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NUCLEAR DATA FOR PROTON ACTIVATION ANALYSIS.

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Abstract: The activation analysis with charged particles (ChPAA), as well as proton activation analysis (PAA), mainly requires separately irradiation of thick (thicker than the range of particles) samples and standard. Therefore for simplicity of determination of traces of chemical elements by instrumental PAA the absolute activity of the radionuclides must be known. Consequently we compilated data for nuclear decays (half life, radiation energy and intensity, type of decay, saturation factor), for nuclear reactions (excitation function, threshold energy, Q-value, yields of ralionuclides), for the element under study (natural isotopic abundance of the nuclide, which yields the nuclear reaction considered, molar mass), stopping power of the irradiated material and the range of the particle that are used in the calculation of the absolute activity of the radionuclides and for the resolution of a nuclear interference problems of PAA. These data are tabulated. The tables of the radionuclides are presented in dependence on increasing atomic number and radiation energy as well as on methods of the radionuclide formation. The thick target yields of analytical radionuclides are presented versus particle energy.

1. INTRODUCTION

Activation analysis is a promising method and holds one of the leading positions among other methods. The most widely used version of nuclear methods, neutron activation analysis (NAA), makes it possible to determine the content of medium weight and heavy elements in quite small samples at the level of 10^{-6} -10^{-12} g. Using this method, however, all the light elements and some others with $Z \geq 10$ can not be determined with sensitivity required. Therefore in solving some special problems on determination of concentration and distribution patterns of light elements in pure materials, on analysis of different objects which are not "convenient" for NAA by their nuclear properties now more often are used activation methods employing charged particle accelerators. Activation analysis with accelerated charged ions, to some extent, bridges gaps in this area [1,2].

Basic analytic characteristics of activation analysis with charged particles depends on a number of physical characteristics of nuclear reactions used, of a particular radionuclide produced, on the effect of interfering reactions. In solving of a particular analytical problem first of all a comparison of capabilities of existing methods is made and the most suitable of them is chosen. It can only be made if sufficiently reliable, precisely measured nuclear data are available. Such data are needed in assessing analytical capabilities of the method (its sensitivity, limit of element determination), in choosing optimal experimental conditions in

order to achieve maximum sensitivity and accuracy, in handling experimental data obtained, in simplifying activity measurements and identifying the radionuclide, in excluding the application of radiochemical method of separation of irradiated samples, and so on. Therefore there was a real need for a handbook covering reference data for activation analysis with charged particles.

Currently available handbook on activation analysis do not involve the full data for activation analysis with charged particles, in particular, for proton-activation analysis (PAA) [3]. Neither do cover this gap existing handbooks on nuclear physics [4,5]. Besides, a specialist whose activity is related to activation analysis does not need in extensive reference material necessary for basic research in nuclear physics. Therefore we have compilated in this book the nuclear data necessary for PAA as such and in so doing we were guided by the principle of maximum simplification of analyst-experimenter's task. All the necessary data are presented in the form convenient for use.

2. PROTON INDUCED NUCLEAR REACTIONS

Activation analysis is based on inducing radioactivity in the target as a result of nuclear reactions. Applicability of a given nuclear reaction for solving analytical problems can be evaluated by its cross sections, threshold energies, by the yields of radionuclides produced, by the contributions of the interfering reactions producing the same radionuclides. When protons with initial energies of 10 to 12 MeV are used the number of reaction channels is small [6]. In this case the (p,n), (p,2n), (p,γ), (p, α) reactions are recommended as analytical ones. Because of resonant nature of the (p,γ) reaction and the fact that the Coulomb barrier is too difficult for α-particle to overcome (especially when Z >20), the (p,γ), (p, α) and (p, αn) reactions are used quite seldom. Therefore PAA mainly uses the (p,n) reaction, while the (p,α) reaction is used in quite a few cases for determination of the light element contents in samples (e.g. that of nitrogen). Increasing the proton energy over 10 MeV makes it possible for the (p,2n), (p,d), (p,pn), (p,3n) etc to occur that increases the probability of production of the interfering radionuclides. For this reason in order to suppress the probability of interfering reaction the initial proton energy is chosen in the range of 10 to 14 MeV. In so doing what should be taken into account is the possibility of production of the radionuclide in question in the neighboring elements through the reactions of the (p,γ), (p,α), (p, αn), (p,pn), (p,d) types. Thus, the initial proton energy of about 10 to 12 MeV is more suitable for PAA.

