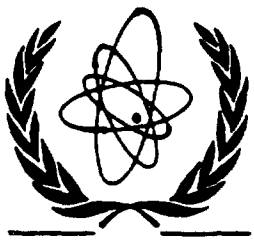

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Measurement and Study of (n,p) Reaction Cross-sections for Cr, Ti, Ni, Co, Zr and Mo Isotopes using 14.7 MeV Neutrons

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Abstract

In this work the (n,p) reaction cross-sections were measured at 14.7 MeV for isotopes of the elements Cr, Ti, Ni, Co, Zr and Mo using the activation method. Simultaneously the (n,α) and (n,2n) reaction cross-sections were also determined. The measured cross-sections were compared with recently published data, with good agreement observed for most of the measurements. The discrepancies observed were attributed to difficulties related to the long half-life of the product nuclei and small abundance of the target isotopes, in addition to possible differences in experimental conditions.

Attempts were also made in this work to study the systematics of the (n,p) as well as the associated (n,α) and (n,2n) reaction cross-sections. The results confirmed the trend theoretically suggested by Levkovski [1] and experimentally realised by Qaim and co-workers [2].

The isotopic dependence of the (n,p) cross-sections and the variations of the cross-section ratios σ (n,p)/σ (n,α) with Z-number of the target isotopes were also studied. The results obtained were found to be in agreement with theoretical predictions.

Contents

1. INTRODUCTION

The basic aim in this work was to measure and study the systematics of the (n,p) reaction cross-sections for some isotopes as well as of some other associated reactions cross-sections such as (n,2n), (n,α) and (n,n'p) using the activation technique and 14.7 MeV neutrons produced by the Neutron Generator at the Department of Physics, University of Khartoum. Measurements were carried out for isotopes of Chromium, Titanium, Nickel, Cobalt, Zirconium and Molybdenum.

2. CROSS -SECTIONS MEASUREMENTS

2.1 IRRADIATION AND FLUX MONITORING

The samples used were foils of the natural elements Al, Cr, Ni, Co, Zr and Mo of 0.1mm thickness and of high purity ($\geq$ 99% pure) from Goodfellow Metals. They were cut in circular shape of one inch diameter. During irradiation the foils were sandwiched between two other foils which served as standard as well as neutron flux monitors. Use was made of the well known cross-section for the reaction $^{27}Al(n,\alpha)^{24}Na$ as standared ,with a half-life of T = 15.02hr and a cross-section of σ =113.7mb, as evaluated by Tagesen and Vonach(1981) [3] . The neutrons were produced using the neutron generator by means of the T(d,n) α reaction. The neutron generator was operated at a high voltage of 120KV and a beam current of 600μA. The samples were irradiated at 0° relative to the incoming deuteron beam direction .They were placed at close geometry i.e they were stuck on the outer surface of the tritium target cover. The sample to target distance was estimated as 0.5cm. The average neutron energy was estimated from the calculation of Pavlik and Winkler [5] and the evaluation of Habbani and Paic [4] to be 14.7MeV. The nuclear data for the relevant isotopes and reactions are given in Table (1).

Table(1): Nuclear data used for the cross-sections measurements[8,9]

Reaction	Half-life	Eγ(KeV)	Branching Ratio Iγ(%)	Isotopic Abundance f(%)
$^{52}Cr(n,p)^{52}V$	3.746m	1434	100	83.79
$^{53}Cr(n,p)^{53}V$	1.6m	1006	90	9.50
$^{54}Cr(n,\alpha)^{51}Ti$	5.8m	320	93.4	2.36
$^{46}Ti(n,p)^{46}Sc$	83.80d	889 1121	100 100	8.2
$^{47}Ti(n,p)^{47}Sc$	3.422d	159	68.52	7.4
$^{48}Ti(n,p)^{48}Sc$	43.67h	983.5 1037 1312	100 100 100	73.7
$^{50}Ti(n,\alpha)^{47}Ca$	4.54d	1297	77	5.2
$^{59}Co(n,p)^{59}Fe$	44.56d	1292 1099	44.1 56.0	100
$^{59}Co(n,\alpha)^{56}Mn$	2.579h	2111 1811 846	14.33 27.19 98.89	100
$^{59}Co(n,2n)^{58}Co$	70.78d	810	99.44	100
$^{58}Ni(n,p)^{58g}Co$	70.78d	810	99.44	67.88
$^{60}Ni(n,p)^{60}Co$	5.2779y	1332 1173	100 100	26.7
$^{58}Ni(n,n`p)^{57}Co$	271.65d	122 136	85.6 10.6	67.88

