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Excitation Functions of $^{63}Cu(p,n)^{63}Zn$, $^{63}Cu(p,2n)^{62}Zn$ and $^{65}Cu(p,n)^{65}Zn$ Reactions in 3-25 MeV Proton Energy Range

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Abstract

Excitation functions of $^{63}Cu(p,n)$ ^{63}Zn, ^{63}Cu (p,2n) ^{62}Zn and $^{65}Cu(p,n)$ ^{65}Zn have been calculated using statistical and preequilibrium nuclear reaction models in 3-25 MeV proton energy range. The calculations have been compared with reported measurements and evaluation.

1. Introduction

Radioisotopes produced using charged particle beams from accelerators find important medical applications [1-4]. The accurate knowledge of cross sections of proton induced radio-activities in copper is needed for monitoring flux and energy of proton beams for production of medical radioisotopes[5]. A large number of measurments of excitation functions of $^{63}Cu(p,n)$ ^{63}Zn, $^{63}Cu(p,2n)$ ^{62}Zn and ^{65}Cu (p,n) ^{65}Zn reactions have been reported with a purpose of testing nuclear reaction models and obtaining reference cross section data for monitoring energy and flux of proton beams of accelerators for production of radioisotopes for medical applications [6-30]. However there is a considerable variation in the existing experimental data in the energy region beyond 10 MeV where different threshold reactions make dominant contributions. As a result the flux and energy monitoring based on the evaluation of the existing empiricial data would entail large uncertainties. The evaluation of these measurements through calculations using nuclear reaction models will be useful for checking the relative accuracy of different measurements as well as validity of parameters of nuclear reaction models. The present paper describes calculations for the excitation functions of $^{63}Cu(p,n)$ ^{63}Zn, $^{63}Cu(p, 2n)$ ^{62}Zn and $^{65}Cu(p,n)$ ^{65}Zn reactions using statistical and preequilibrium nuclear reaction models. Preliminary calculations of these reactions have been reported earlier (31-32). The present work has been carried out under IAEA Research Contract No. 8993.

2. Model Calculations

The calculations for excitation functions of $^{63}Cu(p,n)^{63}Zn$, $^{63}Cu(p,2n)^{62}Zn$ and $^{65}Cu(p,n)^{65}Zn$ reactions were carried out using HFMOD Code [33] based on Hauser-Feshbach theory for statistical model calculations and PREMOD Code [34] using geometry dependent hybrid model for preequilibrium reaction model calculations. Three exit channels characterized respectively by emission of protons, neutrons and deuterons were considered for the first stage reactions. The alpha-particle emission in the first stage reactions was found comparatively negligible. In the second stage four reaction channels involving respectively emission of a photon, neutron, proton and alpha-particle from the excited states of ^{63}Zn and ^{65}Zn above their respective thresholds were included in the calculations. The Q-values of the reactions used in the calculations are listed in Table I. In the case of ^{63}Cu Perey potential parameters [35] were used for incident protons as well as for protons emitted in the first stage except for emitted protons for incident energies below 8 MeV where potential parameters listed in Table II were used. Wilmore-Hodgson potentials [36] were used for neutrons emitted in the first stage. The optical model parameters used for neutrons and protons emitted in the second stage are listed in Table II. In the case of ^{65}Cu Perey potential parameters were used for protons and Wilmore-Hodgson potentials were used for neutrons. The potential parameters used for deuterons were taken from Ref. [37]. The optical model parameters used for alpha-particles were based on Ref. [38]. The potential parameters used for deuterons and alpha-particles are also listed in Table II. Energy level densities were calculated on the basis of back-shifted Fermi-gas model using the formalism of Dilg et al [39] and assuming a rigid-body moment of inertia for nuclei. The energy level density parameters were taken from Ref. [39]. The energy level density parameters used in the present calculations are listed in Table III. Weisskopf single particle model was used for photon emission. The values of 3 MeV and 7.5 MeV for single-particle level spacing were used for ^{65}Zn and ^{63}Zn respectively. In the calculations reported earlier [32] Brink-Axel model was used for ^{65}Zn using a value of 1 MeV for single-particle level spacing. The statistical model calculations take into account the conservation of angular momentum and parity for both the stages of nuclear reactions. The preequilibrium calculations also take into account the conservation of parity and angular momentum. The energy width in the continuum region was taken as 1MeV except in the threshold region where it was taken as 0.5 MeV.