3. BASIC EQUATIONS OF ACTIVATION ANALYSIS WITH CHARGED PARTICLES

In passing through a thick (R<x) target the charged particle may interact with a nucleus at any point of its path, at which its kinetic energy is E(x). As the particle advances deeper into the material its energy decreases gradually. For calculations of nuclear interaction probability it is of importance to know to what energy the particle has slowed down by the moment of nuclear interaction, i.e. to take into account its energy losses in the target material. In such a case the number of nuclear transformations per second taking place in an infinitesimally thin layer Δx at the depth of x is obviously equal to :

$$\frac{d^2N}{dtdx} = F(x)n\sigma(x), \qquad (1)$$

where σ(õ) is the cross section of nuclear interaction at the depth x from the surface of the material being irradiated, F(x) is the particle flux at the same depth which practically does not change until particles stop; n - concentration of target nuclei. If x<<R, i.e. the energy of the particle does not practically change, then

$$\frac{\Delta N}{\Delta t} = Fn\sigma\Delta x \qquad (2)$$

The total number of interactions in a thick layer of the material (when x ≥R) can be obtained by integrating (2):

$$\frac{dN}{dt} = \int_0^R F(x)n\sigma(x)dx = Fn\int_0^R \sigma(x)dx \qquad (3)$$

The fraction of particles that have had a nuclear interaction is called nuclear reaction yield Y:

$$Y(E) = \frac{dN}{Fdt} = n\int_0^R \sigma(x)dx \qquad (4)$$

Nuclear reaction yield is a physical quantity that readily illustrates the analytical capabilities of the activation analysis. In this book radionuclide yields are used as basic nuclear data for PAA.

If a radionuclide is produced as the result of nuclear interaction, then the decay of unstable nuclei should be taken into account. In activation analysis the content of chemical elements is determined by the number of decays of radionuclides produced which is usually determined via "off-line" measurements of their activity. In the course of target irradiation, accumulation of radionuclides and at the same time their decay take place. Therefore the equations mentioned above should be corrected for these factors taking account of saturation and decay;.

$$\frac{d^2N_{act}}{dtdx} = F(x)n\sigma_{act}(x) - \lambda N_{act} \qquad (5)$$

where σ_{act}- activation cross section. Here

$$n = \frac{m_x\theta N_A}{m_0 M_x} = \zeta_x\theta N_A M_x^{-1},$$

where m_x -the mass of the element being determined in the material with mass m_0; θ – the natural abundance of the target isotope, Mx -molecular weight of the element being determined; ζ_x -the weight fraction of admixture in the material being analyzed.

If the distribution of particles in the flux and that of the element being study within the sample are not homogenous, then in (5) n(x) should be used instead of n. We will consider the case when $F(x) \approx$ const and $n(x) \approx$ const. In this case the number of radioactive nuclei accumulated in the target during the irradiation time interval t_{irr} can be found by integrating Eq.(5) over the range:

$$N_{act} = Fn\left(\frac{1-e^{-\lambda t_{irr}}}{\lambda}\right)\int_0^R \sigma(x)dx \qquad (6)$$

If measurement of the activity is carried out during detection time t_{det} then the decay rate A can be found as follows.

$$A = \frac{N_{act}}{t_{det}} = Fn(1-e^{-\lambda t_{irr}})(1-e^{-\lambda t_{det}})\int_0^R \sigma(x) \qquad (7)$$

If the measurement is carried out t_{dis} after irradiation, then disintegration rate of the radionuclide is given by

$$A = Fn(1-e^{-\lambda t_{irr}})(1-e^{-\lambda t_{det}})e^{-\lambda t_{dis}}\int_0^R \sigma(x)dx \qquad (8)$$