$^{58}Ni(n,2n)^{57}Ni$	35.99h	1378 1757 1919	77.6 7.12 14.66	67.88
$^{61}Ni(n,p)^{61g}Co$	1.65h	67	86	1.13
$^{62}Ni(n,p)^{62m}Co$	13.91m	1173	97..9	3.59
$^{62}Ni(n,\alpha)^{59}Fe$	44.56d	1099 1291	56.5 43.2	3.59
$^{90}Zr(n,p)^{90m}Y$	3.19h	480 202	91 97.55	51.1
$^{92}Zr(n,p)^{92}Y$	3.541h	934	13.9	17.1
$^{94}Zr(n,p)^{94}Y$	18.71m	919	56	17.4
$^{90}Zr(n,\alpha)^{87m}Sr$	2.801h	388	82	51.5
$^{96}Zr(n,\alpha)^{93}Sr$	7.43m	590	73	2.80
$^{90}Zr(n.2n)^{89g}Zr$ ^{89m}Zr	78.43h 4.18m	909 588	99.01 89.5	51.5
$^{98}Mo\ (n,p)^{98m}Nb$	51.3m	722 787	72.7 93	23.78
$^{96}Mo(n,p)^{96}Nb$	23.35h	778	96.8	16.53
$^{97}Mo(n,p)^{97g}Nb$	72.1m	658	98.2	9.46
$^{92}Mo(n,p)^{92m}Nb$	10.14d	934	99.2	15.84
$^{92}Mo(n\alpha)^{89g}Zr$	78.43h	909	99	15.84
$^{100}Mo(n,2n)^{99}Mo$	66.02h	739	12.6	9.63

The basic relation for the net counts obtained following irradiation and during measurement of the induced radioactivity is given by :-

$$N_0 = \frac{\varepsilon I_\gamma fm(6.02x10^{23})\phi\sigma(1-e^{-\lambda t_i})(e^{-\lambda t_w})(1-e^{-\lambda t_c})}{\lambda A} \qquad (1)$$

where

ε = efficiency of the detector

I_γ = the branching ratio of the measured gamma line

f = the relative isotopic abundance of the target isotope

m = the mass of the sample in the form of pure natural element.

A = the atomic weight of the element.

σ = cross section of the reaction.

ϕ = neutron flux.

t_i = the irradiation time.

t_w = the waiting time.

t_c = the counting time.

The average neutron flux on the sample was measured using Al foils and was found to be varying between (0.65 - 1.3) $x10^8$ $n/cm^2.sec$ during the course of the measurements.

2.2 ACTIVITY MEASUREMENTS

After the irradiation of the sample and the aluminium standared and monitor foils the induced radioactivity of the reaction products was measured using HPGe detector spectrometer system. The coaxial HPGe detector has a volume of $98.6cm^3$, with a resolution of 1.7KeV for 1332.5KeV of Co-60 gamma-ray source. The spectra were collected for counting times that varied between 15min and several hours. The gamma-ray spectra were acquired by a Canberra series 35plus MCA with 2048

channels connected to personal computer for data storage, and a Hewlett Packard plotter. The sample to detector distance was 1cm, with milar foil in between. The activity at the end of the counting time was found using net area option of the MCA, with automatic subtraction of the background. The activity was subjected to corrections for dead- time, cascade due to summation effects and pile-up losses using a pulser. The standard/monitor foils were measured following the measurement for the sample.

2.3 DATA REDUCTION AND RESULTS

The cross- section for the reaction of a given isotope was found by comparison with the known cross-section of the standard which also served as a neutron flux monitor. The ratio of the cross-section for the sample and standard is given by:

$$\frac{\sigma_s}{\sigma_{st}} = \frac{(N_0\lambda A)_s[\varepsilon I_\gamma fm(1-e^{-\lambda t_i})(e^{-\lambda t_w})(1-e^{-\lambda t_c})]_{st}}{(N_0\lambda A)_{st}[\varepsilon I_\gamma fm(1-e^{-\lambda t_i})(e^{-\lambda t_w})(1-e^{-\lambda t_c})]_s} \qquad (2)$$

Thus by measurement of the net areas of the sample and standard and substituting for appropariate constants and the times t_i, t_w and t_c it would be possible to determine σ_s knowing σ_{st}. In Table(2) are given the measured cross- sections and their errors. Each value of the cross-sections was based on at least two independent measurements. The principal sources of the random and systematic uncertainties in the measurements are given in Table(3). The errors for the cross-sections were estimated by summing up quadratically the individual uncertainties for each measurement.

