Photoneutron Reactions: C^{12}, N^{14}, O^{16}, and F^{19} near Threshold*

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Photoneutron reactions in carbon, nitrogen, oxygen, and fluorine have been studied in the region of threshold using improved efficiency for the detection of the residual activity. The betatron energy calibration used is based on thresholds of deuterium, bismuth, copper, and for scattering from the 15.12-Mev level in carbon. Results show that the thresholds for nitrogen and fluorine correspond well with the expected values for the respective neutron separation energies. For oxygen, the position of threshold is also in good agreement. Assuming a linear extrapolation of the betatron calibration above 15 Mev, it is found that the carbon threshold is 52 kev above the accepted value of the separation energy. The successful correlation between the assignment of known resonance energies with the positions of many of the breaks in the yield curves corroborates the assumed linearity of the betatron energy scale above 15 Mev. It follows that previous betatron calibrations using the carbon threshold must be in error by approximately 100 kev at 18.7 Mev.

I. INTRODUCTION

PHOTONEUTRON yields in the region of threshold have previously been measured for the light elements carbon, nitrogen, oxygen, and fluorine using bremsstrahlung radiation and radioactivity detection methods.[1–7] The results of these measurements showed sharp changes of slope or so-called "breaks" in the measured activation curves especially in the region above threshold. These breaks are attributed to narrow isolated resonances in the photon absorption cross section. Published values for the energy assignments of observed fine structure, however, are in disagreement with one another and with the energy assignments of known levels. These discrepancies are primarily due to uncertainties in the betatron energy scales and are closely connected with difficulties in the measurement of thresholds of light elements.

Since most betatron energy control systems have been calibrated by measuring the photoneutron thresholds of reactions, each with a precisely known *neutron separation energy* (NSE), it is necessary to be certain that the threshold[8] observed actually corresponds to the NSE. There is reason to believe that this requirement has not always been satisfied, particularly in the case of light nuclides. The basic difficulty in using light element NSE values as calibration standards arises just from the presence of the discrete resonances in the photon absorption cross section. Thus, the position of the observed reaction threshold may be determined rather by the strengths, widths and relative spacings of these resonances in the immediate vicinity of the NSE than by the NSE value itself. Thus if a resonance energy occurs at an energy significantly above the NSE, the initial yield may not be detected above the detector background and its onset not observed until the resonance energy is reached. In this case the observed threshold corresponds to the resonance energy rather than to the NSE. In addition there exists the need for periodic revision of the adopted NSE values in the light of more recent experimental data.

Most betatron energy calibrations to date have relied heavily on the $C^{12}(\gamma,n)C^{11}$ threshold to determine the scale in the region of 18.7 Mev. It has generally been assumed that the threshold actually corresponded to the NSE in this case. Similar considerations apply to the use of nitrogen, oxygen, and fluorine thresholds which have also been used for calibration purposes. It seemed desirable therefore to investigate these thresholds using a betatron energy scale which did not include as calibration points any light element thresholds other than deuterium. The establishment of a satisfactory calibration has been discussed fully in an earlier paper.[9] It is based on the standard NSE values: D at 2.226±0.001 Mev, Bi^{209} at 7.43±0.05 Mev, Cu^{63} at 10.826±0.018 Mev, and the threshold for detecting gamma rays elastically scattered from the 15.116±0.006-Mev state in C^{12}. The good agreement between the NSE values reported in I with the predictions from mass data and reaction energies gives support for the linearity of this betatron scale from 2 to 15 Mev. No satisfactory threshold calibration point has been used above 15 Mev; therefore, a linear extrapolation of the calibration beyond 15 Mev has been assumed. Evidence from fine structure in the vicinity of threshold for $O^{16}(\gamma,n)O^{15}$ and $C^{12}(\gamma,n)C^{11}$