Equation (8) is a generally accepted equation of activation analysis. Evidently, in activating thin samples it takes the form:

$$\Delta A = Fn(1-e^{-\lambda t_{irr}})(1-e^{-\lambda t_{det}})e^{-\lambda t_{dis}}\sigma\Delta x \qquad (9)$$

where F is expressed in sec^{-1}; σ -cm^2; n -mg^{-1}; x -mg/cm^2; t -min; λ -min^{-1}. In ChPAA a concept of "thin target yield" is introduced and it is expressed in units of $\frac{Bk}{\mu A * min * mg/cm^2}$:.

$$\delta(x) = \frac{1}{\left(\frac{1-e^{-\lambda t_{irr}}}{\lambda t_{irr}}\right)It_{irr}}\frac{\Delta A}{\Delta x} \qquad (10)$$

where δ, on the other hand, can be presented in the form

$$\delta(x) = \frac{F}{I}n\lambda\sigma = 6.25 10^{12} n\lambda\sigma \qquad (11)$$

Here $F=6.25*10^{12}I$; I -the particles current, μÀ.

For a given reaction $\delta(x)$ is a constant that defines analytical applicability of the reaction since it provides direct information on the activity of the radionuclide in question induced in irradiating 1 mg/cm^2 thick sample during 1 min with current of
1 μÀ.

Equation for activation thin samples will now take the form.

$$\Delta A = It_{irr}\zeta_X\sigma(x)\Delta x\left(\frac{1-e^{-\lambda t_{irr}}}{\lambda t_{irr}}\right)\left(1 - e^{-\lambda t_{det}}\right)e^{-\lambda t_{dis}} \qquad (12)$$

In activating thick samples in each elementary layer the values of $\delta(x)$ should be taken into account. Integration of $\delta(x)$ over the range of x, where activation of the sample and production of the analytical radionuclide take place, gives for the yield of the radionuclide for the thick sample

$$Y = \int_0^x \delta(x)dx \qquad (13)$$

If $x \geq R$, then $x=R_0 - R_{th}$ (where R_0 is the range of a particle with initial energy E_0; R_{th} is that for a particle with $E=E_{th}$). In such a case the yield of the radionuclide from the thick sample is given by [8]

$$Y = 6.25*10^{12}\, n\lambda \int_{R_0}^{R_{th}} \sigma(x)dx \qquad (14)$$

Evidently, if $x<<R$, integration is carried out over the range of x. For this case it follows

$$Y = \frac{1}{\left(\frac{1-e^{-\lambda t_{irr}}}{\lambda a_{irr}}\right)It_{irr}} \int_0^x \frac{dA}{dx}dx = \frac{A}{\left(\frac{1-e^{-\lambda t_{irr}}}{\lambda t_{irr}}\right)It_{irr}} \qquad (15)$$

The basic equation of activation can be derived for the thick target.

$$A = \zeta_X Y It_{irr}\frac{I_m}{I_x}\left(\frac{1-e^{-\lambda t_{irr}}}{\lambda t_{irr}}\right)\left(1 - e^{-\lambda t_{det}}\right)e^{-\lambda t_{dis}} \qquad (16)$$

In practice it is difficult to provide identical conditions for irradiation both the sample and the standard. Quite often the thickness of the sample and the standard differ resulting in considerably different yields and demanding careful analysis of experimental data.

4. NUCLEAR DATA FOR PROTON ACTIVATION ANALYSIS

The following data ChPAA are required:

1. Excitation functions or cross sections of nuclear reactions;
2. Yields of both shortliving and longliving radionuclides;
3. Characteristics of radionuclides - half lives, energies and yields of x- and γ-rays;
4. Ranges of a particle in media;

Consequently we compilated data for nuclear decays (half life, radiation energy and intensity, type of decay, saturation factor), for nuclear reactions (excitation function, threshold energy, Q-value, yields of ralionuclides), for the element

under study (natural isotopic abundance of the nuclide, which yields the nuclear reaction considered, molar mass), stopping power of the irradiated material and the range of the particle that are used in the calculation of the absolute activity of the radionuclides and for the resolution of a nuclear interference problems of PAA. These data are tabulated. The tables of the radionuclides are presented in dependence on increasing atomic number and radiation energy as well as on methods of the radionuclide formation. The thick target yields of analytical radionuclides are presented versus particle energy.

