# Photoneutron Cross Sections of $Li^6$ and $Li^7$†

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The total photoneutron production cross sections for $Li^6$ and $Li^7$ were determined from the yields measured with a neutron detector. The efficiency of the neutron detector was found from the comparison of the detected and computed neutron yield from copper. In the calculation of the cross section the inverse photon matrix formulation of the photon difference method was used. The $Li^6$ cross section has a peak at about 12.5 Mev and its absolute value at the peak is equal to 2.8±0.53 mb. The $Li^7$ cross section has a peak at about 14 Mev and its value at the peak is equal to 3±0.75 mb.

## INTRODUCTION

In the past, a comparatively large number of photoneutron yields from heavy and medium-heavy nuclei have been studied. Among light nuclei only a relatively small number have been investigated and their cross sections measured. In this experiment the photoneutron production cross section of $Li^6$ was determined by detecting the neutrons directly with $BF_3$ counters. Because of the existence of some disagreement among the reported measurements of the photoneutron production cross section of $Li^7$,[1–3] the determination of that cross section was repeated.

## EXPERIMENTAL PROCEDURE

The experimental arrangement used in studying the $(\gamma,n)$ reaction in $Li^6$ and $Li^7$ is shown in Fig. 1. The neutron detection technique used in this experiment was similar to the one used by Halpern *et al.*[4] The gamma rays were hardened and the primary electrons were removed from the beam by means of a 2-in. thick aluminum plate. The beam was collimated by a 16-in. lead collimator to a diameter of 1.3 cm at a distance 212 cm from the gamma-ray target. A 3-in. thick paraffin sheet was placed in the $\gamma$-ray beam in order to diminish the background caused by neutron contamination present in the beam.

The neutron detector assembly was aligned with the gamma-ray beam by exposing x-ray film placed directly on the targets. Neutrons were detected with two boron-lined proportional counters[5] imbedded parallel to the gamma-ray beam in a paraffin-filled moderator box. The 10 in.×10 in.×8 in. box was made from iron sheet plated with a cadmium layer 0.020 in. thick. The box had a vertical slot in the center for the target holder. The minimum thickness of paraffin between the counters and the target was about $1\frac{3}{4}$ in. In order to thermalize the background neutrons present and allow them to be captured by cadmium, the moderator box was surrounded by 14 in. of water and paraffin. To reduce the background further the detector assembly was surrounded by a 24-in. concrete wall made up of heavy concrete blocks. The $Li^7$ target contained 2.6 grams of natural lithium (92.6% $Li^7$, 7.4% $Li^6$) in the form of a cylinder. For $Li^6$, a 3-gram sample enriched to 92.8% $Li^6$ was used. The targets were placed in Lucite containers with walls $\frac{1}{16}$ in. thick and were moved in and out of the beam by a two-position target holder which was remotely controlled.

The signals from the neutron counters were amplified and fed to a discriminator circuit and to the scalers connected in parallel. Each scaler was gated to count when the target assigned to it was placed in the beam and in addition was gated by the betatron expander pulse. For the purpose of visual monitoring, the gate pulse and the gamma-ray pulse were displayed on a cathode-ray oscilloscope. The cycling of the target changer and the scalers was accomplished by an electronic circuit controlled with a current integrator measuring the ionization current from a conventional ionization chamber placed in the gamma-ray beam. The block diagram of the electronic circuitry is shown in Fig. 2.

To obtain an optimum gate width for detecting neutrons, a study was made of the neutron half-life in the moderator. A number of neutrons produced by a

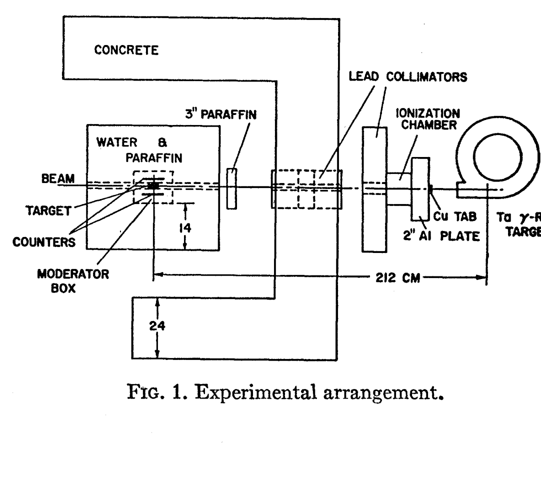


FIG. 1. Experimental arrangement.