3. Discussion

The results of statistical model calculations for excitation functions of reactions taking place in the two stages for ^{63}Cu are listed in Table IV and those for preequilibrium calculations are given in Table V. The relative contributions to the different exit channels from the excited states of ^{63}Zn and ^{65}Zn populated through preequilibrium mode were estimated on the basis of their contributions from statistical model calculations. This is based on the assumption that second emission takes place after the system is fully equilibrated. The details of calculations for $^{63}Cu(p,n)$ ^{63}Zn reaction are listed in Table VI. The present calculations for $^{63}Cu(p,n)$ ^{63}Zn reaction are compared with reported measurements and evaluation by Vukolov and Chukreev[46] in Fig. 1. Some of the numerical data have been taken from Ref. [1]. All the data could not be included in the figure for the sake of clarity. The present calculations agree reasonably well with the measurements reported by Hille et al [24], Colle et al [7] and Grutter [10]. The data of Grutter and Colle et al also contain contribution from $^{65}Cu(p,3n)$ ^{63}Zn reaction above 22 MeV. Measurements of Ghoshal [16] and Meadows[17] are on higher side above 13 MeV. The calculations for ^{63}Cu (p,2n) ^{62}Zn reactions have been listed in Table VII and compared with reported measurements in Fig-2.

The results of calculations for the excitation function of ^{65}Cu (p,n) ^{65}Zn reaction are listed for statistical and preequilibrium models respectively in Table VIII and Table IX. The details of calculations for $^{65}Cu(p,n)$ ^{65}Zn reactions are listed in Table X. The calculations of excitation function for $^{65}Cu(p,n)$ ^{65}Zn reaction are compared with reported measurements in Fig. 3. The present calculations have been done for isotopes of ^{63}Cu and ^{65}Cu. The present data can be converted for natural copper by multiplying the data for ^{63}Cu by 0.691 and those of ^{65}Cu by 0.309. The data for both the cases have been given in Table XI-XIII.

References

1. O. Schwerer and K. Okamoto, Report INDC-(NDS)-218/GZ,IAEA, Vienna, Austria, 1989.
2. Proceedings of IAEA Consultant's Meeting on Data Requirements for Medical Radioisotope Production, 20-24 April 1987, Tokyo Japan, Report INDC-(NDS)-195/Gz edited by K. Okamoto IAEA, Vienna, Austria, 1988.
3. S. M. Qaim, Radiochim., Acta 41, 111 (1987)
4. S. M. Qaim, Radiochim., Acta 30, 147 (1982)
5. P.Oblozinsky, Report INDC (NDS)-249 IAEA Vienna, Austria, 1996.
6. P. Kopecky, Int. J. Appl. Radiat, Isot., 36, 657 (1985)
7. R. Colle, R. Kishore and J. B. Cumming, Phys. Rev. C9, 1819 (1974).
8. C. H. Johnson, A. Galonsky and C. N. Inskeep, Report ORNL-2910, Oak Ridge National Laboratory, USA, 1960
9. L. F. Hansen and R. D. Albert, Phys. Rev. 128, 291 (1962)
10. A. Grutter, Nucl. Phys. A383, 98 (1982)
11. J. Wing and J. R. Huizenga, Phys. Rev. 128, 280 (1962)
12. I. R. Williams and C. B. Fulmer, Phys. Rev. 162, 1055 (1967)
13. M. E. Sevior, L. W. Mitchell, M. R. Anderson, C.A.W. Tingwell and D.G. Sargood, Aust. J. Phys. 36, 463 (1983).
14. M.W. Greene and E. Lebowitz, Int. J. Appl Radiat. Isot., 23, 342 (1972)
15. J.P.Blaser, F. Boehm, P. Marmier and D.C. Peaslee, Helv, Phys. Acta 24, 3 (1951)
16. S. N. Ghoshal, Phys. Rev. 80, 939 (1950)
17. J.W. Meadows, Phys. Rev. 91, 885 (1953)
18. H.A. Howe, Phys. Rev. 109, 2083 (1958)
19. H. Taketani and W.P. Alford, Phys. Rev. 125, 291 (1962)
20. K.F. Chackett, G.A. Chackett and L. Ismail, Proc. Phys. Soc. (London) 80,738 (1962)
21. V. Meyer and N.M. Hintz, Phys. Rev. Lett 5, 207 (1960)
22. V. N. Aleksandrov, M. P. Semyonova and V.G. Semyonova, Atomaja, Energija 62, 411 (1987)