In underenumerated cutting out tables the examples of the presentation of the nuclear data are showed.

In Table 1 characteristics of 83 chemical elements are presented.

In Table 2 the threshold energies of proton induced nuclear reactions and the production of radionuclides for all the isotopes and chemical elements are given.

In Table 3 the radionuclides arranged in increasing order of their atomic numbers in proton induced reactions on all the isotopes of chemical elements are tabulated [9].

In Table 4 the radionuclides arranged in increasing order of their half lives from 0.13 sec to 13.2 year are presented.

In Table 5 the radionuclides arranged in ascending order of energy of their γ–rays from 21.60 keV to 5394 keV are given.

In Table 6 the radionuclides arranged in ascending order of energy of their x–rays from 0.52 keV to 106.18 keV are presented.

In Table 7 yields of 25 radionuclides having $T_{1/2}$ shorter 20 min (Y:10^n Bk*μA^{-1}) are given.

In Table 8 yields of more than 100 radionuclides having $T_{1/2}$ longer than 20 min [Y:10^n Bk/(μA*h)] are presented [6].

In Table 9 ranges for protons and stopping power for 35 chemical elements are given.

In the book the excitation function figures of 140 nuclear reactions (Table 10) are also presented [7].

Table 1. Physical characteristics of chemical elements.

Element	Atomic number	Symbol	Atomic weight	Density, g/cm^3	Weighting point ^{0}Ñ	Boiling point, ^{0}Ñ	Atomic weight and natural abundance of the isotope (%)
Aluminium	13	Al	26.98	2.7	660,1	2500	27 (100)
Antimony	51	Sb	121.75	6.68	630.5	1635	121 (57.25) 123 (42.75)
Argon	18	Ar	39.95	1.78	-189.3	-185.9	36 (0.337) 38 (0,063) 40 (99.6)

Table 2.. Threshold energies (MeV) of proton induced reactions and radionuclide production

Chemical elements				Nuclear reaction (p,n)		Nuclear reaction (p,2n)		Nuclear reaction (p,pn)		Nuclear reaction (p,α)		Nuclear reaction (p,αn)	
Z	Nuc-lide	A	Natural abundance,%	E_{th}, MeV	Radio-nuclide	E_{th}, MeV	Radio-nuclide	E_{th}, MeV	Radio-nuclide	E_{th}, MeV	Radio-nuclide	E_{th}, MeV	Radio-nuclide
3	Li	7	92.58	1.8	^{7}Be								
5	B	10	19.61	4.8	^{10}Ñ					-1.2	^{7}Be		
	B	11	80.39	3.0	^{11}Ñ	17.3	^{10}C					11.2	^{7}Be
6	C	12	98.892					20.2	^{11}C				
	C	13	1.108	3.2	^{13}N								
7	N	14	99.635	6.3	^{14}O			11.3	^{13}N	3.1	^{11}C	17.1	^{10}C
	N	15	0,365	3.7	^{15}O	17.9	^{14}O					14.7	^{11}C
8	O	16	99.759					16.6	^{15}O	5.5	^{13}N		

Table 3. Radionuclides arranged in ascending order of their atomic numbers (h-hour, s-second, m-minute, d-day, y-year)

Z	Radio-nuclide	Half life	Energy of gamma- radiation, keV (quantum yeild,%)
4.	^{7}Be	53.61 d	477.5 (10.3)
6.	^{10}C	19.48 s	1022 (1.47) 718 (100) 511(200)
	^{11}C	20.34 m	511 (199.52)
7.	^{13}N	9.96 m	511 (199.62)
8.	^{14}O	1.14 m	2311 (100) 1634 (0.035) 511 (200)
	^{15}O	2.07 m	511 (199.80)

