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P. Cuzzocrea, S. Notarrigo and E. Perillo : (n,α) CROSS SECTIONS FOR $\sim$14 MeV NEUTRONS. -

431

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Istituto Nazionale di Fisica Nucleare
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INTRODUCTION. -

Recently Chatterjee(24, 26) and Gardner and Yu(39) have tried to analyse the behaviour of the (n, α) reaction cross sections for $\sim$14 MeV neutrons against the mass number, the proton number and the neutron number.

These attempts are based on the compilations of the experimental data made by the same authors(24, 25, 39).

However, the compilation of Gardner and Yu(39) is partial as experimental data are collected only for the elements from Z=6 to Z=30. Moreover, maximum and minimum points are given without the mean values.

Chatterjee(24, 25) collects the experimental data available up to December, 1963 for all the elements. Also in this case no mean values are shown. Moreover, published data repeated by other authors in various papers are often reported by him as being the results of separate measurements and all the results of excitation function measurements around 14 MeV are quoted.

In order to investigate the regularity of these cross sections it appeared desirable to have at one's disposal a more accurate compilation, brought up to date.

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COMPILATION. -

In the table shown are collected the experimental data from the literature in the range 14. 0 ÷ 15. 0 MeV available up to July, 1967 according to the following criteria previously used for a compilation of the (n, p) neutron cross sections(32):

1) - only data quoting the experimental errors were taken;
2) - the result at or nearest to 14. 5 MeV neutron energy was taken in the case of excitation functions;
3) - only the most recent result was taken in the case of various data from the same authors for the same reaction;
4) - differential measurements at particular angles were rejected.

Columns 1 and 2 give the target nucleus and the stated neutron energy. In column 3 are reported the experimental techniques abbreviated thus: A = activation measurements, E = emulsion experiments, D = direct measurements and T = transmission experiments. Columns 4 and 5 give the experimental values and the references for the original sources. In column 6 are reported the weighted means, σ_{av}, calculated as previously shown(32) according to the Birge's consistency criterium, by using $1/((\Delta\sigma_i)^2 + e^2)$ as weights. In fact, in the case of non-consistency of the experimental sets of results the weights $1/(\Delta\sigma_i)^2$ can not long be used as systematic errors are present. In these cases the accuracy index $1/((\Delta\sigma_i)^2 + e_i^2)$ (where e_i is the systematic error of each measurement) must be used. Neither the $\Delta\sigma_i$ nor the e_i are well known as some authors give as $\Delta\sigma_i$ only the statistical errors and others include in $\Delta\sigma_i$ also an estimate of the systematic error. The simplest hypothesis is to consider the $\Delta\sigma_i$ as only the statistical errors, and to assume that the systematic errors are random, following a Gaussian law with mean = 0 and variance = e^2. In this way the cross section is the sum of two variables, $\sigma_i + e_i$, both with Gaussian distribution and therefore with a mean = σ_i and variance $(\Delta\sigma_i)^2 + e^2$.
e^2 must be obtained from the Birge's criterium (see ref. (32))

$$\frac{S_{ext}(e^2)}{S_{int}(e^2)} = 1$$

This equation is unfortunately not linear in e^2 and can be resolved only with numerical methods.
A rough estimate of e^2 can be obtained from the square deviations

$$e^2 = \frac{\sum_{i=1}^{N} (\sigma_i - \bar{\sigma})^2}{N - 1} - \frac{\sum_{i=1}^{N} (\Delta\sigma_i)^2}{N}$$

where $\bar{\sigma}$ is the arithmetic mean $\bar{\sigma} = \frac{\sum_{i=1}^{N} \sigma_i}{N}$.

Sometimes the value of e^2 obtained in this way is very high. It is convenient to lower it and generally to use the smallest value which will still give the consistency in order to maintain a heavier weight to the more precise of the original measurements. (For this method see Parrat: Probability and Experimental Errors in Science - Wiley (1961) and P. G. Guest: Numerical Methods of Curve Fitting - Cambridge Univ. Press (1961)).