The errors in the (n,p) cross-section measurements ranged between 1.2-15%.The cross- sections measured in this work were compared with some recent ones reported by various authers as given in Table(2). The cross-sections measured in this work were found to agree well with most recent literature values and to disagree with some other ones. The disagreements were observed in the case of ^{59}Co(n,2n), ^{58}Ni(n,p), ^{61}Ni(n,p) and ^{100}Mo(n,2n) reactions cross-sections . The difficulty with the measurement of

^{59}Co(n,2n) cross- section may be attributed to the long half- life of the product nucleus of 70.78d. The same product is obtained in case of ^{58}Ni(n,p). The difficulties in case of ^{61}Ni(n,p) and ^{100}Mo(n,2n) may be attributed to the low abundance for the former and both low abundance and long half- life for the latter.

In Fig(1) is shown a plot of (n,p), (n,α) and (n,2n) reactions cross-sections measured in this work versus the asymmetry parameter (N-Z)/A . The plot confirms the increasing trend of (n,2n) reaction cross-sections with (N-Z)/A obtained earlier by Qaim and co-workers [2].

In Fig(2) a plot is given of (n,p) cross-sections for various isotopes of the elements versus the mass number A.The plot indicates decrease of (n,p) cross- sections with the mass number of the isotopes of the elements used (Ti, Cr, Co, Ni, Zr and Mo). Such a trend was obtained earlier by various authors[2,4,6].

In Fig(3) is shown a plot for the cross-section ratio σ(n,p)/σ(n,α) versus proton number of the target isotopes for (n,p) and (n,α) cross-sections measured in this work. The plot indicates that the emission of protons relative to the alpha particles increases with increasing proton number of the target isotopes . The effect may be explained by the fact that for the escape of a proton from the compound nucleus the coulomb barrier potential increases from about 1MeV at Z=3 to about 12MeV at Z=90, whereas for the escape of an alpha particle the coulomb barrier is approximately twice as high as that for proton emission (from about 1MeV for Z=2 to about 22MeV for Z=90). This would indicate sharper decrease of (n,α) reactions cross-sections with Z number than for (n,p) reactions. There may also be greater contribution from direct processes in case of (n,p) reactions than in case of (n,α) reactions .

In Fig(4) a comparison is given between the experimental (n,p) cross-sections measured in this work and the theoretical values obtained using the empirical formula given by Levkovski [1]. A fair agreement is observed between measured and calculated

values of (n,p) cross-sections. A good fit for the present experimental data is given by the following formula :

$$\sigma(n,p) = \sigma_0 \exp(-a_0 s) \qquad (3)$$

where s is the asymmetry parameter (N-Z)/A and σ_0 , a_0 are fitting parameters having the following values : σ_0 = 1057.28 , a_0 = 33.59

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REFERENCES

[1] V.N. Levkovski, JEP, 45(1963)305.

[2]W.I. Molla and S.M. Qaim "Systematic study of (n,p) reactions at 14.7MeV", Nucl.Phys.A283(1977)269.

[3]D.De Soete,R.Gijbels and B.J.Hoste"Neutron activation analysis", Wiley Interscience(1972).

[4]F.Habbani and G.Paic, "Measurement of (n,p)and (n,n`p)cross-sections for some Fe isotopes at 14.7MeV.", Int. J. Appl. Rad.Isotopes,Vol.39,No.10(1988)1041-1043.

[5] A. Pavlik, and G. Winkler, "Calculation of energy spread and the average neutron energy of 14MeV neutrons produced via the T(d,n)^{4}He reaction in solid TiT target", INDC(AUS)-011/ LI, IAEA,Vienna(1986).

[6] S.M.Qaim, "Complex particle emission in fast neutron-induced reactions",Euro. Phys.Topical Conference on Neutron Induced Reactions, (1982).

[7]W.I.Molla, M.M.Rahman,"Activation cross-sections for isotopes of Mg, Ti, V, Ni, Zr, and Mo around 14MeV", INDC(BAN)-003/Cr, INT(86)-8

[8]"Handbook on nuclear activation cross-sections",Technical Reports Series No.156,IAEA,Vienna,(1974).