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[1] M. Birnbaum, Phys. Rev. **93**, 146 (1954); M. D. de Souza Santos et al., *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 2, p. 169.
[2] L. Katz et al., Phys. Rev. **95**, 464 (1954).
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[4] B. M. Spicer and A. S. Penfold, Phys. Rev. **100**, 1375 (1955).
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[6] W. L. Bendel, J. McElhinney, and R. A. Tobin, Phys. Rev. **111**, 1297 (1958).
[7] H. King and L. Katz, Can. J. Phys. **37**, 1357 (1959).
[8] The term threshold will be confined to its definition as the energy at which yield is first detected.
[9] K. N. Geller, J. Halpern, and S. G. Muirhead, Phys. Rev. **118**, 1302 (1960). This paper will be referred to as paper I.

and its agreement with known level schemes supports the linear extrapolation to more than 20 Mev. Details of this fine structure will be presented in Sec. III.

II. EXPERIMENTAL PROCEDURE

Irradiation and Detection

Neutron yields as a function of peak bremsstrahlung energy were inferred from induced residual radioactivity measurements. The samples in the form of solid cylinders, were irradiated at a distance of 25 cm from the betatron target for a fixed x-ray dose as monitored by a thin aluminum-walled ionization chamber and electronic integrator circuit. The decay time of the integrator was set equal to the residual half-life so that the measured yields per unit monitor response were independent of fluctuations in beam intensity. Counting of the radioactive sample began after a fixed delay following irradiation. Except for carbon, the activity was measured using the NaI(Tl) annihilation radiation detector described in paper I. Counting stability was checked periodically with a Na^{22} source in the standard counting position between the crystals. Stability was generally within counting statistics of 0.3% and was well within the required limits for threshold yield measurements. The detection efficiency as measured with this source was 38%. The basic limitation to the sensitivity for detection was set by the NaI(Tl) background which amounted to 325 counts/min. In the case of carbon, a significant improvement in sensitivity over the above method was obtained using plastic scintillators[10] as targets.

Targets

Relatively thick samples were used in each case. Nitrogen samples were compressed cylinders of cyanoguanidine 2-in. diam by $1\frac{1}{2}$ in. long, moulded under a pressure of about 10 ton per square inch. Oxygen samples were prepared in the same manner using boric acid. Teflon cylinders $1\frac{1}{4}$-in. diam by $2\frac{1}{2}$ in. long were used in the fluorine activations. For carbon, plastic scintillators,[11] 1-in. diam by 2 in. long were used. After irradiation the plastic cylinder was optically coupled to the cathode of a 6292 photomultiplier and maintained in a standard counting geometry. Counting stability was checked for each scintillator prior to irradiation by means of a radium source brought to a standard position. After two or three betatron irradiations, (about $3\times10^5 r$) each scintillator became discolored and its efficiency was reduced by about 20%. A sufficient number of samples was available so that only two exposures per sample were required.

Assignment of Threshold Energies

The yield curves were measured in 10–25 kev steps in the vicinity of each threshold. The details of (i) the method of extrapolation of the yield curve into the background, (ii) the assignment of threshold energy and its error, (iii) corrections for long- and short-term stability of the energy calibration using the slope of the $O^{16}(\gamma,n)O^{15}$ reaction at 17.35 Mev have been given in paper I. The quoted error for each threshold includes uncertainties in the extrapolation, energy shift corrections and energy calibration.

III. RESULTS

Carbon

Plastic scintillators were irradiated for 1000 seconds and the induced activity was recorded for 1000 seconds after a 1000-second delay following irradiation. This long delay was required to suppress activities due to traces of oxygen and nitrogen in the scintillating material which showed up in half-life measurements taken below the carbon threshold. The activation curve after background subtraction is shown in Fig. 1. The threshold E_{Th} is observed at 18.79±0.03 Mev on our scale. Correcting for center-of-mass motion gives 18.77±0.03 Mev for the measured threshold. This is to be compared with the currently adopted NSE of 18.721±0.006 Mev.[12]