When the experimental data are originally consistent the value of e^2 is assumed of course equal to 0.
In any case the errors associated with the means are the internal ones or the external ones(32), whichever the larger.
In column 7 are reported the values of $\sigma_{rel.}$, calculated as shown in ref. (32). It can be seen that generally these values agree very well with those calculated with the correct statistical method. The errors are, however, generally higher by a factor of ~ 3.

The last column gives the ratio ε between the maximum and the minimum values, calculated taking into account the stated error limits. One can see that the spread of the various experimental results is often very large.

COMMENTS. -

The situation is worse than in the case of the (n, p) reaction cross sections(32). The data are fewer and many measurements have not been repeated, above all those for the high-Z elements.

It would be advisable to obtain a more complete set of experimental data to prove the existence of the observed trends. Especially, complete sets of measurements under the same experimental conditions are needed for series of isotopes or isotones to check the shell-structure effect.

Table: Experimental and averaged (n, α) cross sections

Target nucleus	E_n (MeV)	Technique	σ exp (mb)	Ref.	σ av (mb)	σ rel (mb)	ε
^{6}Li	14.1	D	26 ± 4	(79)	25.8 ± 1.5	25.8 ± 4.3	1.36
	?	?	25.8 ± 1.6	(74)			
^{9}Be	14.1	A	10 ± 1	(6,7)	10 ± 1		---
^{11}B	14.1	E	35 ± 7	(80)	32.7 ± 4.7	33.0 ± 9.4	1.50
	14.7	E	30.9 ± 6.3	(4)			
^{12}C	14.1	T	80 ± 20 g)	(42)	144 ± 45		---
	14	E	62 ± 15 g)	(2)			
	14	E	82 ± 42 m)	(2)			
^{16}O	14.1	D	290 ± 25	(14)	290 ± 25		---
^{19}F	14.18	A	15.0 ± 5.0	(73)	15 ± 5		---
^{23}Na	14.8	A	222 ± 22	(65)	149 ± 33	180 ± 36	12.2
	14.8	E	185 ± 28	(51)			
	14.18	A	172 ± 20	(73)			
	14.05	D	147 ± 18	(9)			
	14	D	29 ± 9	(12)			
^{26}Mg	14.8	A	89 ± 5	(67)	79.1 ± 6.5	81.3 ± 7.0	1.57
	14.7	A	80 ± 3	(68)			
	14.74 ± 0.20	A	66.5 ± 6.7	(17,18)			
^{27}Al	14.1	A	135 ± 10	(36)	114.8 ± 1.9	114.8 ± 11.9	2.31
	14.42 ± 0.26	A	122 ± 7	(71)			
	14.1	A	120 ± 15	(92)			
	14.5 ± 0.2	A	119.8 ± 6.0	(8)			
	14.1	D	119 ± 10	(84)			
	14.4	A	118 ± 12	(38)			
	14.6	A	118 ± 12	(30)			
	14.1	A	118 ± 5	(13)			
	14.76	A	117 ± 8	(94)			
	14	A	117 ± 8	(64)			
	14.1	A	116 ± 13	(40)			
	15.0	A	116 ± 9	(34)			
	14.24	A	116 ± 4	(23)			
	14.1	A	115 ± 10	(45)			
	14.6	A	115 ± 2	(87)			
	14.8	A	114 ± 7	(76)			
	14	A	111 ± 17	(53,54)			
	14.66	A	111 ± 2	(61)			
	14.9	A	107 ± 11	(48)			
	14.8	E	82 ± 17	(57)			
	14.5	A	78.9 ± 10	(69)			

(g) - only to the ground state
(m) - only to the metastable state.

