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ATLAS OF PHOTONEUTRON CROSS SECTIONS OBTAINED
WITH MONOENERGETIC PHOTONS

Compiled by B. L. Berman

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Atlas of Photoneutron Cross Sections Obtained
With Monoenergetic Photons

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ABSTRACT

Photoneutron cross-section data obtained with monoenergetic photons from positron annihilation in flight are presented in a uniform format. This compilation is current as of early 1973.

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

Over the years, a considerable body of data on photoneutron cross sections obtained with monenergetic photons from the annihilation in flight of fast positrons^{1,2} has been acquired at the Livermore, Saclay, and General Atomic Laboratories. In view of the need for a comprehensive compilation of photoneutron cross-section data, the data on 65 nuclei studied with annihilation photons (49 from Livermore measurements, 25 from Saclay, and two from General Atomic) are gathered together here and presented in a uniform format, in order to serve as a nucleus for a more complete compilation and evaluation (which would include data obtained with continuous bremsstrahlung radiation sources as well). The photonuclear group at the National Bureau of Standards is undertaking such a comprehensive compilation and evaluation, and the data presented here will be part of it. Also, Bülow and Forkman are preparing a selected compilation of photonuclear cross sections, which partly overlaps this one, which emphasizes those nuclei of particular importance for photoactivation analysis.³ Meanwhile, these data are here made available in graphical form, and are available upon request in digital form. It is hoped that this service to the physics community will be utilized both for purposes of theoretical analysis and for those associated with applications to other scientific disciplines and technologies.

The data are presented in order of increasing mass number. When two or three laboratories have measured the same nucleus, the data are presented in chronological order. The top (and sometimes only) data plot for each nucleus is the total photoneutron cross section $\sigma[(\gamma,n)+(\gamma,pn)+(\gamma,2n)+(\gamma,p2n)+(\gamma,3n)+\dots]$; below it, where appropriate, are the single photoneutron cross section $\sigma[(\gamma,n)+(\gamma,pn)]$, the double photoneutron cross section $\sigma[(\gamma,2n)+(\gamma,p2n)]$, and the triple photoneutron cross section $\sigma(\gamma,3n)$. Some of the total-photoneutron data plots for medium and heavy nuclei have Lorentz-curve

fits superposed, while some of the data plots for light nuclei have curves drawn to guide the eye. For more details, one should refer to the original papers.

No attempt is made here to evaluate the data; i.e., to choose between two sets of data for the same nucleus measured at different laboratories, or to compromise between them by presenting a set of recommended intermediate values. It should be noted, however, that the overall agreement and consistency between measurements made at the three laboratories is very good indeed, especially when viewed in the light of the enormous discrepancies between laboratories frequently obtained in the past for bremsstrahlung-induced photonuclear measurements.

Although much credit is due to Tzara and his collaborators for initiating the annihilation-photon work at Saclay, the early results of the original Saclay group⁴ largely have been superseded by more recent measurements performed either at Saclay or Livermore, and hence are not presented here. Also, results on the fissionable nuclei ^{235}U (of Bowman et al.⁵ at Livermore) and ^{232}Th , ^{237}Np , and ^{238}U (of Veyssiere et al.⁶ at Saclay), since they involve the photofission channel and hence require special experimental techniques, are not presented here. Too, the results on $^{12}\text{C}(\gamma, n)$ of Lochstet and Stephens⁷, while impressive, are not presented here because they were obtained with $^3\text{H}(p, \gamma)$ photons, extend only over a limited energy range, and agree substantially with the Livermore results. Finally, the work on the various decay modes and branching ratios of ^{16}O via $(\gamma, n\gamma')$ and $(\gamma, x\gamma')$ measurements reported by Caldwell et al.⁸ also is beyond the scope of the present compilation.