Assuming this NSE and our threshold energy assignment are each correct, it follows that with the present detection sensitivity E_{Th} probably corresponds to a previously unreported weak resonance in the photon absorption cross section at 18.79 Mev. The activation curve above threshold can best be fitted with straight sections, with comparatively sharp changes in slope occurring at 18.86 Mev and 19.00 Mev. The break at 18.86 Mev is in good agreement with the

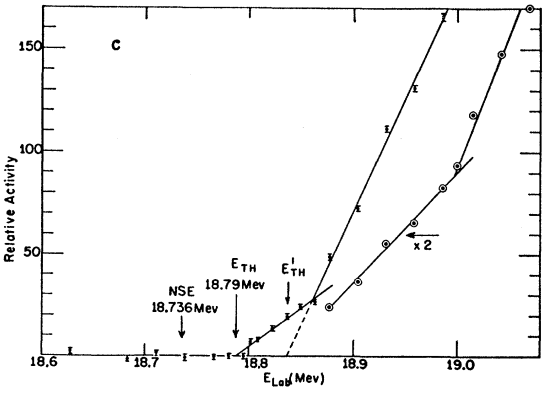

FIG. 1. Activation curve for the reaction $C^{12}(\gamma,n)C^{11}$.

[10] L. Cohen and J. McElhinney, Rev. Sci. Instr. **27**, 773 (1956).
[11] Obtained from Nuclear Enterprise, Ltd., Winnipeg, Canada.
[12] Everling, Konig, Mattauch, and Wapstra, Nuclear Phys. (to be published).

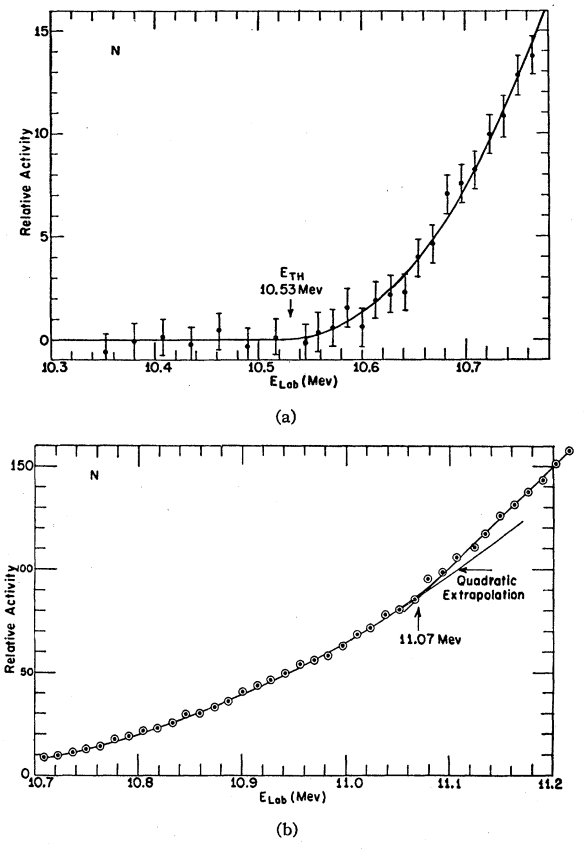

FIG. 2. Activation curve for the reaction $N^{14}(\gamma,n)N^{13}$.

position of a known level in carbon at 18.85 Mev,[13] but the narrow width suggested by the sharp break in the yield curve is inconsistent with the reported width of 90 kev.

Other studies of the $C^{12}(\gamma,n)C^{11}$ reaction using plastic scintillators have been made by Cohen and McElhinney[10] and more recently by Katz.[14] However in the work of these experimenters the observed threshold was assumed to correspond to the NSE of 18.736 Mev, this point in fact being used for calibration purposes. The energy separation between threshold and the first break is given as 0.16 Mev by Katz, and a lower limit for this difference of 0.14 Mev is set by the data of Cohen and McElhinney. These results are inconsistent with the present measurements which give 72 kev for this difference. Their energy difference is however consistent with that between our first and second breaks and it is therefore possible to resolve this discrepancy by assuming that these authors have extrapolated the slope at 18.9 Mev linearly into the background leading to an apparent threshold E_{Th}' at 18.84 Mev (Fig. 1). It is considered possible that the initial slope in Fig. 1 could easily be missed where the points are taken much more than 10 kev apart. The energy scales of these authors are therefore believed to be in error by +100 kev at this point. Thus the break reported by Katz[14] at 18.9 Mev corresponds to that at 19.00 Mev in the present work.