Table 4. Radionuclides arranged in increasing order of their half-life (Reactions type: 1-(p,n); 2-(p,2n); 3-(p,pn); 4-(p,α); 5-(p,αn) (h-hour, s-second, m-minute, d-day, y-year)

$T_{1/2}$	Radio-nuclide	Target isotope	Re-ac-tion type	Q-va-lues, MeV	$T_{1/2}$	Radio-nuclide	Target isotope	Re-ac-tion type	Q-va-lues, MeV
0.13 s	^{24}Al	^{24}Mg	1	-14.6	0.54 s	^{197m}Tl	^{198}Hg	2	-12.0
		^{25}Mg	2	-22.8	0.56 s	^{129m}La	^{130}Ba	2	-15.1
		^{28}Si	5	-24.6	0.59 s	^{41}Sc	^{42}Ca	2	-18.8
0.18 s	^{40}Sc	^{40}Ca	1	-15.1	0.68 s	^{42}Sc	^{42}Ca	1	-7.2

Table 5. Radionuklides arranged in ascending order of energy of their γ–rays (h-hour, s-second, m-minute, d-day, y- year)

Energy of γ-quantum, keV	Guantum yield, %	Radionuklide	$T_{1/2}$	Energy of γ-quantum, keV	Guantum yield, %	Radionuklide	$T_{1/2}$
21,60	4,76	^{151}Gd	120 d	34,49	2,3	^{135}Ce	17,76 h
22,50	2,0	^{149}Eu	93,1d	34,95	0,65	^{206}Bi	6,24 d
22,70	0,14	^{126m}Sb	11 h	35,46	4,6	^{125}Sb	2,77 d
23,54	1,8	^{185m}W	1,67 m	35,48	6,7	^{125}I	59,89 d

Table 6. Radionuclides arranged in ascending order of energy of their x-rays.(h-hour, s-second, m-minute, d-day, y- year)

E_x, keV	Quantum yield, %	Radion uclide	$T_{1/2}$		E_x keV	Quantum yield %	Radion uclide	$T_{1/2}$
0.52	0.04	^{18}F	1.83 h		30.40	14	^{135m}Xe	16.65 m
0.85	0.16	^{22}Na	2.6 y		30.40	23	^{124}Cs	34 s
2.65	0.23	^{34m}Cl	31.99 m		30.40	51	^{125}Cs	45 m
2.65	10.3	^{37}Ar	35.06 d		30.40	12	^{126}Cs	1.64 m

Table 7. Yields of radionuclides having $T_{1/2}$ shorter 20 min ($Y:10^n$ Bk*μA^{-1})

Nuclear reactions	**Ep, MeV**						
	7	**8**	**9**	**10**	**11**	**12**	**n**
B→^{10}C		1.6	3.3	6.3	9.8	15,2	6
B→^{11}C	4.9	6.4	7.7	9.4	10.4	17.3	9
C→^{13}N	1.3	1.7	2.0	2.1	2.3	2.5	8

Table 8. Yields of radionuclides having $T_{1/2}$ longer than 20 min [Y:10^n Bk/(μA*h)]

Nuclear Reactions	E_p, MeV												
	5	6	7	8	9	10	11	12	14	16	18	20	n
Li→^{7}Be	2.38	3.28	4.14	4.74	5.36	5.86		6.75	7.40	7.94	8.38	8.78	6
B→^{7}Bε	0.37	0.47	0.55	0.62		0.71		0.77	0.83	0.95	1.12	1.46	6
O→^{18}F	1.20	1.95	2.88	4.15	5.71	7.64	9.65	10.8	12.2	13.1	14.0	14.8	6
F→^{18}F								2.0	100	572	1330	2270	6

Table 9. Ranges and stopping powers for protons in different media.

