PHYSICAL REVIEW VOLUME 85, NUMBER 5 MARCH 1, 1952

The Reaction $Cl^{37}(p,n)A^{37}$; Excited States in A^{38}*

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(Received November 12, 1951)

The relative neutron yield of the reaction $Cl^{37}(p,n)A^{37}$ has been observed from the threshold, at 1641±2 kev, up to a proton energy of 2510 kev. Over 100 resonances are found; these correspond to excited states in the compound nucleus A^{38}, with an average separation of about 5 kev.

A. INTRODUCTION

THIS is the third in a series of papers on the p,n reaction on light-intermediate weight elements. By observing resonances in the neutron yield, with the best resolution which seemed practical, we have attempted to estimate level widths and level densities in several compound nuclei in the range of excitation somewhat above the neutron binding energy. In our previous work, with targets of Mn^{55},[1] and of Cr^{53} and Cr^{54},[2] the observed average level spacing was only two to three times the experimental resolution width, and it is probable that a substantial number of levels were unresolved. For the present work we have chosen Cl^{37}, which is the lightest stable isotope, above O^{18}, with a p,n reaction threshold known to be below 3.5 Mev. It was hoped that the level spacing would be substantially greater than with Mn and Cr and hence the degree of resolution more complete.

The reaction $Cl^{37}(p,n)A^{37}$ has been studied by Richards, Smith, and Browne,[3] who found the threshold to be at 1640±4 kev. They report that many resonances were found at higher energies, without giving further details. Since the completion of our work Brostrom, Madsen, and Madsen[4] have reported an investigation of the p,n, the p,γ, and the p,α reactions on Cl^{37}. Our p,n results are in good general agreement, but we find many more resonances as a result of the higher resolution which we have employed.

B. EXPERIMENTAL METHODS

The experimental conditions and procedures were similar to those described in reference 2; protons were accelerated by the Rockefeller electrostatic generator and neutrons detected by a paraffin-surrounded, BF_3 proportional counter.

Targets were prepared by evaporating NaCl onto 10-mil tantalum disks‡ which fit on our rotating target. The p,n thresholds of Cl^{35} and Na^{23} are estimated from disintegration data to lie well above 4 Mev. The highest energy covered in this work was 2.5 Mev, which is also below the p,n thresholds of the common target contaminants carbon, nitrogen, and oxygen. We therefore believe that all resonances observed should be attributed to $Cl^{37}(p,n)$.

A number of different targets were used. At first we had difficulty from gradual evaporation of the thin NaCl. By restricting proton currents to 3 μa and by cooling the back side of the target with a fine water spray we were able to operate for many hours with little deterioration of the target.

C. EXPERIMENTAL RESULTS

The neutron yield spectrum was studied over the proton energy range from 1640 (threshold) to 2510 kev, using several targets ranging from about 1.4- to 4.0-kev stopping power. Two sections of this range were examined carefully with a single thin target; the results are shown in Figs. 1 and 2. Experimental points were taken between 0.7 and 0.8 kev apart, and the entrance and exit slit widths of the 38-cm radius magnetic analyzer were set at 0.5 mm, giving an effective energy spread of the incident proton beam of about 0.8 kev.

Figure 3 shows a resonance near 1813 kev, used as a control. The solid dots and the crosses represent readings taken before and after the data reproduced in Fig. 1: the triangles were taken after the run of Fig. 2. Target deterioration and energy-scale shift due to build-up of contamination during the two runs were negligible,§ so that the data should all be consistent.

Table I lists the observed peaks. The column headed "E_r" gives the resonance energies in kilovolts, corrected for target thickness and relativistic change of mass. No particular care was taken in calibrating the energy scale of the generator for this work, so the energies may be consistently in error by as much as 0.1 percent relative to the $Li^7(p,n)$ threshold standard, which is taken to be 1882.2 kev. The absolute error of the standard itself has been estimated as 0.1 percent.[5]

Those resonances covered in Fig. 1 or Fig. 2, and a

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* This work was supported by the Bureau of Ships and the ONR.

† Lt. Commanders, U.S.N. This work was submitted in partial fulfillment of the requirements for the degree of Master of Science in Physics, at MIT by these authors.

[1] J. J. G. McCue and W. M. Preston, Phys. Rev. 84, 1150 (1951).