Target nucleus	E_n (MeV)	Tecnique	σ exp (mb)	Ref.	σ av (mb)	σ rel (mb)	ε
^{30}Si	14.7 14.8 14.5	A A A	175 ± 18 123 ± 15 45.9 ± 25	(68) (52) (69)	117 ± 34	151 ± 61	9.23
^{31}P	14.7 14.5 14.5 ± 0.4 14.1 14.4 14.7 14.8 ± 0.1	A A A D A A A	153 ± 20 146 ± 29 142 ± 17 118 ± 16 117 ± 14 96.8 ± 3.5 129 ± 3	(49) (69) (72) (14) (38) (68) (95)	123 ± 8	121 ± 16	1.88
^{32}S	14.8	E	38 ± 8	(57)	38 ± 8		---
^{34}S	14.8 14.7 14.5 14.1	A A A A	165 ± 23 163 ± 12 138 ± 35 126 ± 7	(52) (68) (69) (3)	143.5 ± 10.5	142 ± 25	1.83
^{35}Cl	14.5 14.8 14.6 ± 0.2 14	A A A A	191 ± 31 122 ± 56 109 ± 17 100 ± 20	(69) (83) (66) (58)	124 ± 20	136 ± 43	3.36
^{37}Cl	14.51 ± 0.18 14.5 14.8	A A A	112 ± 12 52.4 ± 26 43.8 ± 6.9	(19) (69) (83)	70.5 ± 22.1	89.2 ± 33.5	4.69
^{40}Ar	14.1 14.7	A A	31 ± 4.6 24 ± 2	(93) (43)	25.1 ± 2.5	25.7 ± 4.4	1.62
^{39}K	14	D	83 ± 16	(11)	83 ± 16		---
^{41}K	14.5 ± 0.4 14.8 14.7 14.5 14.7 ± 0.2 14	A A A A A D	39 ± 8 33 ± 4 31.5 ± 1.5 31.4 ± 11 30 ± 12 12 ± 5	(72) (52) (68) (69) (21) (12)	28.8 ± 3.9	31.8 ± 10.2	6.71
^{44}Ca	14.8 14.5 14.5 ± 0.4	A A A	113 ± 20 35 ± 10 29 ± 6	(52) (46) (72)	54.3 ± 25.7	69.8 ± 19.5	5.79
^{45}Sc	14 14.7 14.8 14.5 ± 0.2 13.1 ÷ 15.4	A A A A ?	132 ± 25 63 ± 12 63 ± 10 56.3 ± 2.8 34 ± 3.5	(54) (21) (65) (8) (5)	61.9 ± 13.6	57.1 ± 9.5	3.08
^{48}Ti	14.1	A	39 ± 6	(93)	39 ± 6		---
^{50}Ti	14.5 14.1	A A	10 ± 2 9.4 ± 2.8	(47) (93)	9.8 ± 1.6	9.8 ± 3.5	1.85