23. B.L. Cohen, Phys. Rev. 100, 206 (1955).

24. M. Hille, P. Hille, M. Uhl and W. Weisz, Nucl. Phys, A198, 625 (1972)

25. G. F. Dell, W.D. Ploughe and H. J. Hausman, Nucl. Phys. 64, 513 (1965)

26. E. Gadioli et al Nuovo Cimento A22, 547 (1974)

27. S. M. Kormali, D.L. Swindle and E.A. Schweikert, J. Radioanal. Chem. 31, 437 (1976)

28. P. Pulfer Thesis. Univ. Bern (1979)

29. B.W. Shore, N.S. Wall and J.W. Irvine, Jr. Phys. Rev. 123, 276 (1961)

30. S. J. Mills, G. F. Steyn and F.M. Nortier Appl. Radiat. Isot. 43, 1019 (1992)

31. K. Gul, Report SID-9, Pakistan Institute of Nuclear Science and Technology, Nilore, Pakistan, 1996.

32. K. Gul, Report SID-11, Pakistan Institute of Nuclear Science and Technology, Nilore, Pakistan, 1996.

33. K. Gul Report INDC (PAK) 011, IAEA, Vienna, Austria 1995.

34. K. Gul Report SID-8, Pakistan Institute of Nuclear Science and Technology, Nilore, Pakistan.

35. F.G. Perey, Phys. Rev. 131, 745 (1963)

36. D.Wilmore and P.E. Hodgson, Nucl. Phys. 55, 673 (1964)

37. C.M. Perey and F.G. Perey, At. Data and Nucl. Data Tables 17, 1 (1976)

38. V. Avrigeanu, P. E. Hodgson and M. Avrigeanu, Phys. Rev. C49, 2136 (1994)

39. W. Dilg, W. Schantl, H. Vonach, M. Uhl, Nucl. Phys. A217, 269 (1973)

40. C.M. Baglin, Nucl. Data Sheets 69, 733 (1993)

41. M. M. King Nucl. Data Sheets 60, 337 (1990)

42. M. M. King Nucl. Data Sheets 64, 815 (1991)

43. Z. Chummei, Nucl. Data Sheets 67, 271 (1992)

44. B. Singh Nucl. Data Sheets 62, 603 (1991)

45. M. R. Bhat, Nucl. Data Sheets 69, 209 (1993)

46. V.A. Vukolov and F.E. Chukreev, INDC (CCP)-330, IAEA-Vienna, Austria, 1991.

Glossary of Symbols

σ Integral cross section of a reaction specified by superscripts/subscripts

Ep Incident energy of protons in the laboratory system.

FR% Percentage flux reduction due to preequilibrium processes

Subscripts :

p,p Cu(p,p) Cu reaction

p,n Cu(p,n) Zn reaction

p,2n Cu(p,2n) Zn reaction

p,np Cu(p,np) Cu reaction

p,d Cu(p,d) Cu reaction

p,nα Cu(p,nα) Ni reaction

abs Absorption cross section

Superscripts :

e Cross section calculated on the basis of statistical model

pr Cross section calculated on the basis of preequilibrium model

*e Integral cross section of the reaction to all levels of the residual nucleus calculatd on the basis of statistical model

*pr Integral cross section of the reaction to all levels of the residual nucleus calculated on the basis of preequilibrium model.

se Cross section calculated on the basis of statistical model using Weisskopf single particle model for photon emission.

spr Cross section calculated on the basis of preequilibrium model using Weisskopf single particle model for photon emission.

sepr Sum of the cross sections calculated on the basis of statistical model and preequilibrium model while using Weiskopf single particle model for photon emission and applying flux reduction correction.

Table I. Q-values of nuclear reactions used in the calculations.