[2] Lovington, McCue, and Preston, Phys. Rev. 85, 585 (1952).

[3] Richards, Smith, and Browne, Phys. Rev. 80, 524 (1950).

[4] Brostrom, Madsen, and Madsen, Phys. Rev. 83, 1265 (1951).

‡ The NaCl, prepared by Johnson, Matthey, and Company, Ltd. of London and obtained through the Jarrell Ash Company of Boston, was extremely pure and certified "spectrographically standardized." The evaporation was performed by Baird Associates, Cambridge, Massachusetts.

§ It must be remarked that this degree of reproducibility is not typical; it is the most fortunate of our experience.

[5] Herb, Snowdon, and Sala, Phys. Rev. 75, 246 (1949).

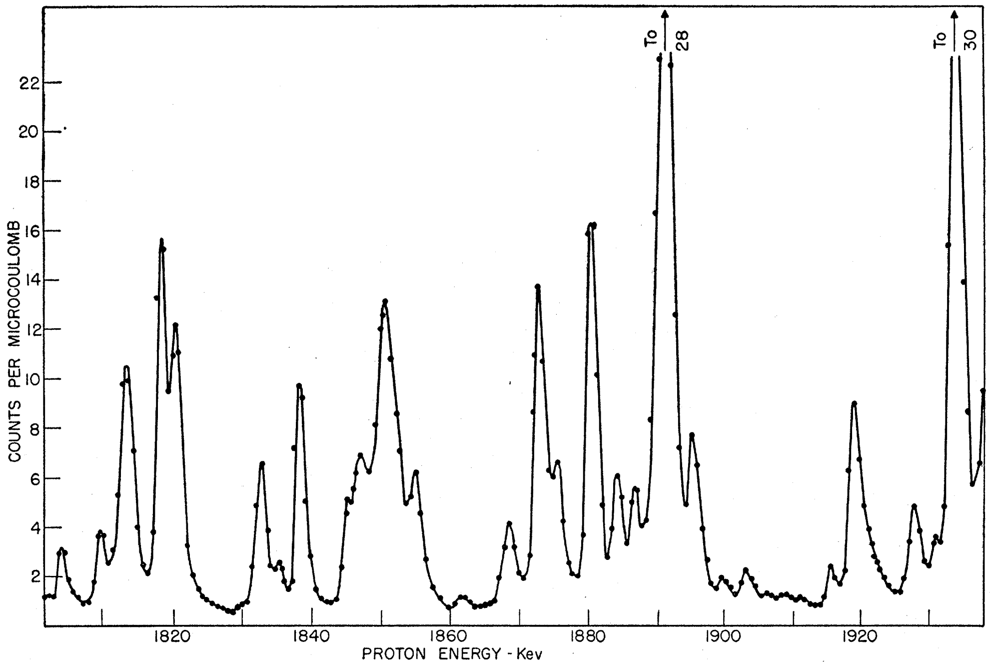

FIG. 1. Relative neutron yield from the reaction Cl^{37}-$(p,n)A^{37}$ in the range of proton energy from 1803 to 1940 kev, effective resolution 1.4 kev.

few others measured with the same target, are designated by the letter "*A*" in column 2 of Table I. All data for these resonances are more reliable than for the others. In column 3 the letters *G* (good), *M* (medium), and *P* (poor) indicate the degree of resolution of each peak from its neighbors. Column 4 gives the relative observed maximum yield Y_m at the peak of each resonance, without correction for imperfect resolution. The measured yields of resonances covered only with targets other than *A* have been adjusted to roughly the same scale as *A* in order to be comparable.

The average observed width Γ_0 of the four narrowest resonances in Fig. 1 is 1.4 kev. We have set the resolution width $\Delta=1.4$ kev at this energy. (If the natural width Γ is not negligible for these resonances, Δ may actually be somewhat less.) From the calculated energy spread in the proton beam and the variation with proton energy of energy loss in the target, Δ can be estimated for other energies. For the other targets, which were all thicker than *A*, the target thickness could be set equal to Γ_0 of any narrow resonance, with little error. Values of Δ are listed in column 5 of Table I.