[9] M. Lederer and Virginia S.Shirley, "Table of isotopes", Seventh Edition (1985).

[10] S.M.Qaim,"14MeV neutron activation cross-sections", Handbook of spectroscopy, VolumeIII(1981)8.

[11] Hoang Dac Luc,Phan Nhu Ngoc,Nguyen Van Do,Ly Ba Bach, "Activation cross-sections of (n,p) and (n,n`p) reactions induced by 14.8MeV neutrons on Cr isotopes", INDC(VN)-oc/CI;INT(85)-5(1985).

[12] Hoang Dac Luc,Phan Nhu Ngoc, Ngugen Van Do, Ly Ba Bach,"Determination of some (n,p), (n,n`p) and (n,α) reaction cross- sections induced by 14.8MeV on Cr and Ti" , INDC(VN)-5/GI;INT(86)-9.

[13] Julius Csikai , "Handbook of fast neutron generators", Vol.II,CRC Press(1980).

[14] S.M. Qaim, "Progress report on nuclear data research in the Federal republic of Germany" (1984).

TABLE(2): Nuclear reaction cross-sections measured in this work

Nuclear Reaction	Gamma Energy(MeV)	Cross-section(mb) This Work	Cross-section(mb) Literature values
^{52}Cr (n, p) ^{52}V	1434	78±2	94±10[8]82±8[10] 80±6[9]70.7±3[11]
^{53}Cr (n,p)^{53}V	1006	34 ±2	36± 6[8]46± 6[10]
^{54}Cr (n,α)^{51}Ti	320	7 ±1	12 ±1[11]14± 2[10]
^{46}Ti (n, p) ^{46}Sc	889 1121	261±27 264±27	253 ±24[7] 280± 25[8] 166 ±15[11]
^{47}Ti (n, p) ^{47}Sc	159	151±4	116 ±14[9] 169 ±6[11]
^{48}Ti (n, p) ^{48}Sc	983 1037 1313	76±2	61 ±7[7] 72± 2.6 [11]
^{50}Ti (n, α) ^{47}Ca	1297	11±2	10 ±2[8]17± 4[12] 8 ±2[9]
^{59}Co (n, p)^{59}Fe	1292 1099	70±3 67±2	80 ±23[8]73± 10[9]

^{59}Co (n, α) ^{56}Mn	2111 1811 846	38±1 37±1 32±0.8	30± 2[8,9]
^{59}Co (n, 2n) ^{58}Co	810	633±16	720 ± 50[8]
^{58}Ni (n, p) ^{58g}Co	810	305±8	397 ±36[7] 375± 2[8]
^{60}Ni (n, p) ^{60}Co	1332 1173	120±18	122 ±12[7] 112 ±12[9]
^{58}Ni (n, n'p) ^{57}Co	122 136	576±15	370 ±49[7] 526± 45[9]
^{62}Ni (n, α) ^{59}Fe	1099 1291	18±4	17 ±4[8]0 ±3[9]
^{61}Ni (n, p) ^{61g}Co	67	61±2	95 ±10[9]
^{58}Ni (n, 2n) ^{57}Ni	1757 1919	28±3 31±2	31± 3[8[35± 3[9]
^{90}Zr (n, p) ^{90m}Y	480 202	9±0.2 9±0.2	8 ±1[9]11± 2[8]
^{92}Zr (n, p) ^{92}Y	934	17±0.9	18.6± 2[8] 19.5± 3[7]
^{94}Zr (n, p) ^{94} Y	919	8±0.2	8 ±3[8]11± 1[9]
^{90}Zr (n, α) ^{87m} Sr	388	3±0.1	3 ±1[8]2.8± 0.3[9]
^{96}Zr (n, α) ^{93}Sr	590	3±0.1	3 ±1[8]2.3± 0.3[9]
^{90}Zr (n, 2n) ^{89g} Zr ^{89m} Zr	909 588	612±16 85±2	517 ±47[7] 740± 50[8] 84 ±12[8]80± 6[9]

