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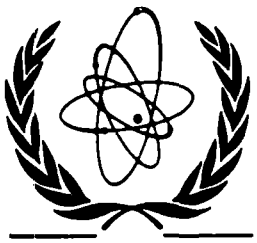

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# THE CHARACTERISTICS OF PHOTO-ACTIVATION OF LIGHT ELEMENTS

M.G. Davydov, A.P. Naumov, V.A. Shcherbachenko

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# THE CHARACTERISTICS OF PHOTO-ACTIVATION OF LIGHT ELEMENTS

M.G. Davydov, A.P. Naumov, V.A. Shcherbachenko

The present level of development of photo-activation analysis, the broadening of its range of applications, and in particular the proliferation of calculational techniques used in the development of practical methods has necessitated a systematization of the available reference material. There is as yet no reference book on photo-activation analysis. Even the most exhaustive published tables [1, 2] merely enable the user to evaluate the main possibilities of the photo-activation method; they do not give a full set of nuclear physical constants, especially on the photonuclear reaction cross-sections needed to develop practical methods.

That is why the authors undertook the analysis and systematization of nuclear physical constants for photo-activation analysis [3, 4]. This paper presents material on the photo-activation of light elements, which were chosen because light nuclei have a distinct fine structure in the photonuclear reaction cross-sections. They are of particular interest in photo-activation analysis because they are difficult to determine by neutron activation methods.

The collected material set out in the Table is identified as follows: Type I reaction means ($\gamma$, n) reactions, Type II ($\gamma$, p), Type III ($\gamma$, pn), Type IV ($\gamma$, 2n), Type V ($\gamma$, 2p) and Type VI ($\gamma$, d) reactions. The following limiting considerations have been observed: the abundance of the irradiated element is $\geq 1\%$, the half-life of the photo-activation products is $10^{-6}\text{s} \leq T_{\frac{1}{2}} \leq 10^{7}\text{s}$ and the intensity of $\beta$- and $\gamma$- radiation is $\geq 1\%$. The columns of the Table are combined in three groups.

The first group (column 1) describes the properties of those isotopes of the irradiated element that produce radioactive isotopes as a result of photo-activation.

The second group (columns 2-5) describes the properties of the photo-activation products. In column 2 the type of reaction (Roman numeral in brackets), the element symbol, the mass number of the isotope and the half-life are indicated. Isomers are identified by the letter "m". Columns 3-5 show the radiation energy and the radiation yield (in brackets) for electrons, $\gamma$-quanta and positrons, respectively. The yield is expressed in terms of per cent of total decay; in those cases where the yield information is underlined, it is given in units relative to a given $\gamma$-line.

The third group (columns 6-9) describes the photo-activation cross-section parameters: $E_{thresh}$ is the reaction threshold, $E_m$ the energy of the resonance peak, $\sigma_m$ the cross-section at the resonance peak, and $\Gamma$ the resonance width at half height. If an activation product obtained from the ($\gamma$, p) or ($\gamma$, n) reaction on the original isotope can also be obtained from another stable isotope by means of the more complex reactions ($\gamma$, pn), ($\gamma$, 2p) or ($\gamma$, d), then column 1 shows (in brackets and next to the corresponding activation product) this isotope and the type of reaction leading to interference; column 6 shows the threshold of the reaction (in brackets).

The abundance of stable isotopes and the spectroscopic data on the photo-activation products were entered in the Table after adaptation of the information in the references [5-7].

The photonuclear reaction thresholds were either taken from the experimental data of Ref. [8], or, in the absence of such data, determined from the masses given in Ref. [9].

The experimental information on photonuclear reaction cross-sections for various elements was taken from the literature, as follows: Li [10]; Be [11]; C [12-15]; N [16]; O [12, 17-19]; F [18]; Mg [8, 20]; Al [21]; Si [8, 21]; P [8]; S [21]; Cl, Ar [8] and K [22].