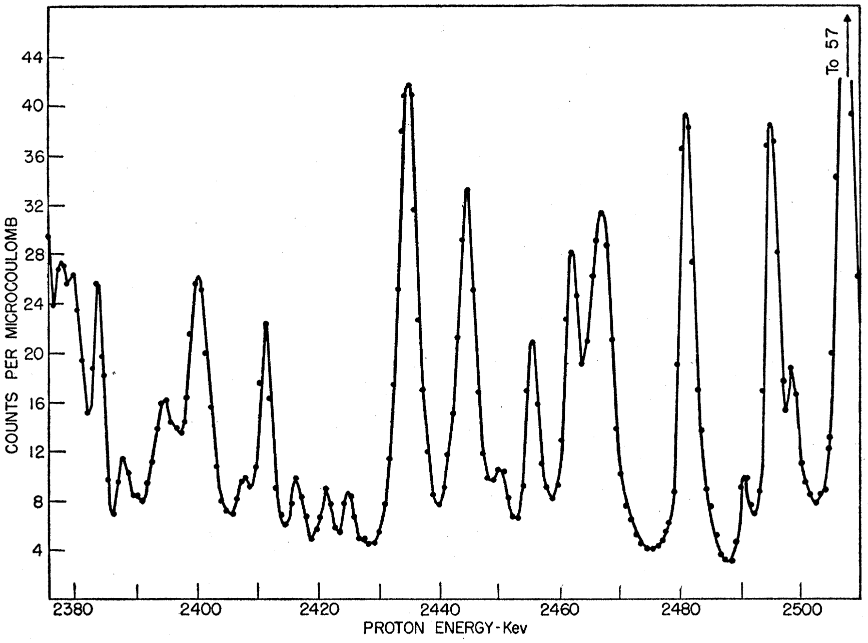

FIG. 2. Relative neutron yield from the reaction Cl^{37}-$(p,n)A^{37}$ in the range from 2370 to 2510 kev, estimated effective resolution 1.6 kev.

TABLE I. Proton energies at resonance, E_r; relative maximum yields, Y_m; and estimated natural half-widths, Γ, of resonances in A^{38} from the reaction Cl$^{37}(p,n)$A^{37}. The data for resonances marked "*A*" in column 2 are more reliable than for others. In column 3 the letters *G*, *M*, and *P* designate, respectively, good, medium, or poor resolution of a particular resonance from its neighbors. Column 5 gives the estimated experimental resolution, usually set by the finite target thickness.