Reaction	Q-Value (MeV)
$^{63}Cu(p,n)^{63}Zn$	−4.149
$^{63}Cu(p,d)^{62}Cu$	−8.614
$^{63}Cu(p,2n)^{62}Zn$	−13.311
$^{63}Cu(p,np)^{62}Cu$	−10.838
$^{63}Cu(p,n\alpha)^{59}Ni$	−7.629
$^{65}Cu(p,n)^{65}Zn$	−2.131
$^{65}Cu(p,d)^{64}Cu$	−7.686
$^{65}Cu(p,2n)^{64}Zn$	−10.120
$^{65}Cu(p,np)^{64}Cu$	−9.910
$^{65}Cu(p,n\alpha)^{61}Ni$	−6.247

Table II. Optical model parameters used in calculations for deuterons in the first stage and for neutrons, protons and alpha-particles in the second stage reactions.

Parameters	Neutrons	Protons	Deuterons	α-particles
V_r(MeV)	46.6	57.0	100.0	150.0
r_r(fm)	1.25	1.25	1.05	1.245
a_r(fm)	0.65	0.65	0.84	0.79
W_v(MeV)	0.0	0.0	0.0	8.0
W_s(MeV)	2.0	13.0	17.0	0.0
r_i(fm)	1.25	1.35	1.43	1.57
a_i(fm)	0.48	0.65	0.51	0.6
V_{so}(MeV)	8.0	7.2		
W_{so}(MeV)	0.0	0.0		
r_{so}(fm)	1.12	1.25		
a_{so}(fm)	0.65	0.65		
r_c(fm)		1.2	1.4	1.3

Table III. Energy level density parameters of back-shifted Fermi gas model.

Nuclide	a(MeV^{-1})	Δ(MeV)
^{59}Ni	5.77	−0.76
^{62}Cu	8.1	−1.86
^{63}Cu	6.63	−0.67
^{62}Zn	8.0	0.60
^{63}Zn	6.9	−0.67
^{61}Ni	6.69	−0.56
^{64}Cu	8.4	−1.07
^{65}Cu	7.24	−0.77
^{64}Zn	8.4	1.07
^{65}Zn	7.5	−0.84

Table IV. Details of proton induced equilibrium reaction calculations for ^{63}Cu.

Ep (MeV)	$\sigma^{*e}_{p,p}$ (mb)	$\sigma^{*e}_{p,n}$ (mb)	$\sigma^{*e}_{p,d}$ (mb)	$\sigma^{se}_{p,2n}$ (mb)	$\sigma^{se}_{p,np}$ (mb)	$\sigma^{se}_{p,n\alpha}$ (mb)	$\sigma^{se}_{p,n}$ (mb)
24.4	460.5	537.6	114.5	96.3	409.0	24.8	7.5
22.5	466.1	535.4	103.8	87.3	397.0	34.6	16.5
21.3	469.7	546.9	76.2	74.7	389.7	47.5	35.0
19.5	467.9	555.3	51.9	71.1	369.4	60.1	54.7
18.5	464.0	558.6	38.9	69.5	347.4	58.3	83.4
17.5	457.9	560.4	28.2	66.4	305.0	53.1	135.9
16.5	450.6	560.2	19.6	53.4	263.6	39.2	204.0
15.5	440.7	559.1	12.9	32.9	201.6	23.2	301.4
14.5	430.4	554.0	7.7	9.1	110.3	10.4	424.2
13.5	419.6	543.8	3.9	0.0	16.5	1.0	526.3
12.5	407.6	526.8	1.1	0.0	0.0	0.0	526.8
11.5	395.9	498.4	0.0	0.0	0.0	0.0	498.4
10.5	384.0	456.0	0.0	0.0	0.0	0.0	456.0
9.5	370.2	401.0	0.0	0.0	0.0	0.0	401.0
8.5	344.6	345.0	0.0	0.0	0.0	0.0	345.0
7.5	314.5	281.7	0.0	0.0	0.0	0.0	281.0
6.5	225.6	258.3	0.0	0.0	0.0	0.0	258.3
5.5	137.2	206.5	0.0	0.0	0.0	0.0	206.5

Table V. Details of proton induced preequilibrium reaction cross sections for ^{63}Cu.