E_P, MeV	Range μm	Range g/cm^2	Stopping powers MeV *cm^2/g	Correction factor
Hydrogen				
1.	1,138 02	8,082 - 04	7,063 02	- 5,622 02
2.	3,892 02	2,764 - 03	4,033 02	- 1,653 02
3.	8,084 02	5,740 - 03	2,886 02	- 7,988 01
4.	1,362 03	9,766 - 03	2,271 02	- 4,749 01

Table 10. NUCLEAR REACTIONS FOR WHICH EXCITATION FUNCTIONS ARE LISTED IN THE BOOK

1. $^{7}Li(p,n)^{7}Be$	45. $^{63}Cu(p,n)^{63}Zn$	90. $^{117}Sn(p,n)^{117}Sb$
2. $^{10}B(p,n)^{10}C$	46. $^{65}Cu(p,n)^{65}Zn$	91. $^{118}Sn(p,n)^{118}Sb$
3. $^{11}B(p,n)^{11}C$	47. $^{63}Cu(p,2n)^{62}Zn$	92. $^{119}Sn(p,n)^{119}Sb$
4. $^{10}B(p,\alpha)^{7}Be$	48. $^{63}Cu(p,pn)^{62}Cu$	93. $^{120}Sn(p,n)^{120m}Sb$
5. $^{13}C(p,n)^{13}N$	49. $^{65}Cu(p,pn)^{64}Cu$	94. $^{122}Sn(p,n)^{122}Sb$
6. $^{12}C(p,pn)^{11}C+$	50. $^{66}Zn(p,n)^{66}Ga$	95. $^{120}Sn(p,\alpha)^{117m}In$
7. $^{12}Cp,d)^{11}C$	51. $^{64}Zn(p,n)^{64}Ga$	96. $^{128}Te(p,n)^{128}I$
8. $^{14}N(p,n)^{14}O$	52. $^{57}Zn(p,n)^{67}Ga$	97. $^{130}Te(p,n)^{130}I$
9. $^{14}N(p\ \alpha)^{11}C$	53. $^{68}Zn(p,n)^{68}Ga$	98. $^{120}Te(p,n)^{120m}I$
10. $^{15}N(p,n)^{15}O$	54. $^{64}Zn(p,\alpha n)^{60}Cu$	$^{120}Te(p,n)^{120g}I$
11. $^{14}N(p,pn)^{13}N$	55. $^{69}Ga(p,n)^{69}Ge$	$^{120}Te(p,2n)^{119}I$
12. $^{14}N(p,2a)^{7}Be$	56. $^{75}As(p,n)^{75}Se$	99. $Te_{nat}(p,xn)^{121}I$,
13. $^{17}O(p,n)^{17}F$	57. $^{80}Se(p.n)^{80}Br$	^{123}I, ^{124}I, ^{125}I,
14. $^{18}O(p,n)^{18}F$	58. $^{80}Se(p.n)^{80m}Br$	^{126}I, ^{128}I, ^{130}I
15. $^{16}O(p,\alpha)^{13}N$	59. $^{82}Se(p,n)^{82}Br$	100. $^{123}Te(p,n)^{123}I$
16. $^{19}F(p,n)^{19}Ne$	60. $^{79}Br(p,n)^{79}Kr$	$^{123}Te(p,2n)^{122}I$
17. $^{20}Ne(p,\alpha)^{17}F$	61. $^{79}Br(p,pn)^{78}Br$	101. $^{127}I(p,n)^{127}Xe$
18. $^{23}Na(p,n)^{23}Mg$	62. $^{81}Br(p.pn)^{80}Br$	102. $^{127}I(p,pn)^{126}I$
19. $^{24}Mg(p,\alpha)^{21}Na$	63. $^{81}Br(p,pn)^{80m}Br$	103. $^{124}Xe(p,2n)^{123}Cs$
20. $^{27}Al(p,n)^{27}Si$	64. $^{88}Sr(p,n)^{88}Y$	$^{124}Xe(p,pn)^{123}Xe$
21. $^{29}Si(p,2p)^{28}Al$	65. $^{88}Sr(p,2n)^{87}Y$	104. $^{137}Cs(p,n)^{137m}Ba$