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[1] T. Goldemberg and L. Katz, Phys. Rev. **95**, 471 (1954).
[2] F. Heinrich and R. Rubin, Helv. Phys. Acta **28**, 185 (1955).
[3] T. W. Rybka and L. Katz, Phys. Rev. **110**, 1123 (1958).
[4] Halpern, Nathans, and Mann, Rev. Sci. Instr. **23**, 678 (1952).
[5] U. S. Atomic Energy Commission Model BP-X7(B), manufactured by General Electric Company.

given irradiation in a 25-$\mu$sec gate was detected as a function of time between the gamma-ray burst and the onset of the gate. The neutron half-life determined in such a way was about 80 $\mu$sec and was independent of the gamma-ray energy. From these measurements a gate width of 300 $\mu$sec was found desirable for the experiment. In order to determine the over-all stability of the experiment, the neutron yield from $Cu(\gamma,n)$ reaction at 17.6-Mev gamma-ray peak energy was determined after every lithium measurement. The copper yield monitored the stability of the betatron, the gamma-ray dose measurements, and the neutron detector. A beam-independent check on the stability of the neutron detector was frequently made with a standard Ra-Be neutron source. Further, a precision pulser was used to check the discriminator level and the amplifier gain in the neutron detection system. Finally, to provide monitoring ofthe betatron and the ionization chamber separately from the neutron detector, copper tabs $\frac{1}{16}$ in. thick and $\frac{3}{4}$ in. in diameter were exposed in a standard geometry to the unhardened gamma-ray beam with the peak energy at 17.6 Mev. The copper tabs were also counted in standard geometry by means of an end-window Geiger counter. The stability of the Geiger counter was frequently checked with a standard $Cs^{137}$ source. The data obtained from the stability checks were subjected to a statistical analysis. In each case the observed deviation was found for the accumulated number of runs and it was compared with the statistical deviation for the test runs.

From the yields observed by means of direct neutron detection and from the activations determined by the Geiger counter, the observed instabilities in yield and activation were expressed as an energy instability. The energy instability determined in this fashion was found to be less than 0.2 Mev. The possibility of a change in beam direction was ruled out on the basis that there was a good correlation observed between the $(\gamma,n)$ yield as measured by copper tabs and by the $BF_3$ counters. The copper tabs were irradiated close to the $\gamma$-ray target with the uncollimated beam and therefore the copper activation measured was considerably less sensitive to the changes of the beam direction. Assuming that the changes of the activation of the copper tabs were caused by the change of the $\gamma$-ray beam direction, one would obtain bigger changes than observed in the neutron yields measured by $BF_3$ counters.

The absolute energy calibration of the betatron was accomplished by detecting the $Cu^{63}(\gamma,n)$ threshold at 10.7 Mev and by detecting a break in the $C^{12}(\gamma,n)$ yield which occurs at 19.8 Mev.[6] The absolute energy calibrations were performed twice—once at the beginning of the experiment and once at the end of the experiment. Both calibrations performed five months apart agreed within the experimental error.

[6] Robinson, McPherson, Greenberg, Katz, and Haslam, "Betatron Energy Calibration", Physics Department Report, University of Saskatchewan, Canada (unpublished).

To express the yield in number of neutrons/100 r mole, one must know the number of roentgens per given gamma-ray dose as a function of the peak energy of the gamma-ray beam. This measurement was performed using a secondary standard as recommended by the National Bureau of Standards.[7]

The efficiency of the neutron detector was determined by comparing a computed yield from the natural isotope of copper with the experimentally determined yield. The photoneutron production cross section for copper was calculated by adding[8] $Cu^{63}(\gamma,n)$ and[9] $Cu^{65}(\gamma,n)$ cross sections according to the natural abundance ratio of $Cu^{63}$ and $Cu^{65}$. The spectrum used in the calculation was prepared in this laboratory for the case[10] when $Z=73$ and $C=191$ and the spectrum was modified to account for the gamma-ray absorption in the 2-in. thick aluminum beam-hardener. From the comparison of the detected and computed neutron yield at 17.25 Mev, the efficiency for the neutron detector was found to be $0.53\pm0.06\%$. This energy lies close to the thresholds for the $(\gamma,np)$ and $(\gamma,2n)$ reactions in copper so that the contributions from these competing reactions were negligible.