Nitrogen

The nitrogen samples were irradiated for 10 minutes and the activity recorded for 10 minutes following a 40-second delay. The activation curve from 10.5 to 11.2 Mev is presented in Fig. 2. The threshold energy is found to be 10.53±0.04 Mev in the center-of-mass system. This result is consistent with the NSE value of 10.553±0.005 Mev evaluated from the mass data tabulations of Everling et al.[12] It is to be noted that there is a level known at 10.57 Mev observed in the $C^{12}(d,p)C^{13}$ reaction.[13]

The yield curve is apparently smooth over an energy interval for 500 kev above the threshold and can be fitted quite well by a quadratic energy dependence as illustrated in Fig. 2. Deviation from a quadratic fit occurring at 11.07 Mev may be attributed to a resonance in the nitrogen photon absorption cross section. This result is in good agreement with the N^{14} level listed at 11.07 Mev.[13]

Oxygen

The oxygen samples were irradiated for 5 minutes and the activity counted for 5 minutes after a 30-second delay. Each yield point was measured at least three times and the average values with their statistical uncertainties are plotted as a function of energy in Fig. 3.

The shape of the activation curve at threshold is not well defined due to poor statistics. Nevertheless, if we assume the residual background component to be flat below 15.60 Mev, there is a definite increase in net yield at 15.65 Mev. This gives the threshold energy for the reaction in the center-of-mass system as 15.64±0.04 Mev. This value is in better agreement with the NSE value of 15.647±0.007 Mev given by Bendel et al.,[6] although not inconsistent with the value of 15.669

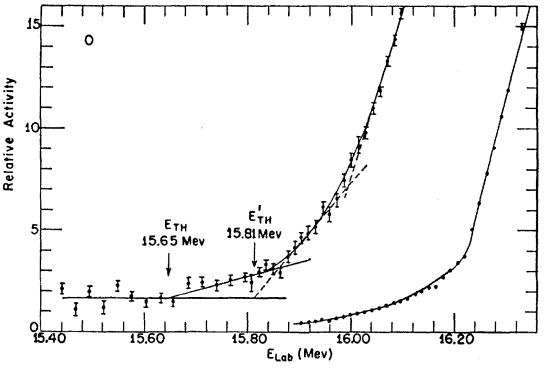

FIG. 3. Activation curve for the reaction $O^{16}(\gamma,n)O^{15}$.

[13] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[14] L. Katz, Can. J. Phys. **37**, 1455 (1959).

TABLE I. Comparison of results for $O^{16}(\gamma,n)O^{15}$ with those of previous experiments.

Reference	Threshold (Mev)	Apparent threshold E_{Th}' in Fig. 3 (Mev)	Lower break (Mev)	Upper break[a] (Mev)
Bendel et al.[6]		15.74±0.05	16.18±0.02	
King and Katz[7]	15.69 ±0.06		16.14±0.04	17.18±0.04
Penfold and Garwin[16]		15.77±0.05	16.19±0.04	17.25±0.03
Present work	15.65 ±0.04[b]	15.81±0.04	16.22±0.02	17.27±0.03
Reaction energies and NSE	15.655±0.007[c]		16.21[d]	17.29[d]

[a] The upper break, claimed to be a close-spaced doublet by the authors of references 7 and 16, is found by us to be a single level about 100 kev wide.
[b] Assumes flat background below threshold.
[c] See reference 6.
[d] See reference 15.