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<u>Nucleus</u>	<u>Reference</u>	<u>Nucleus</u>	<u>Reference</u>	<u>Nucleus</u>	<u>Reference</u>
³ He	70Bel	⁹⁰ Zr	67Bel, 71Le1	¹⁴⁶ Nd	71Ca1
⁴ He	71Bel	⁹¹ Zr	67Bel	¹⁴⁸ Nd	71Ca1
⁶ Li	65Bel	⁹² Zr	67Bel	¹⁵⁰ Nd	71Ca1
⁷ Li	73Br1	⁹³ Nb	71Le1	Nat _{Sm}	69Be2
¹² C	66Fu1	⁹⁴ Zr	67Bel	¹⁵³ Eu	69Be3
¹⁴ N	70Be2	¹⁰⁷ Ag	69Bel	¹⁵⁹ Tb	64Br1, 68Be1
¹⁶ O	64Br1, 65Ca1	¹¹⁵ In	69Fu1	¹⁶⁰ Gd	69Be3
²³ Na	71Al1	¹¹⁶ Sn	69Fu1	¹⁶⁵ Ho	68Bel, 69Be3
²⁴ Mg	71Fu1	¹¹⁷ Sn	69Fu1	Nat _{Er}	69Be2
²⁵ Mg	71Al1	¹¹⁸ Sn	69Fu1	¹⁷⁵ Lu	69Be2
²⁶ Mg	71Fu1	¹¹⁹ Sn	69Fu1	¹⁸¹ Ta	63Br1, 68Be1
²⁷ Al	66Fu1	¹²⁰ Sn	69Fu1	¹⁸⁶ W	69Be3
Nat _{Si}	63Ca1	¹²⁴ Sn	69Fu1	¹⁹⁷ Au	62Fu2, 70Ve1
⁵¹ V	62Fu1	¹²⁷ I	66Br1, 69Be2	²⁰⁶ Pb	64Ha1
⁵⁵ Mn	73Al1	¹³³ Cs	69Bel	²⁰⁷ Pb	64Ha1
⁵⁸ Ni	73Fu1	Nat _{Ba}	71Be2	²⁰⁸ Pb	64Ha1, 70Ve1
⁵⁹ Co	73Al2	¹³⁸ Ba	70Be2	²⁰⁹ Bi	64Ha1
⁶⁰ Ni	73Fu2	¹³⁹ La	68Bel, 71Be2		
⁶³ Cu	64Fu1, 68Su1	Nat _{Ce}	69Be2, 71Be2		
⁶⁵ Cu	64Fu1	¹⁴¹ Pr	66Br1, 70Su1, 71Be2		
⁷⁵ As	69Bel	¹⁴² Nd	71Ca1		
Nat _{Rb}	71Le1	¹⁴³ Nd	71Ca1		
Nat _{Sr}	71Le1	¹⁴⁴ Na	71Ca1		
⁸⁹ Y	67Bel, 71Le1	¹⁴⁵ Nd	71Ca1		

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Fig. 1. (Top) Photoneutron cross section for ^3He . (Livermore)
 (Bottom) Photoneutron cross section for ^4He . (Livermore)

Fig. 2. Photoneutron cross sections for ${}^6\text{Li}$. (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 3. Photoneutron cross sections for ${}^7\text{Li}$. (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 4. (Top) Photoneutron cross section for ^{12}C . (Livermore)
 (Middle) Photoneutron cross section for ^{14}N . (Livermore)
 (Bottom) Photoneutron cross section for ^{16}O . (Livermore)

Fig. 5

Fig. 5. Photoneutron cross sections for ^{23}Na . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 6. (Top) Photoneutron cross section for ^{24}Mg (Livermore)
(Bottom) Photoneutron cross section for ^{28}Si (Livermore)

Fig. 7. Photoneutron cross sections for ^{25}Mg . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 8. Photoneutron cross sections for ^{26}Mg . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 9. Photoneutron cross sections for ^{27}Al . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 10. Photoneutron cross sections for ^{51}V . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 11. Photoneutron cross sections for ^{55}Mn . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 12. Photoneutron cross sections for ^{58}Ni . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 13. Photoneutron cross sections for ^{59}Co . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 14. Photoneutron cross sections for ^{60}Ni . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 15. Photoneutron cross sections for ^{63}Cu . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 16. Photoneutron cross sections for ^{63}Cu . (a) Single; (b) Double. (General Atomic)

Fig. 17. Photoneutron cross sections for ^{65}Cu . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 18. Photoneutron cross sections for ^{75}As . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 19. Photoneutron cross sections for ^{85}Rb . (a) Total; (b) Single; (c) Double. (Sacalay)

Fig. 20. Photoneutron cross sections for NatSr . (a) Total; (b) Single; (c) Double. (Saclay)

Fig. 21. Photoneutron cross sections for ^{89}Y . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 22. Photoneutron cross sections for ^{89}Y . (a) Total; (b) Single; (c) Double. (Saclay)

Fig. 23. Photoneutron cross sections for ^{90}Zr . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 24. Photoneutron cross sections for ^{90}Zr . (a) Total; (b) Single; (c) Double. (Sacalay)

Fig. 25. Photoneutron cross sections for ^{91}Zr . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 26. Photoneutron cross sections for ^{92}Zr . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 27. Photoneutron cross sections for ^{93}Nb . (a) Total; (b) Single; (c) Double. (Saclay)