The detection efficiency of the neutron detector can depend on the neutron energy and their angular distribution. In the case of copper the energies of the detected neutrons are in the range from 0 to 10 Mev, and their angular distribution is isotropic.[11,12]

It was found that both the computed and the measured copper yields agreed within the experimental errors in the energy region from 12–20 Mev. In order to check the neutron detector efficiency dependence on the angular distribution of the neutrons from the $(\gamma,n)$ reaction, the neutron yield from deuterium was measured in the energy region from 6–13 Mev. The angular distribution of the photoneutrons from deuterium is peaked at 90° to the gamma-ray beam.[11,13] The detected

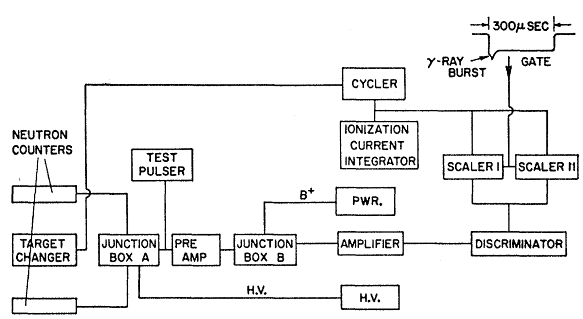


FIG. 2. Electronic circuitry.

[7] *National Bureau of Standards Handbook* (U. S. Government Printing Office, Washington, D. C., 1954), Vol. 55, p. 32.

[8] V. E. Krohn and E. F. Shrader, Phys. Rev. **87**, 685 (1952).

[9] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).

[10] P. M. Rose, M. S. thesis, Case Institute of Technology, 1955 (unpublished).

[11] G. A. Pirce and D. W. Kerst, Phys. Rev. **77**, 806 (1950).

[12] W. R. Dixon, Can. J. Phys. **33**, 785 (1955).

[13] Fabricand, Allison, and Halpern, Phys. Rev. **103**, 755 (1956).

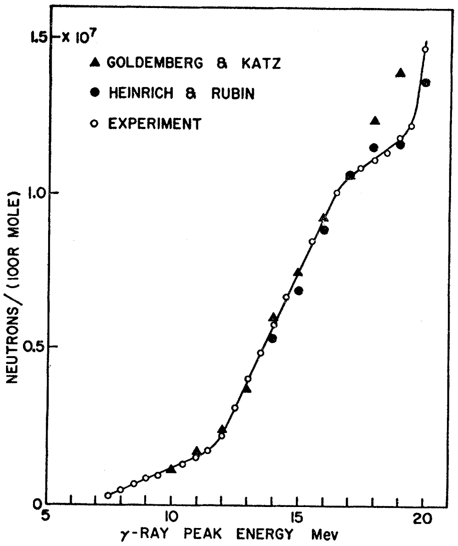


FIG. 3. $(\gamma,n)$ yield from $Li^7$ as a function of $\gamma$-ray peak energy.

yield was also compared to the computed one. Both yields agreed in shape. The neutron detector efficiency obtained from deuterium at 13 Mev was $0.46\pm0.02\%$. From the comparison of the efficiencies obtained from copper and deuterium it is evident that the neutron detector efficiency does not depend strongly on the angular distribution of the photoneutrons.

## EXPERIMENTAL DATA AND ITS TREATMENT

Lithium yields were measured as a function of the gamma-ray peak energies in half-Mev intervals from thresholds to 20 Mev. In a run the target received an irradiation dose of 8–12 roentgens depending on the