Proceeding from the photonuclear reaction theory that the cross-sections of light nuclei consist of a superposition of resonances, we have made an approximation of the experimental cross-section data having a fine structure by means of a summation of Lorentz curves. The calculations were performed on a computer by the least squares method. For carbon and oxygen the cross-sections approximated were values averaged from the data of various authors. The results of the approximation are given in the Table. The mean relative deviation of the experimental points from the approximations obtained does not exceed 20%.

Analysis of the table shows that 15 of the 19 light elements (excluding H, He, B and Na) can be reliably determined by the photo-activation method.

Photo-activation of Li and Be produces pure electron emitters with short half-lives ($T_{\frac{1}{2}} < 1$ s), which makes it very difficult to determine them by photo-activation.

The rest of the light elements can conveniently be divided into two groups according to the half-life of the photo-activation products:

(1) $T_{\frac{1}{2}} \leq 110$ min: C, N, O, F, Ne, Mg, Si, S, P, Cl, Ar, K;

(2) $T_{\frac{1}{2}} < 20$ s: Ne, Mg, Al, Si, P, S, Cl.

Almost all light elements belong to the first group. Determinations of Ne and S in the presence of F and P, respectively, are impossible because of interfering reactions with lower thresholds.

The determination of elements from the second group has not been mastered yet because of technical difficulties. If this time range could be mastered, the scope of photo-activation for determining light elements would be enlarged considerably.

The Table shows that most photo-activation products are positron emitters. This creates certain practical problems in photo-activation determination of elements from annihilation radiation, especially in the case of pure positron emitters.

In conclusion it should be noted that we now know the characteristics of the main body of cross-sections for photonuclear reactions in light nuclei that are of practical interest in photo-activation analysis. Thus, calculational techniques can be used to develop practical methods of photo-activation determination of light elements.

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TABLE OF PHOTOACTIVATION PARAMETERS

