and described excited states as combinations of particle-hole excitations in a deformed well. The result-

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[17] T. Lauritsen and F. Ajzenberg-Selove, *Energy Levels of Light Nuclei–1962*, *Nuclear Data Sheets* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.).

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[19] S. G. Nilsson, J. Sawicki, and N. K. Glendenning, Nucl. Phys. **33**, 239 (1962). See also *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961* (Academic Press Inc., New York, 1961), p. 323.

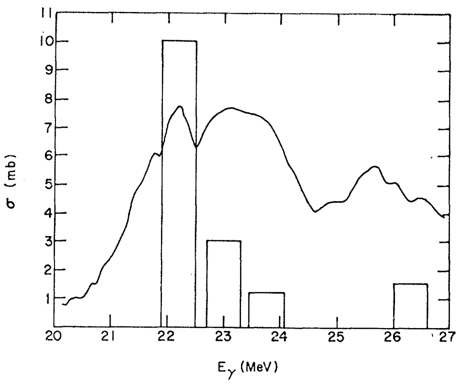

FIG. 6. Comparison of ^{12}C absorption calculations of Nilsson, Sawicki, and Glendenning with the ^{12}C$(\gamma,n)^{11}$C activation curve of the present experiment.

ing photonuclear effect is dominated by 1^-, $T=1$ states. These include a very strong level at 22.21 MeV, a weaker one at 22.97 MeV, and two still weaker levels at 23.74 and 26.31 MeV. They also predicted two moderately strong states at 29.50 and 31.91 MeV.

Mikeska[20] has calculated the shape of the giant resonance for ^{12}C using a square-well potential of finite depth and considering the mixing of the one-particle–one-hole excitations due to residual interactions. The results predict a peak at 21.7 MeV containing 60% of the dipole strength and a very broad peak near 25 MeV containing about 15% of the dipole strength. In addition there are two very sharp resonances, one at 18.3 MeV, and the other at 34.3 MeV.

Gillet and Vinh-Mau[21] have calculated tables of the excited states of ^{12}C using a finite-range force with an exchange mixture. The resulting 1^-, $T=1$ states in the giant-resonance region include a very strong state at 21.9 MeV and a weaker state at 24.2 MeV. Two other states are predicted, one at 17.7 MeV, and the other at 33.8 MeV.

Mihailovic and Rosina[22] have calculated the influence of the configurations with two or more particle-hole pairs on the structure of the giant resonance. In carbon, they find the usual dipole strength moved up in energy and hence, not so much agreement with experiment.

The results of the calculations described above are shown in Table I along with the results of this and several other experiments. Where energies are printed in italics in this table it indicates the peak or peaks of the giant resonance. From this comparison it appears that the results of Vinh-Mau and Brown, of Gillet and Vinh-Mau, and of Mikeska are not wholly adequate to explain the results of the present work because they do not find the secondary peaks at 25.5 and 23 MeV, respectively.

The results of Nilsson, Sawicki, and Glendenning show at least crude agreement with the presently reported experimental levels. The energy levels and relative strengths of their predicted levels are shown in Fig. 6, together with the results of this experiment. While relative strengths are not in complete agreement, the general trend appears consistent.

As pointed out above, there is a noticeable amount of gamma absorption in ^{12}C which seems to result in the ejection of neutrons leaving ^{11}C in an excited state. This suggests that one or more two-particle–two-hole excitations are mixed in with the usual single-particle-hole states. For instance, a configuration $(1p_{3/2})^{-1}(1p_{1/2})$; $(1p_{3/2})^{-1}(1d_{3/2\text{ or }5/2})$ could be mixed into the single-particle-hole excited states near 23 to 24 MeV in ^{12}C. When the $1d$ neutron from this configuration emerges it would leave the ^{11}C in its 2-MeV excited state $(1p_{3/2})^{-2}(1p_{1/2})$. Such a transition would contribute to the excess in the time-of-flight spectrum near 21 to 22 MeV. However, since the time-of-flight curve is not deficient at 23 to 24 MeV, there is no clear-cut confirmation of this possible transition. In fact, the only noticeable deficiency exists at 26 MeV. Consequently, either the transition is in fact from 26 MeV in ^{12}C to a higher state in ^{11}C [say, the 4.85-MeV $(\frac{1}{2}$ to $\frac{3}{2})^-$ state] or from 26 MeV in ^{12}C to the 2-MeV state in ^{11}C as well as from the 23 MeV ^{12}C to the 2 MeV ^{11}C.

CONCLUSION

The photonuclear cross section for ^{12}C$(\gamma,n)^{11}$C has been measured in the giant-resonance region with improved resolution and accuracy. The resulting curve shows an irregular giant resonance with added structure on the high-energy side. Comparison of the data with neutron time-of-flight results suggests some excited-state transitions. Comparison with photo proton work suggests some isotopic-spin impurities in the ^{12}C states in this region. Comparison with theoretical calculations indicates that the deformed-nucleus assumption of Nilsson, Sawicki, and Glendenning comes closest to describing the experimental results.

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[20] H. J. Mikeska, Z. Physik **177**, 441 (1964).

[21] V. Gillet and N. Vinh-Mau, Nucl. Phys. **54**, 321 (1964). See also, A. Goswami and M. K. Pal, *ibid.* **44**, 294 (1963).

[22] M. V. Mihailovic and M. Rosina, Nucl. Phys. **40**, 252 (1963).