(1) E_r(kev)	(2)	(3)	(4) Y_m	(5) Δ	(6) Γ	(1) E_r(kev)	(2)	(3)	(4) Y_m	(5) Δ	(6) Γ
1643.0		*G*	0.8	3.7		2063.0		*G*	17	3.0	
1654.6		*G*	0.8	3.7		2075.4		*P*	4	3.0	
1664.3		*P*	0.2	3.7		2080.3		*P*	3	3.0	
1667.7		*P*	0.2	3.7		2083.7		*P*	5	3.0	
1685.0		*M*	3.2	3.7		2088.7		*P*	25	3.0	
1690.8	*A*	*G*	7.3	1.4	1.5	2094.0		*P*	32	3.0	
1702.7		*G*	3.1	3.7		2097.8		*P*	···	3.0	
1721.5		*M*	2.1	3.7		2104.1		*P*	3	3.0	
1727.7		*M*	4.0	3.7		2112.0		*G*	25	3.0	
1733.2		*M*	5	3.7		2123.5		*P*	34	3.0	
1739.8		*P*	0.6	3.7		2128.9		*P*	34	3.0	
1745.3		*M*	12	3.7		2135.0		*P*	7	3.0	
1750.1		*P*	3	3.7		2145.7		*P*	2	3.0	
1754.5		*M*	11	3.7		2148.7		*M*	5	3.0	
1763.0		*M*	7	3.7		2158.8		*M*	7	3.0	
1772.4	*A*	*G*	10	1.4	1.6	2165.7		*M*	10	3.0	
1777.6		*M*	2.4	3.8		2172.7		*M*	9	3.0	
1783.8		*P*	0.6	3.8		2179.6		*M*	6	3.0	
1788.0		*M*	3.6	3.8		2184.6		*M*	3.4	3.0	
1794.7		*M*	3.6	3.8		2189.2	*A*	*G*	30	1.5	2.7
1803.7	*A*	*M*	3.4	1.4	<1.0	2208.6		*G*	13	3.0	
1809.3	*A*	*M*	3.4	1.4	<1.0	2214.1		*P*	3	3.0	
1812.9	*A*	*G*	10	1.4	1.6	2221.5		*M*	19	3.0	
1817.8	*A*	*M*	16	1.4	<1.0	2226.1		*M*	20	3.0	
1819.9	*A*	*M*	11	1.4	1.6	2237.1		*G*	20	3.0	
1831.8	*A*	*M*	6.5	1.4	1.3	2248.8		*P*	2	3.0	
1834.9	*A*	*P*	1.5	1.4		2255.6	*A*	*P*	···	1.6	
1837.7	*A*	*G*	9 5	1.4	<1	2259.6	*A*	*G*	70	1.6	3.5
1844.8	*A*	*P*	1.0	1.4		2265.4	*A*	*P*	5	1.6	
1846.4	*A*	*P*	5	1.4	2.2	2277.9		*M*	20	2.0	
1850.0	*A*	*M*	12	1.4	2.5	2286.6		*G*	36	2.0	
1854.2	*A*	*P*	5	1.4	2.2	2302.8		*M*	14	2.0	
1863.0	*A*	*P*	0.5	1.4		2308.0		*M*	20	2.0	
1868.0	*A*	*M*	3.5	1.4	1.6	2314.0		*M*	18	2.0	
1872.3	*A*	*M*	13	1.4	<1	2323.1	*A*	*M*	34	1.6	
1875.0	*A*	*P*	6	1.4	<1	2328.6		*M*	18	2.0	
1880.0	*A*	*G*	16	1.4	<1	2348.6		*M*	10	2.0	
1883.9	*A*	*M*	5	1.4		2355.9		*P*	6	2.0	
1885.9	*A*	*M*	4	1.4		2360.3		*M*	8	2.0	
1890.9	*A*	*G*	28	1.4	2.3	2365.2		*M*	10	2.0	
1894.7	*A*	*M*	6	1.4		2370.8		*P*	12	2.0	
1899.2	*A*	*P*	1	1.4		2374.0		*M*	24	2.0	
1902.5	*A*	*M*	1.5	1.4		2376.5	*A*	*P*	15	1.6	
1914.9	*A*	*M*	2	1.4		2378.5	*A*	*P*	15	1.6	
1918.3	*A*	*M*	8	1.4		2382.5	*A*	*M*	22	1.6	
1920.3	*A*	*P*	···	1.4		2386.5	*A*	*M*	7	1.6	
1927.3	*A*	*M*	4	1.4		2393.4	*A*	*M*	10	1.6	3.3
1933.1	*A*	*G*	30	1.4	1.5	2399.1	*A*	*M*	25	1.6	4.1
1941.0	*A*	*G*	40	1.4	2.3	2406.3	*A*	*P*	6	1.6	2.5
1946.1		*M*	13	1.1		2410.0	*A*	*M*	21	1.6	1.8
1953.3		*P*	···	1.1		2414.8	*A*	*M*	8	1.6	1.8
1955.8		*M*	6	1.1		2419.9	*A*	*M*	8	1.6	
1959.4		*M*	9	1.1		2423.4	*A*	*M*	7	1.6	
1964.2		*M*	23	1.1		2433.6	*A*	*G*	42	1.6	3.1
1979.3		*P*	19	1.1		2443.2	*A*	*G*	32	1.6	3.3
1986.1	*A*	*M*	63	1.5	3.8	2448.7	*A*	*P*	6	1.6	1.8
1990.2		*P*	12	1.1		2454.0	*A*	*M*	20	1.6	2.4
1995.9		*M*	4	1.1		2460.8	*A*	*M*	22	1.6	2.1
1999.6		*M*	12	3.0		2465.4	*A*	*M*	31	1.6	4.3
2010.1		*M*	10	3.0		2479.7	*A*	*G*	40	1.6	2.4
2017.6		*G*	22	3.0		2489.0	*A*	*M*	8	1.6	
2026.5	*A*	*G*	47	1.5	4.4	2493.5	*A*	*M*	36	1.6	2.5
2042.0	*A*	*P*	10	1.5		2496.8	*A*	*M*	10	1.6	
2045.2	*A*	*M*	30	1.5		2505.9	*A*	*G*	56	1.6	2.6
2051.6		*M*	17	3.0							