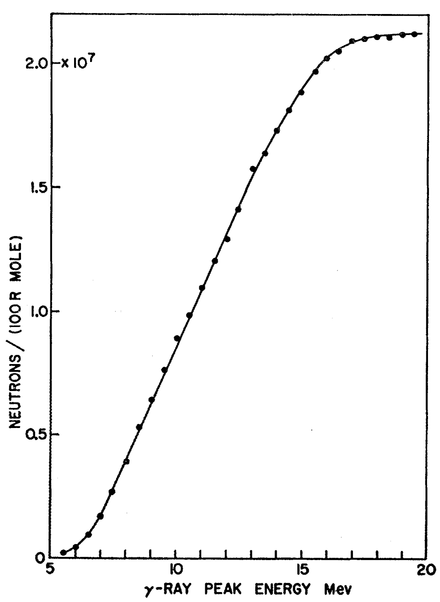


FIG. 4. $(\gamma,n)$ yield from $Li^6$ as a function of $\gamma$-ray peak energy.

energy region. In order to obtain the required statistical accuracy, many runs were taken at each gamma-ray peak energy. The runs were accumulated by taking them in succession over the gamma-ray peak energy range until the necessary total was obtained at each energy.

The threshold for the $Li^6(\gamma,n)$ reaction was determined to be $5.3\pm0.2$ Mev which is in good agreement with the data of Sher *et al.*[14] The detected $(\gamma,n)$ threshold in $Li^7$ was $6.9\pm0.2$ Mev which is also in essential agreement with Goldemberg and Katz.[15] The statistical errors in $Li^7$ yields ranged from 2.5–1.4% in the range from 13–20 Mev gamma-ray peak energy and from 20–2.5% in the range from threshold to 13 Mev. $Li^6$ yields were detected with the statistical error 1.8–1.3% in the energy range 7.5–20 Mev and with errors from 14.3–2.6% in the range from threshold to 7.5 Mev. The real counting rate was approximately equal to the background rate for both Li targets. For copper at 17 Mev the real-to-background ratio was 13:1.

In $Li^6$ the following reactions are possible:

| | Threshold energies |
|---|---|
| $Li^6+\gamma=He^4+n+p$ | 3.7 Mev |
| $Li^6+\gamma=Li^5+n$ | 5.5 Mev |
| $Li^6+\gamma=He^5+p$ | 4.7 Mev |
| $Li^6+\gamma=Li^4+2n$ | |

In this experiment all neutrons were detected and in effect the cross section determined from the yields will be the total cross section for the reactions mentioned above.

Similarly in $Li^7$ neutrons from the following reactions were determined:

| | Threshold energies |
|---|---|
| $Li^7+\gamma=Li^6+n$ | 7.0 Mev |
| $Li^7+\gamma=He^4+p+n$ | 11.6 Mev |
| $Li^7+\gamma=Li^5+2n$ | 14.0 Mev |

It might be added that the residual nuclei in these reactions have either short half-lives ($Li^5$ and $He^5$) of the order of $10^{-21}$ sec or they are stable.

The yields were normalized to 100 r/mole (Figs. 3 and 4), and were corrected for the absorption of the gamma rays in target and paraffin sheet. Further, the correction to the yields arising from the absorption of neutrons in $Li^6$ target according to the reaction $Li^6(n,\gamma)He^3$ was investigated and was found to be negligible. Also the contribution to the yields from $(n,2n)$ reactions was negligible.

## RESULTS AND CONCLUSIONS

The absolute yield from $Li^7$ was compared to the yields observed by Heinrich and Rubin[16] and by Goldemberg and Katz. The yields were normalized to

[14] Sher, Halpern, and Mann, Phys. Rev. **83**, 370 (1951).
[15] J. Goldemberg and L. Katz, Can. J. Phys. **32**, 49 (1954).
[16] A. Heinrich and R. Rubin, Helv. Phys Acta **28**, 185 (1955).

the observed yield in this experiment at 17 Mev (Fig. 3). From the observed yields the total cross section for the $(\gamma,n)$ reaction for $Li^6$ and $Li^7$, Fig. 5 and Fig. 6, were calculated using the photon difference method.[17] The $Li^6$ integrated cross section from threshold to 19 Mev is equal to 0.021 Mev barn. The $Li^6$ cross section at 17.6 Mev in this experiment agrees with the one determined by Titterton and Brinkley.[18] The $Li^7$ integrated cross section from threshold to 19 Mev is equal to 0.018 Mev barn. The statistical errors for the $Li^6$ cross section varied from 20% at 5.5 Mev to 24% at 19.5 Mev, and for the $Li^7$ cross section from 24% at 7.5 Mev to 30% at 19.5 Mev.