| Isotope (Content %) | Reaction Type, Isotope, $T_{\frac{1}{2}}$ | $E_{\beta-}$ (KeV) | $E_{\gamma}$ (KeV) | $E_{\beta+}$ (KeV) | $E_{thresh}$ (MeV) | $E_m$(MeV) | σ(mb) | Γ (MeV) |
|---|---|---|---|---|---|---|---|---|
| $^{7}Li$ (92,58) | (II) $^{6}He$ | 3507(100) | | | 9,98 | 11,0 | 0,59 | 0,85 |
| | 0,80 sec | | | | | 13,7 | 1,23 | 1,72 |
| | | | | | | 15,5 | 1,15 | 1,19 |
| | | | | | | 17,9 | 1,32 | 1,87 |
| | | | | | | 21,7 | 1,31 | 1,73 |
| | | | | | | 25,0 | 0,91 | 1,96 |
| | | | | | | 27,0 | 0,38 | 1,49 |
| $^{9}Be$ (100) | (II) $^{8}Li$ | 13000(89) | | | 16,88 | 24,4 | 2,4 | 13,2 |
| | 0,847 sec | | | | | | | |
| $^{12}C$ (98,89) | (I) $^{11}C$ | | 511,(199,6) | 968,(99,8) | 18,72 | 22,1 | 6,26 | 1,60 |
| | 20,74 min | | | | | 29,9 | 0,66 | 0,21 |
| | | | | | | 23,5 | 6,24 | 1,78 |
| $^{13}C$ (1,108) | (II) $^{12}C$ | 13373(97) | 4430(1,3) | | 17,53 | | | |
| | 0,02 | | 3230(1,5) | | | | | |
| $^{14}N$ (99,63) | (I) $^{13}N$ | | 511(200) | 1190(100) | 10,55 | 13,2 | 0,70 | 1,59 |
| | 9,96 min | | | | | 15,3 | 0,70 | 0,20 |
| | | | | | | 20,0 | 1,40 | 4,04 |
| | | | | | | 23,2 | 3,26 | 2,70 |
| $^{16}O$ (99,76) | (I) $^{15}O$ | | 511(200) | 1730(100) | 15,67 | 17,3 | 3,54 | 0,20 |
| | 123 sec | | | | | 19,0 | 1,30 | 0,38 |
| | | | | | | 19,4 | 1,30 | 0,44 |
| | | | | | | 21,0 | 2,72 | 0,68 |
| | | | | | | 22,3 | 9,87 | 0,67 |
| | | | | | | 23,1 | 4,57 | 0,64 |
| | | | | | | 24,1 | 7,62 | 0,82 |
| $^{19}F$ (100) | (I) $^{18}F$ | | 511(194) | 649(97) | 10,44 | 12,4 | 4,03 | 0,25 |
| ($^{20}Ne$ III) | 109,9 min | | | | (21,06) | 14,0 | 1,76 | 3,79 |
| | | | | | | 16,1 | 1,85 | 1,50 |
| | | | | | | 19,3 | 2,19 | 2,40 |
| | (IV) $^{17}F$ | | 511(200) | 1748(100) | 19,58 | | | |
| | 66,6 sec | | | | | | | |
| $^{20}Ne$ (90,92) | (I) $^{19}N$ | | 511(200) | 2240(100) | 16,87 | | | |
| | 17,43 sec | | | | | | | |
| $^{22}Ne$ (9,21) | (II) $^{21}F$ | 5400 | 345(0,13) | | 15,27 | | | |
| | 4,35 sec | | 1380(1,00) | | | | | |
| | (III) $^{20}F$ | 5420(100) | 1629(100) | | 21,15 | | | |
| | 11,56 sec | | | | | | | |
| $^{24}Mg$ (78,6) | (I) $^{23}Mg$ | | 440(9,1) | 2640(9,1) | 16,53 | 16,8 | 0,80 | 0,21 |
| | 12,1 sec | | 511(181,8) | 3099(90,9) | | 17,2 | 4,20 | 0,20 |
| | | | | | | 18,3 | 4,36 | 0,30 |
| | | | | | | 18,8 | 6,58 | 0,55 |
| | | | | | | 19,0 | 8,00 | 0,12 |
| | | | | | | 20,0 | 7,70 | 0,78 |
| | | | | | | 20,8 | 3,72 | 0,64 |
| | | | | | | 23,3 | 5,00 | 2,0 |
| $^{25}Mg$ (10,11) | (II)$^{24}Na$ | 6000 | 472 | | 12,53 | | | |
| ($^{26}Mg$ III) | 0,020 sec | | | | (21,01) | | | |
| | (II)$^{24}Na$ | 1389(100) | 1368(100) | | 12,06 | 20,5 | 27,0 | 3,2 |
| | 14,95 h | | 2754(100) | | (20,94) | | | |
| $^{26}Mg$ (11,29) | (II)$^{25}Na$ | 2600(6,5) | 370(9,5) | | 14,12 | 22 | 25 | 2,5 |
| | 60 sec | 3150(28,5) | 580(9,5) | | | | | |
| | | 4000(65) | 980(9,5) | | | | | |
| | | | 1610(6,5) | | | | | |