Target nucleus	En (MeV)	Tecni que	σ exp (mb)	Ref.	σ av (mb)	σ rel (mb)	ε
^{65}Cu	14.7 ± 0.2	A	14 ± 10 g)	(21)	15.9 ± 10		---
	14.7	A	7.5 ± 2 g)	(49)			
	14.10± 0.15	A	4.8 ± 1.4g)	(17)			
	14.5	A	1.9 ± 0.6m)	(20,21)			
^{68}Zn	14.7 ± 0.2	A	18 ± 5	(21)	10.0 ± 4.4	8.9 ± 2.6	3.38
	14.05	A	7.6 ± 0.8	(10)			
^{70}Zn	14	?	11.4 ± 3.2	(62)	11.4 ± 3.2		---
^{69}Ga	14.5	A	105 ± 55	(69)	105 ± 55		---
^{72}Ge	14.4 ± 0.3	A	15.2 ± 1.5	(91)	15.2 ± 1.5		---
^{73}Ge	14.0	D	0.13 ± 0.02g)	(99)	---	---	---
	14.1 + 14.8	D	0.10 ± 0.02g)	(98)			
^{74}Ge	14	A	40 ± 8	(54)	20.0 ± 7.8	18.5 ± 6.0	5.34
	14.5	A	15 ± 6	(69)			
	14.4 ± 0.3	A	13.3 ± 1.3	(91)			
^{75}As	14	E	29 ± 3	(51)	14.3 ± 3.5	15.0 ± 3.1	5.16
	14.10±0.15	A	12.5 ± 1.5	(17,18)			
	14.5	A	12.3 ± 2.3	(69)			
	14.68±0.26	A	10.2 ± 0.7	(8)			
	14.7 ± 0.2	A	9.3 ± 3.1	(21)			
^{78}Se	14.3 ± 0.3	A	6 ± 1	(78)	6 ± 1		---
^{80}Se	14.5	A	38 ± 16	(69)	38 ± 16		---
^{79}Br	14.8 ± 0.1	A	20 ± 10	(95)	13.6 ± 1.3	14.8 ± 4.0	2.85
	14	A	18 ± 2.5	(64)			
	14.9	D	16.1 ± 2.5	(96)			
	14.7	A	15.3 ± 1.5	(97)			
	14.1	D	13.6 ± 3.5	(14)			
	14.05	A	10 ± 1.8	(10)			
	14.7 ± 0.2	A	9.2 ± 2.0	(21)			
^{81}Br	14.6	A	107 ± 20	(87)	32.6 ± 17.4	33.5 ± 12.0	57.7
	14.5	A	103 ± 20	(69)			
	14.8 ± 0.1	A	14 ± 10	(95)			
	14	A	10 ± 1	(64)			
	14.9	D	7.5 ± 1.5	(96)			
	14.7 ± 0.2	A	6.6 ± 1.4	(21)			
	14.7	A	3.2 ± 1	(97)			
^{85}Rb	14.6	A	142 ± 9	(87)	73.8 ± 67.5	82.5 ± 7.9	23.2
	14.10±0.47	A	7 ± 0.5	(18)			
^{87}Rb	14.6	A	59 ± 12	(87)	51.8 ± 9.6	55 ± 25	3.09
	14.5	A	39 ± 16	(69)			
^{88}Sr	14.6	A	87 ± 31	(87)	87 ± 31		---
	14.5	A	64 ± 20m)	(69)			

Target nucleus	E_n (MeV)	Tecnique	σ exp (mb)	Ref.	σ av (mb)	σ rel (mb)	ε
^{89}Y	14.6	A	96 ± 24	(87)	48.7 ± 29.2	18.8 ± 8.6	26.7
	14.5	A	70 ± 41	(69)			
	14.5 ± 0.2	A	5 ± 0.5	(8)			
	14.7 ± 0.2	A	0.91±0.45m)	(21)			
^{90}Zr	14.5	A	194±107 m)	(69)	---	---	---
	14.05	A	3.3±0.6 m)	(10)			
	14.1	A	3.1±0.2 m)	(22)			
	14.7 ± 0.2	A	2.8±1.3 m)	(21)			
^{92}Zr	14.68± 0.26	A	10.6 ± 0.9	(8)	10.6 ± 0.9		---
^{94}Zr	14.5 ± 0.2	A	5.5 ± 0.4	(8)	4.70 ± 0.35	4.98 ± 0.91	1.90
	14.1	A	4.9 ± 0.6	(22)			
	14	A	4.7 ± 0.8	(58)			
	14.7 ± 0.2	A	4.3 ± 1.1	(21)			
	14.05	A	3.6 ± 0.5	(10)			
^{96}Zr	14.7 ± 0.2	A	5 ± 4	(21)	2.34 ± 0.50	2.48 ± 2.05	5.00
	14	A	2.3 ± 0.5	(58)			
^{93}Nb	14.5 ± 0.2	A	9.5 ± 0.5	(8)	9.47 ± 0.48	9.47 ± 2.62	1.86
	14.7	D	9.3 ± 2.8	(55)			
	14.05	A	9.0 ± 2.2	(10)			
	14.7 ± 0.2	A	5.9 ± 2.0 g)	(21)			
	14.7	A	5 ± 2 m)	(1)			
^{92}Mo	14.7 ± 0.2	A	20 ± 8 g)	(21)	---	---	---
^{100}Mo	14.6	A	14 ± 6	(87)	15.5 ± 5.6	17.7 ± 13.0	5.00
	14.1 ± 0.2	A	25 ± 15	(33)			
^{99}Tc	14.1	?	2.02 ± 0.22	(41)	2.02 ± 0.22		---
^{104}Ru	14.7	A	2.6 ± 1.0	(44)	2.6 ± 1.0		---
^{103}Rh	14.5	A	63 ± 26	(69)	63 ± 26		---
^{108}Pd	14.05	A	2.3 ± 0.4	(10)	2.3 ± 0.4		---
^{110}Pd	14.5	A	13.8 ± 6	(69)	13.8 ± 6		---
^{109}Ag	14	A	38 ± 10	(54)	20.9 ± 12.3	19.4 ± 6.0	4.80
	14.8	A	12 ± 2	(65)			
^{106}Cd	14.1	A	100 ± 40	(93)	100 ± 40		---
^{112}Cd	14.5 ± 0.2	A	3.1 ± 0.2	(8)	2.3 ± 0.5	2.89 ± 0.58	3.30
	14.1	A	2.4 ± 0.36	(93)			
	14	A	1.3 ± 0.3	(35,58)			
^{114}Cd	14	A	0.51 ± 0.13g)	(35)	0.68 ± 0.07	0.69 ± 0.17	1.56
	14.1	A	0.5 ± 0.07g)	(93)			
	14.1	A	0.2 ± 0.03m)	(93)			
	14	A	0.13 ± 0.04m)	(35)			