22. $^{37}Cl(p,n)^{37}Ar$	66. $^{89}Y(p,n)^{89}Zr$	105. $^{134}Ba(p,n)^{134}La$
23. $^{43}Ca(p,n)^{43}Sc$	67. $^{90}Zr(p,n)^{90}Nb$	106. $^{136}Ba(p,n)^{136}La+$
24. $^{44}Ca(p,n)^{44}Sc$	68. $^{93}Nb(p,n)^{93m}Mo$	$^{137}Ba(p,2n)^{136}La$
25. $^{48}Ca(p,n)^{48}Sc$	69. $^{92}Mo(p,n)^{92}Tc$	107. $^{139}La(p,n)^{139}Ce$
26. $^{45}Sc(p,n)^{45}Ti$	70. $^{96}Mo(p,n)^{96}Tc$	108. $^{140}Ce(p,n)^{140}Pr$
27. $^{47}Ti(p,n)^{47}V$	71. $^{100}Mo(p,n)^{100}Tc$	109. $^{140}Ce(p,2n)^{139}Pr$
28. $^{48}Ti(p,n)^{48}V$	72. $^{96}Mo(p,2n)^{95}Tc$	110. $^{142}Ce(p,n)^{142}Pr$
29. $^{51}V(p,n)^{51}Cr$	73. $^{110}Pd(p,pn)^{109}Pd$	111. $^{142}Ce(p,\gamma)^{143}Pr$
30. $^{52}Cr(p,n)^{52}Mn$	74. $^{109}Ag(p,n)^{109}Cd$	112. $^{141}Pr(p,n)^{141}Nd$
31. $^{52}Cr(p,n)^{52m}Mn$	75. $^{107}Ag(p,pn)^{106}Ag$	113. $^{141}Pr(p,2n)^{140}Nd$
32. $^{55}Mn(p,n)^{55}Fe$	76. $^{107}Ag(p,pn)^{106m}Ag$	114. $^{148}Nd(p,n)^{148}Pm$
33. $^{56}Fe(p,n)^{56}Co$	77. $^{110}Cd(p,n)^{110}In$	115. $^{148}Nd(p,n)^{148m}Pm$
34. $^{57}Fe(p,n)^{57}Co$	78. $^{111}Cd(p,n)^{111}In$	116. $^{151}Eu(p,n)^{151}Gd$
35. $^{56}Fe(p,\alpha n)^{52}Mn$	79. $^{112}Cd(p,n)^{112}In$	117. $^{153}Eu(p,n)^{153}Gd$
36. $^{59}Co(p,pn)^{58}Co$	80. $^{113}Cd(p,n)^{113m}In$	118. $^{160}Gd(p,n)^{160}Tb$
37. $^{60}Ni(p,n)^{60}Cu$	81. $^{114}Cd(p.n)^{114}In$	119. $^{169}Tm(p,n)^{169}Yb$
38. $^{61}Ni(p,n)^{61}Cu$	82. $^{114}Cd(p,n)^{114m}In$	120. $^{181}Ta(p,n)^{181}W$
39. $^{64}Ni(p,n)^{64}Cu$	83. $^{116}Cd(p,n)^{116m}In$	121. $^{181}Ta(p,pn)^{180}Ta$
40. $^{58}Ni(p,2n)^{57}Cu$	84. $^{110}Cd(p,2n)^{109}In$	122. $^{197}Au(p,n)^{197}Hg$
41. $^{60}Ni(p,\alpha)^{57}Co$	85. $^{112}Cd(p,2n)^{111}In$	123. $^{205}Tl(p,2n)^{204m}Pb$
42. $^{58}Ni(p,2p)^{57}Co$	86. $^{113}Cd(p,2n)^{112}In$	124. $^{206}Pb(p,n)^{206}Bi$
43. $^{58}Ni(p,pn)^{57}Ni$	87. $^{114}Cd(p,2n)^{113m}In$	125. $^{204}Pb(p,n)^{204}Bi$
44. $^{58}Ni(p,\alpha)^{55}Co$	88. $^{116}Cd(p,2n)^{115m}In$	126. $^{209}Bi(p,n)^{209}Po$
	89. $^{116}Sn(p,n)^{116}Sb$	127. $^{232}Th(p,n)^{232}Pa$