^{98}Mo (n, p) ^{98m} Nb	722 787	5.1±0.1 5.1±0.1	4.2± 0.5[7 3± 0.7[9]
^{96}Mo (n, p) ^{96} Nb	778	34±0.9	19 ±2[9]
^{97}Mo (n, p) ^{97g} Nb	658	17±0.4	18± 2[7]15.9± 1[8] 14 ±1.8[9]
^{92}Mo (n, p) ^{92m} Nb	934	59±3	65± 6[7]60± 5[9]
^{92}Mo (n, α) ^{89g} Zr	909	16±0.7	22±3[9]
^{100}Mo (n, 2n) ^{99} Mo	739	1134±29	1418 ±175[7] 390±60[9]

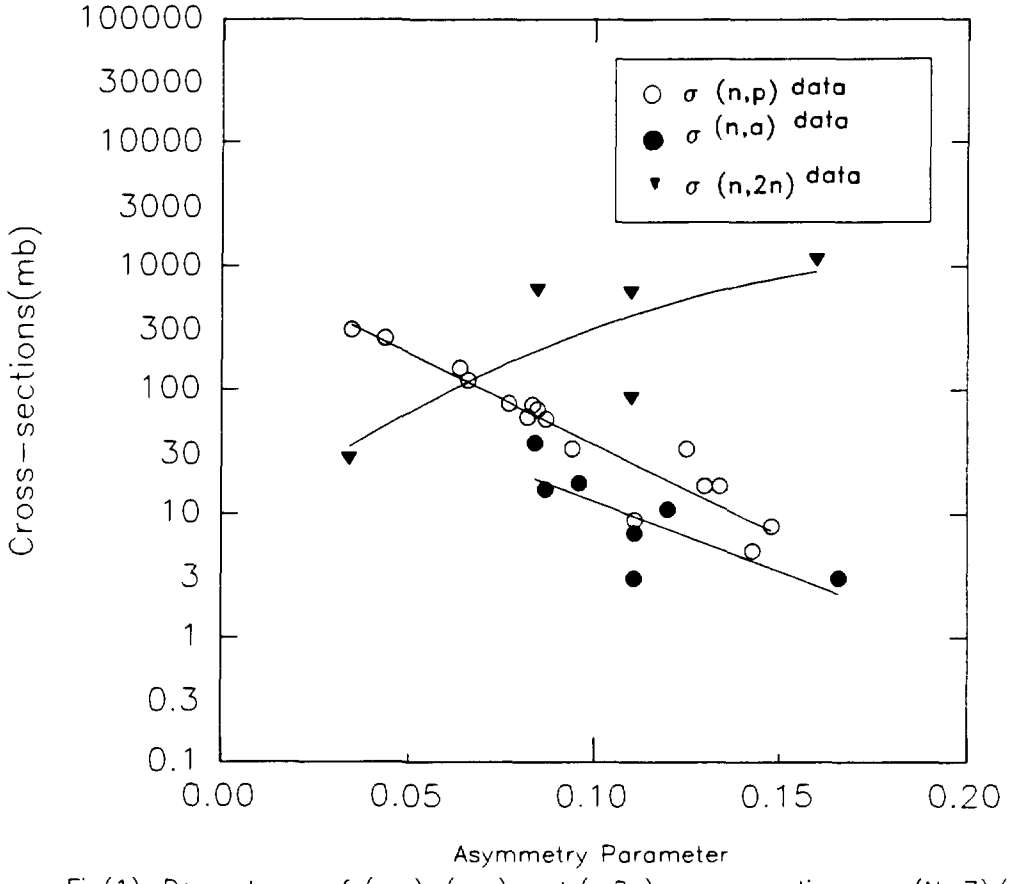
TABLE(3): Estimated principal sources of uncertainties in cross-sections measurements

Source of Uncertainty	Magnitude (%)
1. Sample positioning	0.3
2.Irradiation time,Counting time and Waiting time	0.5
3.Error in neutron flux	1.0
4. Efficiency of the detector	1.5
5.Decay constants of reaction products (half-life and branching ratio)	1.5
6.Counting statistics	0.3-25
7.Reference cross-cross	0.6