The $Li^7$ cross section was compared with the cross section reported by Heinrich and Rubin[16] and by Goldemberg and Katz[15] (Fig. 7). The cross section of

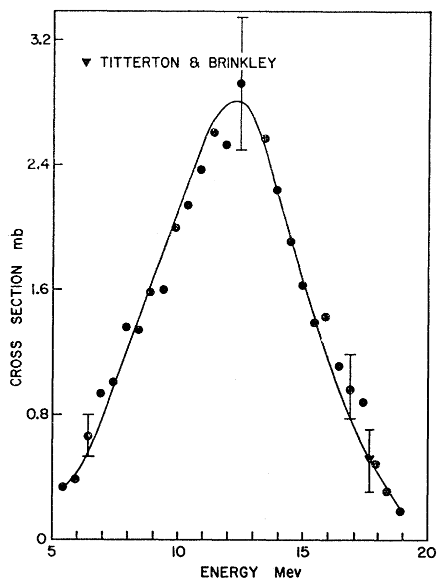


FIG. 5. $(\gamma,n)$ cross section for $Li^6$ as a function of $\gamma$-ray energy.

Heinrich and Rubin was normalized to the cross section obtained in this experiment at 14 Mev.

Comparison between the $(\gamma,n)$ cross section and the $(\gamma,p)$ cross section[10] shows that both agree in shape. This agreement is expected because there is a small Coulomb barrier for the protons in the $Li^7$ nucleus. The absolute magntitude of the peak of the $(\gamma,p)$ cross section is about 1.6 mb as compared to the $(\gamma,n)$ peak which is about 3.5 mb.

The apparent existence of a second peak in the $Li^7(\gamma,n)$ cross section could be caused by the dipole resonance in the $(\gamma,2n)$ reaction. The small peak near the threshold is probably due to magnetic quadrupole interaction. To check if the existence of the small peak

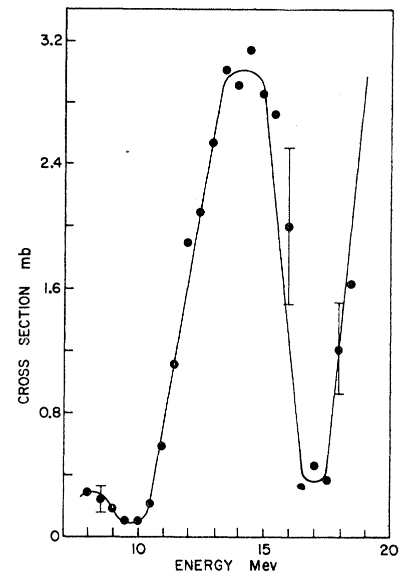


FIG. 6. $(\gamma,n)$ cross section for $Li^7$ as a function of $\gamma$-ray energy.

was caused by the smoothing procedure, the procedure was applied twice. Both times the small peak at the threshold was obtained. The correctness of the computed cross section depends on the validity of the bremsstrahlung spectrum and on the smoothing of the yield differences. The over-all shape of the bremsstrahlung spectrum is known with a better accuracy than the accuracy of the computed cross section. A relatively small possible error in the shape of the spectrum would not appreciably change the computed cross section. However, errors arising from the somewhat arbitrary smoothing procedure could be appreciable. In the experiment there was no direct stability measurement on the ionization chamber monitor and the current integrator circuit. The limits on this stability were given by the measurements of the energy stability which

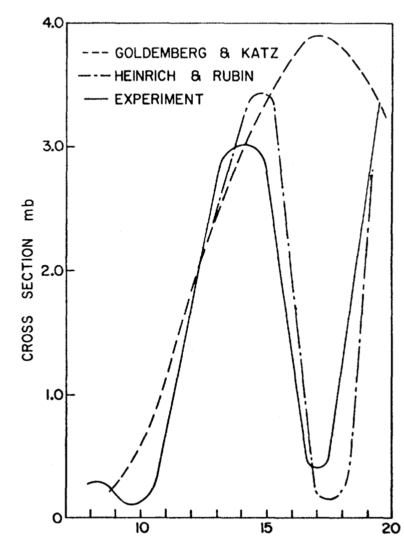


FIG. 7. Comparison of $Li^7$ cross sections.