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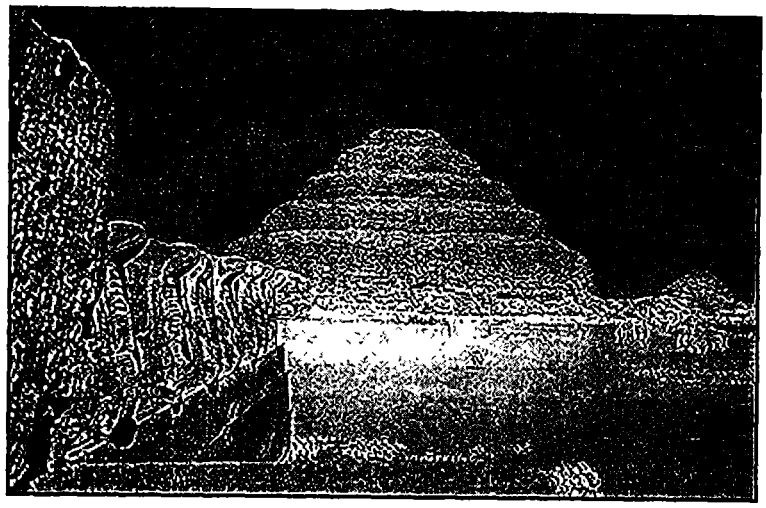
The Step Pyramid of King Djoser of the Old Kingdom

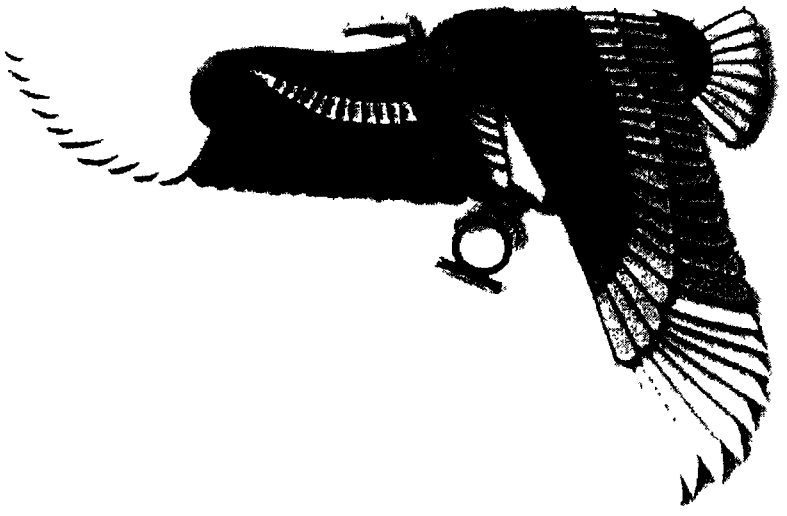


The Step Pyramid of King Djoser of the Old Kingdom

The Step Pyramid of King Djoser of the Old Kingdom (2900 B.C)

The Step Pyramid was designed for King Djoser (Dynasty 3) by his vizier Imhotep. The pyramid is located in Saqqara, the main necropolis of Memphis. The multiple uraei (plural of *uraeus*, a rearing cobra with a spread hood), on the left in the foreground, are divine protectors of the king. The view is across the South Court.

The Step Pyramid is the first known monumental structure made of stone anywhere in the world. As its name suggests, it is a series of six levels of stone decreasing in size as they ascend to about 200 feet/60 meters in height. Until this time, mastabas had been the principal form of tomb architecture. A mastaba (Arabic for "bench") is a low rectangular structure which was built over a shaft which descended to the burial location. The Step Pyramid originally began as a mastaba, and it may have been visualized as a series of mastaba shapes, decreasing in size, stacked one on top of another. Whatever the origin, it creates an impressive geometrical form rising from the floor of the desert.



HIGH ENERGY AND PARTCLE PHYSICS

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