E_p (MeV)	$\sigma^{*pr}_{p,n}$ (mb)	$\sigma^{*pr}_{p,p}$ (mb)	σ^{*pr}_{sum} (mb)	σ_{abs} (mb)	FR%
24.0	49.1	49.9	99.0	1112	8.9
22.5	44.3	45.1	89.4	1104	8.1
21.0	39.6	40.3	79.9	1092	7.3
19.5	34.9	35.6	70.5	1075	6.6
18.5	31.7	32.4	64.0	1061	6.0
17.5	28.4	29.2	57.6	1046	5.5
16.5	25.3	26.0	51.3	1030	5.0
15.5	22.2	23.0	45.1	1013	4.5
14.5	19.3	20.0	39.3	992	4.0
13.5	16.7	17.1	33.8	961	3.5
12.5	14.1	14.3	28.4	935	3.0
11.5	11.3	11.5	22.8	894	2.6
10.5	8.5	8.7	17.2	839	2.1
9.5	5.8	6.0	11.8	771	1.5
8.5	3.4	3.6	7.0	690	1.0

Table VI. Details of calculations of $^{63}Cu(p,n)^{63}Zn$ reaction cross sections from preequilibrium and fully equilibrated stages.

E_p (MeV)	FR%	$\sigma^{se}_{p,n}$ (mb)	$\sigma^{spr}_{p,n}$ (mb)	$\sigma^{sepr}_{p,n}$ (mb)
24.0	8.9	7.5	19.0	25.8
22.5.	8.1	16.5	19.3	34.5
21.0	7.3	35.0	19.4	51.9
19.5	6.6	54.7	20.0	71.1
18.5	6.0	83.4	20.0	98.4
17.5	5.5	135.9	20.0	148.4
16.5	5.0	204.0	20.0	213.8
15.5	4.5	301.4	19.7	307.5
14.5	4.0	424.2	18.6	425.8
13.5	3.5	526.3	16.7	524.6
12.5	3.0	526.8	14.1	525.1
11.5	2.6	498.4	11.3	496.7
10.5	2.1	456.0	8.5	454.9
9.5	1.5	401.0	5.8	400.8
8.5	1.0	345.0	3.4	345.0
7.5		281.0		281.0
6.5		258.3		258.3
5.5		206.5		206.5

Table VII. Details of calculations of excitation function of $^{63}Cu(p,2n)\ ^{62}Zn$ reaction.

Ep (MeV)	FR%	$\sigma^{se}_{p,2n}$ (mb)	$\sigma^{spr}_{p,2n}$ (mb)	$\sigma^{sepr}_{p,2n}$ (mb)
24.0	8.9	96.3	4.4	92.1
22.5	8.1	87.3	3.6	83.8
21.0	7.3	74.7	2.6	71.9
19.5	6.6	71.1	2.1	68.5
18.5	6.0	69.5	1.7	67.0
17.5	5.5	66.4	1.3	64.1
16.5	5.0	53.4	0.8	51.5
15.5	4.5	32.9	0.3	31.7
14.5	4.0	9.1	0.0	8.7

Table VIII. Results of statistical model calculations for $^{65}Cu(p,n)\ ^{65}Zn$ reaction using Weisskopf single particle model for photon emission.

Ep (MeV)	$\sigma^{*e}_{p,p}$ (mb)	$\sigma^{*e}_{p,n}$ (mb)	$\sigma^{*e}_{p,d}$ (mb)	$\sigma^{e}_{p,2n}$ (mb)	$\sigma^{se}_{p,np}$ (mb)	$\sigma^{se}_{p,n\alpha}$ (mb)	$\sigma^{se}_{p,n}$ (mb)
21.4	274.4	845.7	23.6	502.6	224.1	66.6	52.4
20.4	239.4	848.2	18.5	496.8	200.9	86.7	64.3
19.4	230.1	850.0	13.9	496.5	176.9	93.1	83.5
18.4	220.0	849.1	10.3	509.1	154.3	92.2	93.2
17.4	208.1	847.6	7.4	539.1	109.3	82.7	116.5
16.4	196.7	843.7	5.2	547.6	77.3	62.6	156.2
15.4	183.9	839.4	3.7	544.0	45.8	34.3	215.3
14.4	171.1	833.1	2.6	500.2	20.2	13.1	299.6
13.4	158.1	823.8	1.8	394.6	5.6	3.9	419.7
12.4	146.3	807.8	1.1	237.0	0.3	0.5	570.0
11.4	131.5	785.6	0.3	74.1	0.0	0.0	711.5
10.4	115.4	749.5	0.0	0.0	0.0	0.0	749.5
9.4	100.5	692.3	0.0	0.0	0.0	0.0	692.3
8.4	86.8	614.7	0.0	0.0	0.0	0.0	614.7
7.4	74.6	520.7	0.0	0.0	0.0	0.0	520.7
6.4	58.0	414.3	0.0	0.0	0.0	0.0	414.3
5.4	32.1	295.3	0.0	0.0	0.0	0.0	295.3
4.4	9.7	166.5	0.0	0.0	0.0	0.0	166.5
3.4	1.2	55.5	0.0	0.0	0.0	0.0	55.5