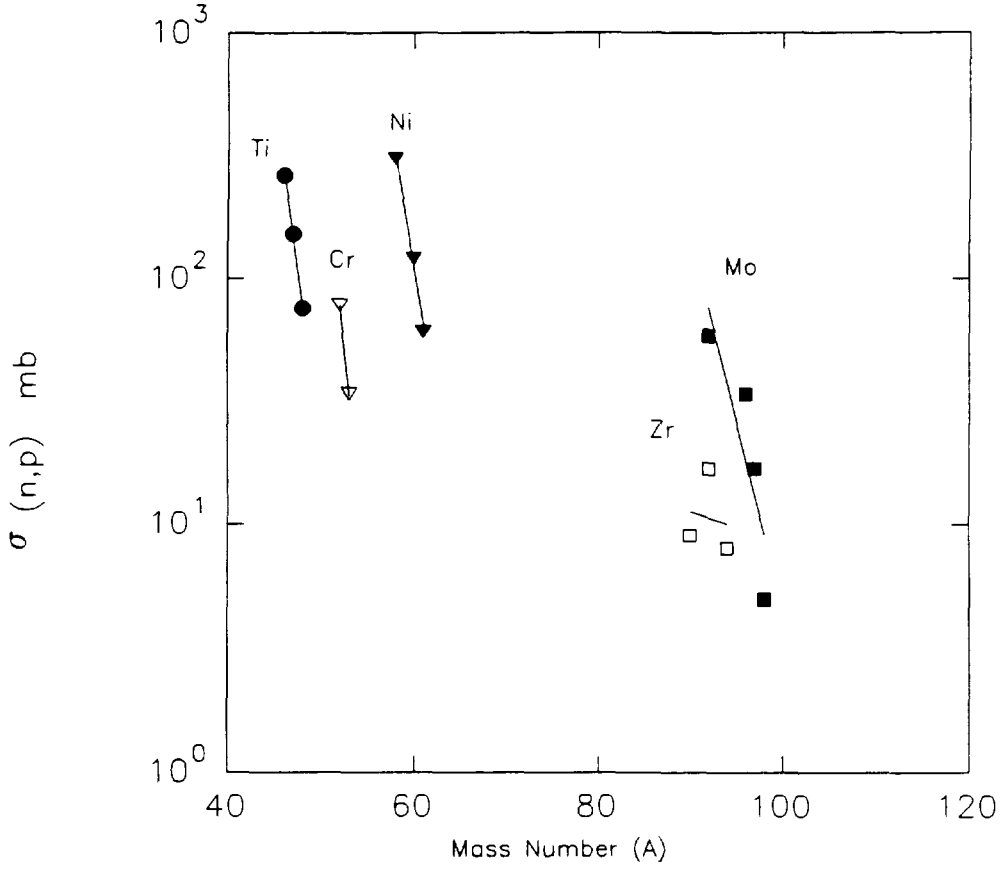
TABLE(4): Ratio of (n,p) to (n,α) cross-sections for the studied isotopes and corresponding proton number

Target Isotope	Proton Number	σ(n,p)/ σ (n,α)
^{50}Ti *	22	1.30
^{54}Cr *	24	2.30
^{59}Co	27	1.84
^{62}Ni *	28	1.38
^{90}Zr	40	3.00
^{92}Mo	42	3.68

* From Ref(14)