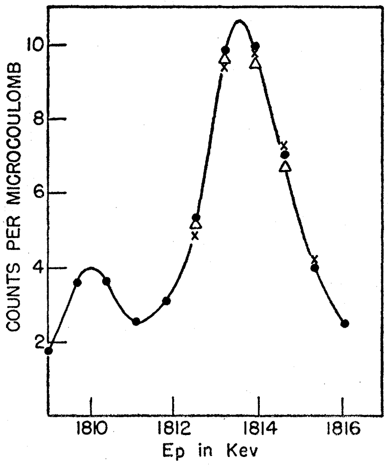

FIG. 3. A resonance near 1813 kev, used to check target deterioration and energy calibration shift. The solid dots and crosses were taken before and after the run shown in Fig. 1, the triangles after the run of Fig. 2.

Column 6 gives the natural width Γ computed from $\Gamma=(\Gamma_0^2-\Delta^2)^{\frac{1}{2}}$. In view of the approximations involved, values of Γ are not considered significant unless $\Gamma_0 \geqslant \sqrt{2}\Delta$.

Figure 4 shows the neutron yield near the p,n reaction threshold, taken with a target about 4 kev thick. An upper limit for the threshold is $E_T = 1641 \pm 2$ kev, which agrees well with the value of 1640 ± 4 kev given by Richards *et al.*[3] Below 1641 kev, the scatter in the background counting rate is within the statistical error. Clearly, the true threshold (energetically speaking) may be somewhat lower if by chance there is no intervening resonance level for the emission of neutrons with low angular momentum. This illustrates the point that reaction yield thresholds do not necessarily yield accurate Q-values; it is necessary, in addition, to measure the energy of the emitted particles. It is likewise clear from Fig. 5 that there is often no advantage in using thick targets for precise threshold determinations. The large variations in the size and separation of resonances would make it impossible in the present case to extrapolate a thick target yield-curve to zero yield.

TABLE II. Observed average level spacing, D, in A^{38}. ΔE is the energy interval in kev, N the observed number of levels, and $D=(37/38)\times(\Delta E/N)$.

Interval	ΔE	N	D(kev)	
1643–1733	90	9	9.7	
1733–1795	62	10	6.0	
1795–1846	51	10	5.0	Region of Fig. 1 (good resolution) average $D=4.9$
1846–1891	45	10	4.4	
1891–1946	55	10	5.4	
1946–2010	64	10	6.2	Poorer resolution average $D=7.1$
2010–2089	79	10	7.7	
2089–2159	70	10	6.8	
2159–2237	78	10	7.6	
2237–2323	86	10	8.4	
2323–2383	60	10	5.8	
2383–2443	60	10	5.8	Region of Fig. 2 (good resolution) average $D=6.3$
2443–2506	63	9	6.8	
1643–2506	863	128	6.5	

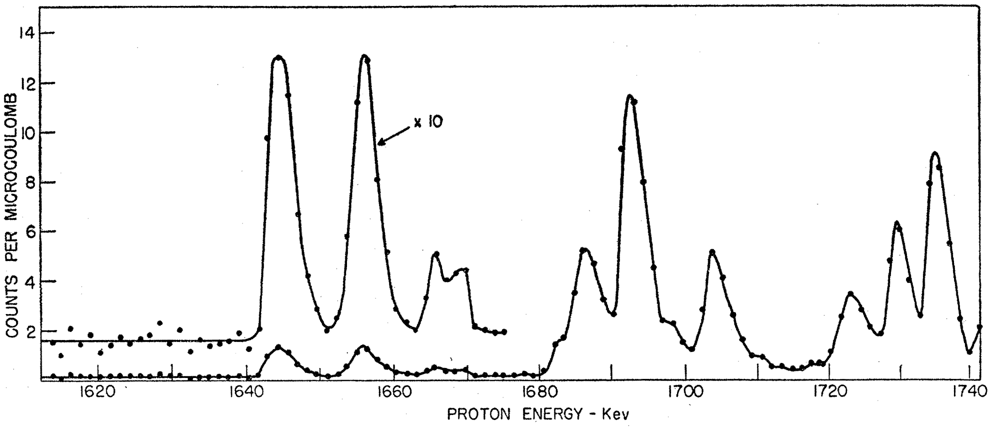

FIG. 4. Neutron yield from $Cl^{37}(p,n)$-A^{37} near the reaction threshold. The threshold is at 1641 ±2 kev, relative to the $Li(p,n)$ threshold taken as 1882 kev.