Target nucleus	E_n (MeV)	Tecni que	σ exp (mb)	Ref.	σ av (mb)	σ rel (mb)	ε
^{116}Cd	14. 1	A	0.5 ± 0.5	(93)	0. 5 ± 0. 5		---
^{115}In	14. 6 ± 0. 2 14. 5 14. 05	A A A	3.0 ± 1.2 2.9 ± 0.3 2.5 ± 0.4	(66) (28) (10)	2.76 ± 0.23	2.8 ± 0.9	2. 33
^{118}Sn	14. 5 ± 0. 2	A	1.14 ± 0.08g)	(8)	---	---	---
^{124}Te	14. 8	A	3.7 ± 2	(60)	3. 7 ± 2		---
^{126}Te	14. 8	A	0.6 ± 0.3	(60)	0. 6 ± 0. 3		---
^{130}Te	14. 8 14. 5	A A	0.94 ± 0.3 0.37 ± 0.05	(60) (28)	0.46 ± 0.21	0.46 ± 0.16	2. 00
^{127}I	14. 05 14. 5	D A	1.39 ± 0.17 18.4 ± 3 m)	(9) (69)	---	---	---
^{133}Cs	14. 5 14. 7 ± 0. 2 14. 05	A A A	1.9 ± 0.2 1.0 ± 0.9 1.0 ± 0.3	(28) (21) (10)	1.60 ± 0.21	1.79 ± 1.21	21. 0
^{138}Ba	14. 1 14. 0 ± 0. 2 14. 1	A A A	13 ± 2 g) 3.6 ± 0.5g) 13 ± 2 m)	(37) (31) (37)	---	---	---
^{139}La	14. 6 14. 5	D A	3 ± 0.8 1.9 ± 0.2	(56) (28)	1.96 ± 0.26	2.05 ± 0.59	2. 24
^{140}Ce	14 14. 5 14.53 + 0.14 14. 8	? A A A	7 ± 2 12.1 ± 6 m) 11.0 ± 1.1m) 9 ± 2 m)	(86) (69) (17) (90)	7 ± 2		---
^{142}Ce	14. 8 14. 5	A A	8 ± 2 7.0 ± 0.7	(90) (28)	7.1 ± 0.7	7.1 ± 1.9	1. 67
^{141}Pr	14. 6	D	3 ± 0.5	(56)	3 ± 0. 5		---
^{142}Nd	14 14. 8 14. 8	? A A	10 ± 3 2 ± 1 g) 10 ± 2 m)	(86) (90) (90)	11.3 ± 1.8	11.4 ± 4.0	2. 03
^{146}Nd	14. 8 14. 6	A A	8.3 ± 2 2.6 ± 0.4	(90) (28)	4.7 ± 2.7	4.2 ± 1.2	4.64
^{148}Nd	14. 8	A	5 ± 1	(90)	5 ± 1		---

g) only to the ground state
m) only to the metastable state.