±0.006 Mev calculated from recent mass data tabulations.[12]

Figure 3 shows that the activity data above 15.83 Mev can be fitted either with a smooth curve or by straight sections which in either case suggests changes in curvature at 15.86 and 15.99 Mev. Cross section analysis of the smooth curve also indicates the presence of weak resonances at about these energies. The pronounced increase in activity at 16.22 Mev is attributed to a strong narrow level in O^{16}. The energy assignment is in good agreement with the 24-kev level at 16.21 Mev in the $N^{15}(p,n)O^{15}$ reaction.[15]

Use is made of a strong break at 17.27 Mev in the $O^{16}(\gamma,n)O^{15}$ activation curve to monitor the long-term energy stability of the betatron. This energy assignment is in good agreement with the 17.25±0.04 Mev value reported by Penfold and Garwin[16] and with the level in O^{16} observed at 17.29 Mev in the $N^{15}(p,n)O^{15}$ reaction,[15] and 17.24 Mev in the $N^{15}(p,\gamma)O^{16}$ reaction.[17]

The results of these measurements are compared with those of other workers in Table I. The apparent threshold (E_{Th}' in Fig. 3) at 15.81 Mev is obtained as in the case of carbon by linearly extrapolating the activity above 15.86 Mev into the background. Energy assignments based on the assumption that E_{Th}' corresponds to the NSE are therefore expected to be in error by about 150 kev. The agreement between published values for the positions of the strong lower and upper breaks is seen to be good. The residual discrepancies are undoubtedly connected with uncertainties in the respective betatron scales. For example the energy assignments made by Bendel et al.[6] and King and Katz[7] were based on a calibration which is likely to be in error by 100 kev at the carbon threshold. Assuming linear scales, this implies an error of 80 kev in their oxygen energy assignments. Applying this correction to their published results leads to much better agreement. The energy assignments made by Penfold and Garwin[16] are based on magnetic field measurements and inferences from the data of Penfold and Spicer.[5]

Fluorine

Teflon cylinders were irradiated for 40 minutes and the activity was counted for 20 minutes after a 1-minute delay. The activation curve for fluorine near threshold is shown in Fig. 4. The energy assigned to the threshold is 10.45±0.03 Mev in the center-of-mass system. This is in better agreement with the NSE of 10.442±0.007 Mev calculated from recent mass data tabulations[12] than with the older value at 10.401±0.011 Mev.[18]

The large increase in activity observed at 10.53 Mev is attributed to the level in F^{19} at 10.549 Mev observed in the $O^{18}(p,n)F^{18}$ reaction. The level at 10.533 Mev, observed in the $O^{18}(p,\alpha)N^{15}$ reaction but not in the $O^{18}(p,n)F^{18}$ reaction will also not be observed in the (γ,n) reaction. Since the alpha-particle binding energy in F^{19} is 3.99 Mev, the energy available for alpha emission is large at these excitation energies. Thus the (p,α) reaction can excite quite high spin states in F^{19}, the alpha particle being capable of carrying off large angular momentum. Near the neutron threshold, however, neutron decay will be strongly inhibited for large changes in angular momentum and these high spin states will not be observed.

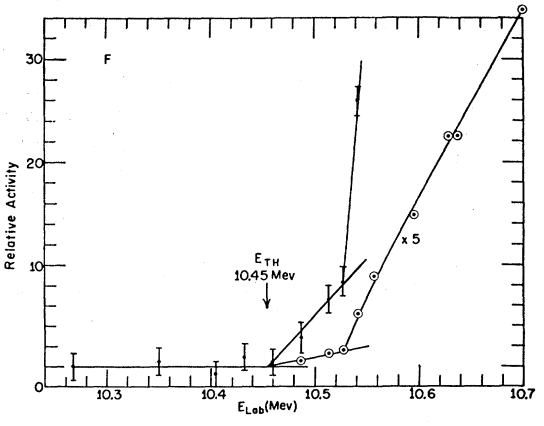

FIG. 4. Activation curve for the reaction $F^{19}(\gamma,n)F^{18}$.