D. DISCUSSION

Table II gives the average observed level spacing, D, for successive groups of 10 levels each. The fluctuations are probably partly statistical and partly experimental. In general, two adjacent resonances will be counted as one unless their separation is equal to or greater than the observed width Γ_0 of the narrower resonance. The fraction of the total number missed will be some function of Γ_0/D. The average observed value of D is 4.9 kev for 30 levels in Fig. 1 (mean proton energy 1870 kev) and 6.3 kev for 19 levels in Fig. 2 (mean proton energy 2440 kev); both these regions were covered carefully and with approximately equal resolution, but the average value of Γ_0 of peaks in the higher energy region is greater. The average D for 60 levels in between is 7.1 kev, in a region covered with poorer resolution. It seems likely, therefore, that a value $D \sim 5$ kev is closer to the true average for the whole region covered than the observed value of 6.5 kev.

In the region 2370–2510 kev, of Fig. 2, the natural widths of the broadest resonances are significantly greater than the experimental resolution, and run from 3 to 4 kev. The partial width for emission of a particle a with angular momentum l may be expressed as $\Gamma_a^l = T_a^l(D_J/2\pi)$, where T_a^l is the centrifugal and Coulomb barrier penetration factor and D_J is a nuclear factor related to the average spacing between levels in the compound nucleus of spin J and the same parity. The widest levels observed will involve neutron emission with $l=0$; for these levels, the total half-width $\Gamma \approx \Gamma_n^0$, since the penetration factor for $l=0$ neutrons is considerably larger than for $l=0$ protons or α-particles, and Γ_γ is negligible. At $E_p=2440$, neutrons emitted to the ground state of A^{37} have an energy $E_n=780$ kev, and $T_n^0=0.55$.[6] If we set $\Gamma_n=3.5$ kev, the experimental value,

$$D_J \approx (2\pi\Gamma_n/T_n^0) = 40 \text{ kev}.$$

The number of states which may be formed by protons of $l=0$, 1, or 2 with the Cl^{37} nucleus ($I=\frac{3}{2}$), and differing in J and parity, is 9. If there is any significance in so literal an interpretation of the quantities D, our result that $D_J/D \approx 8$ indicates that the observable resonances from which D has been computed include those formed by protons up to $l=2$. This is reasonable on the basis of calculated values for the barrier penetration factors, which indicate that transitions from states formed by $l=3$ protons should be unobservably weak under our experimental conditions.

The result that the average level spacing in A^{38} is about 5 kev may be compared with data for Mn^{54}, Mn^{55}, and Fe^{56}, shown in Fig. 6 of reference 2. The binding energy of a proton in A^{38} is 10.14 Mev.[7] Our value of $D=5$ kev is averaged over a small region 1.80 Mev above the proton binding energy. The excitation energy in A^{38} is therefore 11.94 Mev above the ground state, or 9.75 Mev above the reference level "R" from which the excitation energy should more properly be measured, according to Hurwitz and Bethe.[8] If we measure excitation energy from "R," the regions investigated in A^{38} and in Mn^{55} and Fe^{56} are rather closely comparable. The observed level spacing is about the same, whereas one would expect the two heavier nuclei to have a much smaller level spacing. It is possible that Mn^{55} and Fe^{56}, since they have only two more neutrons than the closed shell of 28, have smaller level densities than might otherwise be expected. Alternatively, our estimates of D for the heavier nuclei may have been considerably too large because of the less favorable ratio of resolution width to natural width.

We wish to express our appreciation to Mr. Donald Thompson and to Mr. I. E. Slawson for their invaluable aid with the Rockefeller generator.

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[6] From curves in *Report of the Fast Neutron Data Project*, Nuclear Development Associates, by B. T. Feld *et al.*, January 31, 1951. We assume a nuclear radius $R=1.5A^{\frac{1}{3}}\times 10^{-13}$ cm.

[7] Calculated from $Cl^{37}+n\rightarrow Cl^{38}+6.11$ Mev [Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 481 (1950)] and $Cl^{38}\rightarrow A^{38}+4.81$ Mev [L. M. Langer, Phys. Rev. **77**, 50 (1950)].

[8] H. Hurwitz and H. A. Bethe, Phys. Rev. **81**, 898 (1951).