Fig(1): Dependence of (n,p), (n,α) and (n,2n) cross-sections on (N-Z)/A



Fig(2): σ(n,p) versus mass number of the target isotope

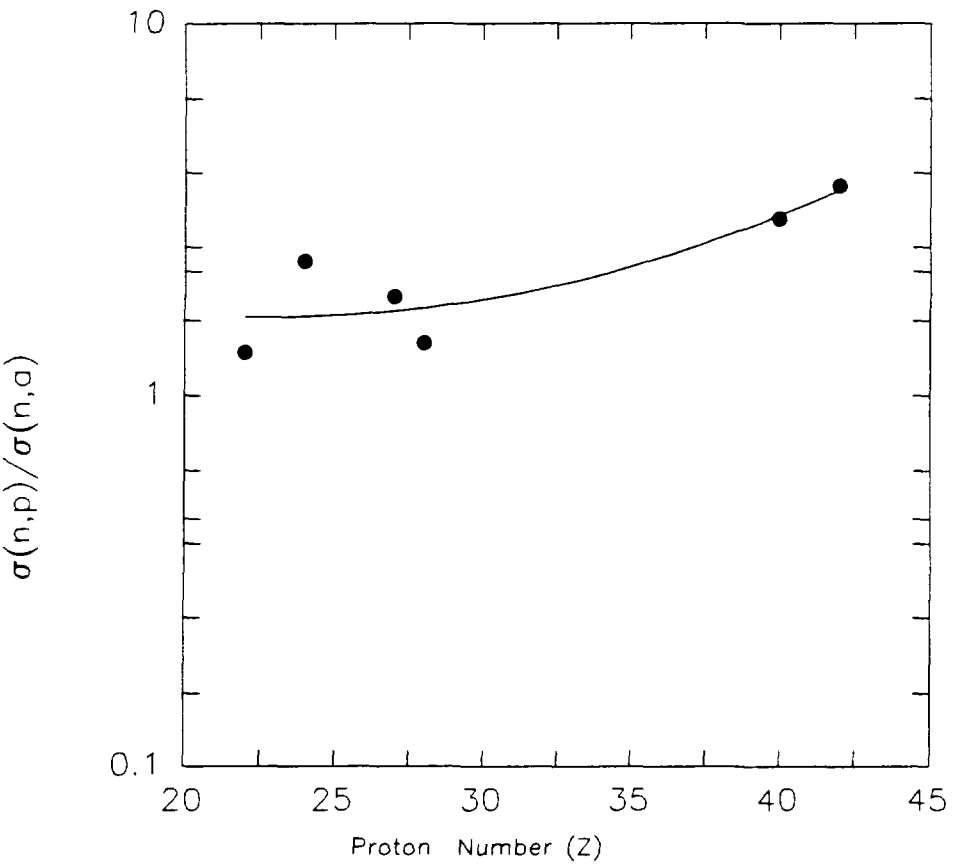
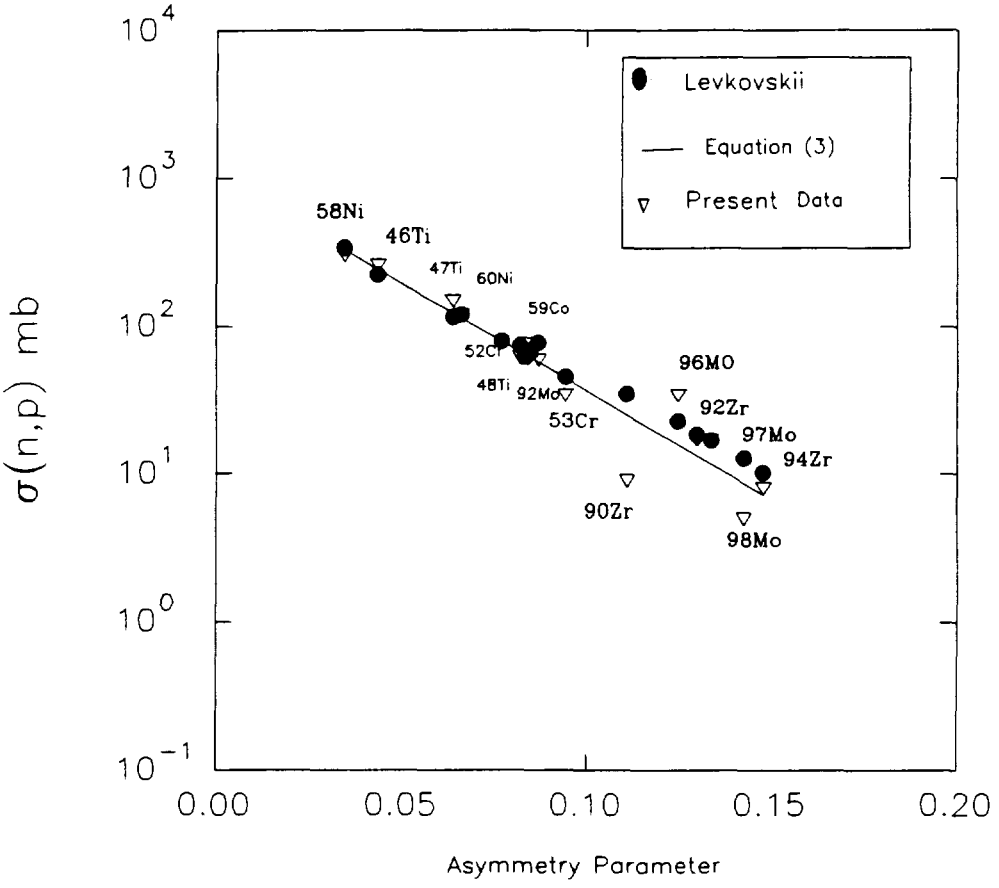


Fig (3): Variation of σ (n,p)/σ(n,α) versus Z



Fig(4): Dependence of (n,p) cross-section on (N−Z)/A

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