[17] A. S. Penfold and J. E. Leiss (unpublished report).
[18] E. W. Titterton and T. A. Brinkley, Proc. Roy Soc. (London) A64, 212 (1951).

showed that the variation in the dose monitoring was less than 1.5%.

The cross section obtained was compared with cross sections computed on the basis of two models for the $Li^6$ nucleus.[19,20] One model considered $Li^6$ as an alpha-particle core with a neutron and proton independently bound, the other with a deuteron bound to the alpha-particle core. Both of these calculations are based on the general phenomenological formulation of the interaction between the nuclear fields and the electromagnetic field.[21] The calculations considered electric and magnetic interaction contributions to the cross section. Neither of the models gives a cross section which agrees with the experimental results.

[19] G. E. Bing, Ph.D. thesis, Case Institute of Technology, 1954 (unpublished).

[20] E. F. Corome, Ph.D. thesis, Case Institute of Technology, 1954 (unpublished).

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[21] L. L. Foldy, Phys. Rev. 92, 178 (1953).

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# $C^{12}(n,p)B^{12}$ Cross Section for 14.9- to 17.5-Mev Neutrons

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The cross section for the $C^{12}(n,p)B^{12}$ reaction has been measured for 14.9- to 17.5-Mev neutrons. The neutrons were obtained from the $T(d,n)He^4$ reaction and their flux density was determined by counting the recoil alpha particles or by counting the neutrons directly with a $Li^6I(Eu)$ scintillation counter. A cylindrical plastic scintillator 5 inches in diameter and 3 inches in length served as the carbon-containing target and permitted the counting of the $B^{12}$ decay beta rays in nine consecutive 7-msec intervals during the "beam off" period of a pulsed neutron beam cycle. The cross section rises from slightly above the reaction threshold of 13.6-Mev to a value of 29.09±4.36 millibarns at 17.5-Mev. The $B^{12}$ beta-decay half-life has been redetermined as 18.87±0.50 milliseconds.

## INTRODUCTION

BORON-12 has been observed to decay by emission of beta particles having a maximum energy of 13.4 Mev and a half-life whose measured values have ranged from 18 to 27 milliseconds.[1,2] Detailed studies[3] of the decay have shown that 97% of the beta transitions go directly to the ground state of $C^{12}$. For most of the studies of this decay, the $B^{12}$ has been formed by the $B^{11}(d,p)B^{12}$ reaction. However, it is also possible to form the radioactive $B^{12}$ by the $C^{12}(n,p)B^{12}$ reaction, and the cross section for this reaction is of some general theoretical interest. Mass determinations ascribe a $Q$ value of −12.5 Mev for this reaction and a neutron energy threshold of 13.6 Mev. An attempt to observe this reaction has been made by Jelley and Paul,[4] who used the neutrons from 0.9-Mev deuterons on a lithium target; the occurrence of the reaction was not established with certainty. An earlier measurement at this laboratory[5] determined the cross section as 29±23 millibarns for neutrons of energy 17.3-Mev, but the method used the inefficient detection of the 4.43-Mev gamma rays from the de-excitation of the first excited state of $C^{12}$ and it was not possible to obtain satisfactory accuracy. The present report describes a measurement of the cross section at several neutron energies using a method in which the beta rays are detected with high efficiency. In the course of this work the half-life for the beta decay has been redetermined.

* On leave of absence from the University of Kentucky, Lexington, Kentucky.

[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).

[2] B. C. Cook, Phys. Rev. 106, 300 (1957).

[3] Cook, Fowler, Lauritsen, and Lauritsen, Phys. Rev. 107, 508 (1957).

[4] J. V. Jelley and E. B. Paul, Proc. Cambridge Phil. Soc. 44, 133 (1948).

## EXPERIMENTAL APPARATUS AND TECHNIQUES

It was decided to measure the $C^{12}(n,p)B^{12}$ cross section by counting the energetic beta particles in the time interval from 7 to 70 milliseconds after the bombardment of a carbon-containing target with monoenergetic neutrons. The carbon was contained in a solid plastic scintillator, which as a component of a scintillation spectrometer made it possible to record the pulse-height distribution with a 100-channel pulse-height analyzer and also to record the integral counts

[5] Kreger, Bolotin, and Edelsack, Bull. Am. Phys. Soc. Ser. II, 1, 325 (1956).