Fig. 28. Photon neutron cross sections for ^{94}Zr . (a) Total; (b) Single; (c) Double, (d) Triple. (Livermore)

Fig. 29. Photoneutron cross sections for ^{107}Ag . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 30. Photoneutron cross sections for ^{115}In . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 31. Photoneutron cross sections for ^{116}Sn . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 32. Photoneutron cross sections for ^{117}Sn . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 33. Photoneutron cross sections for ^{118}Sn . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 34. Photoneutron cross sections for ^{119}Sn . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 35. Photoneutron cross sections for ^{120}Sn . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 36. Photoneutron cross sections for ^{124}Sn . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 37. Photoneutron cross sections for ^{127}I . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 38. Photoneutron cross sections for ^{127}I . (a) Total; (b) Single; (c) Double; (d) Triple. (Sacalay)

Fig. 39. Photoneutron cross sections for ^{133}Cs . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 40. Photoneutron cross sections for ^{nat}Ba . (a) Total; (b) Single; (c) Double. (Saclay)

Fig. 41. Photoneutron cross sections for ^{138}Ba . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 42. Photoneutron cross sections for ^{139}La . (a) Total; (b) Single; (c) Double; (d) Triple. (Saclay)

Fig. 43. Photoneutron cross sections for ^{nat}Ce . (a) Total; (b) Single; (c) Double; (d) Triple. (Saclay)

Fig. 44. Photoneutron cross sections for ^{141}Pr . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 45. Single photoneutron cross section for ^{141}Pr . (General Atomic)

Fig. 46. Photo neutron cross section for ^{141}Pr . (Saclay)

Fig. 47. Photoneutron cross sections for ^{142}Nd . (a) Total; (b) Single; (c) Double. (Saclay)

Fig. 49. Photoneutron cross sections for ^{143}Nd . (a) Total; (b) Single; (c) Double. (Saclay)

Fig. 49. Photoneutron cross sections for ^{144}Nd . (a) Total; (b) Single; (c) Double. (Saclay)

Fig. 50. Photoneutron cross sections for ^{145}Nd . (a) Total; (b) Single; (c) Double. (Saclay)

Fig. 51. Photoneutron cross sections for ^{146}Nd . (a) Total; (b) Single; (c) Double. (Saclay)

Fig. 52. Photoneutron cross sections for ^{148}Nd . (a) Total; (b) Single; (c) Double. (Sacalay)

Fig. 53. Photoneutron cross sections for ^{150}Nd . (a) Total; (b) Single; (c) Double. (Saclay)

Fig. 54. Photoneutron cross sections for ^{147}Sm . (a) Total; (b) Single; (c) Double; (d) Triple. (Saclay)

Fig. 55. Photoneutron cross sections for ^{153}Eu . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 56. Photoneutron cross sections for ^{159}Tb . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 57. Photoneutron cross sections for ^{159}Tb . (a) Total; (b) Single; (c) Double; (d) Triple. (Saclay)

Fig. 58. Photoneutron cross sections for ^{160}Gd . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 59. Photoneutron cross sections for ^{165}Ho . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 60. Photoneutron cross sections for ^{165}Ho . (a) Total; (b) Single; (c) Double; (d) Triple. (Sacalay)

Fig. 61. Photoneutron cross sections for ^{168}Er . (a) Total; (b) Single; (c) Double; (d) Triple. (Saclay)

Fig. 62. Photoneutron cross sections for ^{175}Lu . (a) Total; (b) Single; (c) Double; (d) Triple. (Saclay)

Fig. 63. Photoneutron cross sections for ^{181}Ta . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 64. Photoneutron cross sections for ^{181}Ta . (a) Total; (b) Single; (c) Double; (d) Triple. (Saclay)

Fig. 65. Photoneutron cross sections for ^{186}W . (a) Total; (b) Single; (c) Double; (d) Triple. (Livermore)

Fig. 66. Photoneutron cross sections for ^{197}Au . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 67. Photoneutron cross sections for ^{197}Au . (a) Total; (b) Single; (c) Double; (d) Triple. (Saclay)

Fig. 68. Photoneutron cross sections for ^{206}Pb . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 69. Photoneutron cross sections for ^{207}Pb . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 70. Photoneutron cross sections for ^{208}Pb . (a) Total; (b) Single; (c) Double. (Livermore)

Fig. 71. Photoneutron cross sections for ^{208}Pb . (a) Total; (b) Single; (c) Double; (d) Triple. (Saclay)

Fig. 72. Photoneutron cross sections for ^{209}Bi . (a) Total; (b) Single; (c) Double. (Livermore)