TABLE OF PHOTOACTIVATION PARAMETERS

| Isotope (Content %) | Reaction Type, Isotope, $T_{\frac{1}{2}}$ | $E_{\beta^-}$ (KeV) | $E_\gamma$ (KeV) | $E_{\beta^+}$ (KeV) | $E_{thresh}$ (MeV) | $E_m$ (MeV) | σ (mb) | Γ (MeV) |
|---|---|---|---|---|---|---|---|---|
| $^{27}Al$ (100) | (I) $^{26m}Al$ | | 511(200) | 3208(100) | 13,07 | 16,6 | 0,39 | 2,00 |
| ($^{28}Si$ III) | 6,37 sec | | | | (23,42) | 20,2 | 8,06 | 4,88 |
| | | | | | | 21,9 | 0,36 | 2,31 |
| | | | | | | 24,8 | 4,70 | 6,13 |
| $^{28}Si$ (92,18) | (I) $^{27}Si$ | | 511(199,6) | 3850(99,3) | 17,18 | 18,8 | 9,84 | 1,48 |
| | 4,22 sec | | | | | 19,7 | 11,59 | 0,48 |
| | | | | | | 20,8 | 14,66 | 0,55 |
| | | | | | | 21,8 | 8,67 | 1,58 |
| | | | | | | 23,6 | 5,00 | 1,00 |
| | | | | | | 24,8 | 5,50 | 1,61 |
| | | | | | | 25,8 | 3,60 | 0,16 |
| | | | | | | 26,5 | 5,40 | 0,70 |
| | | | | | | 27,4 | 21,90 | 0,24 |
| | | | | | | 28,7 | 11,35 | 0,90 |
| $^{29}Si$ (4,71) | (II) $^{28}Al$ | 2878(100) | 1780(100) | | 12,33 | 20,5 | 33,0 | 7,9 |
| ($^{30}Si$ III) | 2,31 sec | | | | (20,73) | | | |
| $^{30}Si$ (13,51) | (II) $^{29}Al$ | 1500(94) | | | 13,51 | 21,5 | 31,0 | 6,1 |
| ($^{31}P$ V) | 6,56 min | 2500(94) | 2430(6) | | (?) | | | |
| $^{31}P$ (100) | (I) $^{30}P$ | 511(199) | 511(199) | 3240(99,5) | 12,31 | 19,3 | 18 | 7,5 |
| ($^{32}S$ III) | 2,5 min | | | | (21,72) | | | |
| $^{32}S$ (95) | (I) $^{31}S$ | | 511(199,8) | 3120(1,1) | 15,08 | 17,7 | 6,40 | 2,05 |
| | 2,61 sec | | 1270(1,1) | 4390(98,9) | | 19,2 | 10,60 | 0,75 |
| | | | | | | 20,5 | 7,18 | 1,28 |
| | | | | | | 21,7 | 11,05 | 0,61 |
| | | | | | | 23,0 | 9,09 | 0,63 |
| | | | | | | 24,0 | 6,84 | 0,72 |
| | | | | | | 25,0 | 6,95 | 0,55 |
| | | | | | | 26,0 | 7,95 | 1,08 |
| | | | | | | 27,5 | 7,00 | 1,50 |
| $^{34}S$ (4,22) | (II) $^{33}P$ | 249(100) | | | 10,89 | | | |
| ($^{37}Cl$ VI) | 24,6 days | | | | (7,86) | | | |
| | (III) $^{32}P$ | 1707,6(100) | | | 18,76 | | | |
| | 14,29 days | | | | | | | |
| $^{35}Cl$ (75,53) | (I) $^{34m}Cl$ | | 145(46) | 1330(27) | 12,79 | 19 | 18 | 5 |
| | 31,99 min | | 511(200) | 2480(27) | | | | |
| | | | 1170(13,5) | | | | | |
| | | | 2140(40,5) | | | | | |
| | | | 3320(13,5) | | | | | |
| | (I) $^{34}Cl$ | | 511(200) | 4460(100) | 12,57 | 19,9 | 16,0 | 6,25 |
| | 1,56 sec | | | | | | | |
| $^{37}Cl$ (24,47) | (III) $^{35}S$ | 167,6(100) | | | 16,06 | | | |
| | 87,9 days | | | | | | | |
| $^{40}Ar$ (99,6) | (II) $^{39}Cl$ | 1910(85) | 246(44) | | 12,52 | 23,5 | 67 | 5 |
| | | 2180(8) | 1266(52) | | | | | |
| | 55,5 min | | | | | | | |
| | (III) $^{38m}Cl$ | | 660(100) | | 19,03 | | | |
| | 0,74 sec | | | | | | | |
| | (III) $^{38}Cl$ | 1110(31) | 1642(31) | | 18,37 | 27,0 | 21,0 | 6,0 |
| | | 2770(16) | 2167(47) | | | | | |
| | 37,29 min | 4810(53) | | | | | | |
| $^{39}K$ (93,22) | (I) $^{38}K$ | | 511(200) | 5170(100) | 13,20 | 20 | 12 | 3,5 |
| | 0,95 sec | | | | | | | |
| | (I) $^{38}K$ | | 511(198) | 2680(99) | 13,08 | 20 | 11 | 3,5 |
| | 7,71 min | | 2170(100) | | | | | |