[15] K. W. Jones, L. J. Lidofsky, and J. L. Weil, Phys. Rev. **112**, 1252 (1958).
[16] A. S. Penfold and E. L. Garwin, Phys. Rev. **115**, 420 (1959).
[17] N. W. Tanner, G. C. Thomas, and W. E. Meyerhof, Nuovo cimento **14**, 257 (1959).
[18] J. Mattauch, L. Waldmann, R. Bieri, and F. Everling, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1956), Vol. 6, p. 179.

TABLE II. Comparison of observed threshold energies with the NSE values.

Photoneutron reaction in	Observed[a] threshold (Mev)	Separation energy (NSE) (Mev)	Level energy near NSE (Mev)
C^{12}	18.77±0.03	18.721±0.004[b]	
N^{14}	10.53±0.04	10.553±0.005[b]	10.57[d]
O^{16}	15.64±0.04	15.647±0.007[c]	
		15.669±0.006[b]	
F^{19}	10.45±0.03	10.442±0.007[b]	10.479[d]

[a] Present work.
[b] See reference 12.
[c] See reference 6.
[d] See reference 13.

The relative separation between threshold and the first break is 75±22 kev. This is in good agreement with the energy separation of 70 kev between excited states in F^{19} at 10.479 and 10.549 Mev.[13] Excellent agreement is also obtained with the results of Bendel et al.[6] who measured 72±20 kev for this difference. However, their absolute energy assignments were determined by the earlier NSE value mentioned above which is a large enough change to bring their results into agreement with the present work at 10 Mev.

DISCUSSION

The difficulties arising from the use of the thresholds of light nuclei have been pointed out on several occasions.[4,6] The present results show that with current detection techniques it is possible to get right to the NSE in the case of nitrogen and fluorine. The technique is being strained to the limit in the case of oxygen and a significant discrepancy between the observed threshold and NSE exists for carbon. In the case of fluorine and nitrogen there are known levels in the immediate vicinity of the NSE values in contrast to oxygen or carbon. This probably accounts for the relative success in observing activity right to the NSE for fluorine and nitrogen.

It is imperative to obtain a satisfactory and unambiguous calibration point in the vicinity of 20 Mev. The carbon NSE point may still be the desirable one but it will require a more sophisticated approach in terms of experimental technique. While the present sensitivity in terms of induced activity may be adequate, it will be necessary to use carbon samples free from traces of oxygen and nitrogen together with low level counting techniques.

There exists the possibility of using the well defined breaks in the oxygen and carbon activation curves for this purpose, but at present there is not complete agreement regarding the exact interpretation of these breaks and their correlation with known resonance levels in all cases. In the immediate vicinity of threshold however there is good agreement between laboratories for the relative positions of the first two or three breaks in the respective yield curves for oxygen and carbon. On the basis of this identification, a comparison between the existing energy calibrations for the various betatrons can be made.

TABLE III. Comparison of fine structure observed near threshold with presently known level structure.

Photoneutron reaction in	Break energy[a] (Mev)	Level energy (Mev)	Level width (kev)
C^{12}	18.79		
	18.86	18.85[b]	90[b]
	19.00		
N^{14}	11.07	11.07[b]	120[b]
O^{16}	15.86		
	15.99		
	16.22	16.21[c]	24[c]
	...		
	17.27	17.29[c]	84[c]
		17.24[d]	280[d]
F^{19}	10.53	10.549[b]	

[a] Present work.
[b] See reference 13.
[c] See reference 15.
[d] See reference 17.

SUMMARY

Table II summarizes the four values for the observed thresholds and their comparison with the NSE values calculated from other nuclear data. The agreement is good except for carbon. The threshold for oxygen assumes a flat background below the threshold. Difficulty in measuring the oxygen and carbon thresholds is ascribed to the absence of resonances in the photon absorption cross section in the immediate vicinity of the NSE values in these two instances. Conversely levels are known to exist close to the NSE values for nitrogen and fluorine.

Table III gives the observed fine structure in the vicinity of threshold together with the positions of levels known from other reactions. No strong conclusions can be drawn regarding the measure of agreement owing to experimental uncertainties both in the photonuclear and charged particle reactions.

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