Target nucleus	E_n (MeV)	Tecni-que	σ exp (mb)	Ref.	σ av (mb)	σ rel (mb)	ε
^{152}Sm	14. 8 ± 0. 9 14. 5	A A	10 ± 2 8.9 ± 5	(89) (69)	9.8 ± 1.9	9.9 ± 5.9	3. 56
^{154}Sm	14. 8 ± 0. 9	A	9 ± 3	(89)	9 ± 3		---
^{153}Eu	14. 8	A	9 ± 2	(52)	9 ± 2		---
^{156}Gd	14. 5	A	3.2 ± 0.5	(28)	3. 2 ± 0. 5		---
^{160}Gd	14. 8	A	2 ± 1	(90)	2 ± 1		---
^{159}Tb	14. 1	D	2.2 ± 0.5	(56)	2. 2 ± 0. 5		---
^{162}Dy	14. 5	A	3.6 ± 0.4	(28)	3. 6 ± 0. 4		---
^{164}Dy	14. 8 14. 8	A A	4.5 ± 0.8 4 ± 1	(90) (52)	4.3 ± 0.6	4.33 ± 1.33	1. 77
^{168}Er	14. 8 14. 8	A A	0.5 ± 0.2g) 1.0 ± 0.2m)	(90) (90)	1. 5 ± 0. 3		---
^{170}Er	14. 8	A	1.0 ± 0.2	(90)	1. 0 ± 0. 2		---
^{178}Hf	14. 5	A	2.0 ± 0.2	(28)	2. 0 ± 0. 2		---
^{187}Re	14. 5	A	0.94 ± 0.14	(28)	0. 94 ± 0. 14		---
^{190}Os	14. 5 14. 6 ± 0. 2	A A	0.57 ± 0.08 0.47 ± 0.06	(28) (66)	0.51 ± 0.05	0.51 ± 0.10	1. 59
^{191}Ir	14. 5	A	2.4 ± 0.4	(28)	2. 4 ± 0. 4		---
^{193}Ir	14	A	11 ± 2	(54)	11 ± 2		---
^{194}Pt	14. 5	A	1.26 ± 0.25	(28)	1. 26 ± 0. 25		---
^{196}Pt	14. 5	A	0.55 ± 0.11	(28)	0. 55 ± 0. 11		---
^{197}Au	14. 5 14. 5 ± 0. 2	A A	0.43 ± 0.04 0.35 ± 0.02	(28) (8)	0.37 ± 0.02	0.37 ± 0.04	1. 42
^{200}Hg	14. 5	A	1.77 ± 0.35	(28)	1. 77 ± 0. 35		---
^{202}Hg	14. 5	A	1.01 ± 0.10	(28)	1. 01 ± 0. 10		---
^{203}Tl	14. 5	A	0.37 ± 0.04	(28)	0. 37 ± 0. 04		---
^{206}Pb	14. 1	A	2.7 ± 0.4	(93)	2. 7 ± 0. 4		---
^{208}Pb	14. 5	A	1.58 ± 0.25	(28)	1. 58 ± 0. 25		---
^{209}Bi	14. 5 14. 8 14. 8 14. 5	A A A A	1.2 ± 1 1.1 ± 0.3 0.6 ± 0.1 0.52 ± 0.08	(69) (76) (65) (28)	0.58 ± 0.07	0.64 ± 0.33	5. 00
^{230}Th	14. 5	A	4.6 ± 1.2	(28)	4. 6 ± 1. 2		---
^{238}U	14. 5	A	1.5 ± 0.3	(28)	1. 5 ± 0. 3		---

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