Table IX. Results of preequilibrium model calculations for $^{65}Cu(p,n)\,^{65}Zn$ reaction..

E_p (MeV)	σ_{abs} (mb)	$\sigma^{*pr}_{p,n}$ (mb)	$\sigma^{*pr}_{p,p}$ (mb)	σ^{*pr}_{sum} (mb)	FR%	$\sigma^{pr}_{p,n}$ (mb)
21.4	1118	47.6	33.9	81.5	7.3	15.4
20.4	1103	43.0	30.2	73.2	6.6	16.0
19.4	1096	41.3	28.5	69.8	6.4	16.0
18.4	1081	38.1	25.8	63.9	5.9	16.1
17.4	1065	34.9	23.1	58.0	5.4	17.1
16.4	1067	31.7	20.4	52.1	4.9	17.5
15.4	1028	28.6	17.8	46.5	4.5	17.8
14.4	1008	26.1	15.3	41.4	4.1	18.4
13.4	985	22.6	12.8	35.4	3.6	18.2
12.4	956	19.6	10.4	30.0	3.1	17.8
11.4	919	16.8	8.0	24.8	2.7	16.4
10.4	866	13.8	5.7	19.5	2.3	13.8
9.4	794	10.5	3.7	14.2	1.8	10.5
8.4	702	7.3	2.1	9.4	1.3	7.3

Table X. Details of the calculations of excitation function of $^{65}Cu(p,n)\,^{65}Zn$ reaction.

E_p(MeV)	FR%	$\sigma^{pr}_{p,n}$ (mb)	$\sigma^{se}_{p,n}$ (mb)	$\sigma^{sepr}_{p,n}$ (mb)
21.4	7.3	15.4	52.4	64.0
20.4	6.6	16.0	64.3	76.1
19.4	6.4	16.0	83.5	94.2
18.4	5.9	16.1	93.2	103.8
17.4	5.4	17.1	116.5	127.3
16.4	4.9	17.5	156.2	166.0
15.4	4.5	17.8	215.3	223.4
14.4	4.1	18.4	299.6	305.7
13.4	3.6	18.2	419.7	422.8
12.4	3.1	17.8	570.0	570.1
11.4	2.7	16.4	711.5	708.7
10.4	2.3	13.8	749.5	746.1
9.4	1.8	10.5	692.3	690.3
8.4	1.3	7.3	614.7	614.0
7.4	-	-	520.7	520.7
6.4	-	-	414.3	414.3
5.4	-	-	295.3	295.3
4.4	-	-	166.5	166.5
3.4	-	-	55.5	55.5

Table XI. Recommended values of cross sections for $^{63}Cu(p,n)\ ^{63}Zn$ reaction for natural copper and copper enriched 100 percent in ^{63}Cu-isotpe

Ep (MeV)	Cross section (mb)[a]	Cross section (mb)[b]
24.0	25.8	17.8
22.5	34.5	23.8
21.0	51.9	35.9
19.5	71.1	49.1
18.5	98.4	68.0
17.5	148.4	102.5
16.5	213.8	147.7
15.5	307.5	212.5
14.5	425.8	294.2
13.5	524.6	362.5
12.5	525.1	362.8
11.5	496.7	343.2
10.5	454.9	314.3
9.5	400.8	277.0
8.5	345.0	238.4
7.5	281.0	194.2
6.5	258.3	178.5
5.5	206.5	142.7

a 100 percent enriched copper in ^{63}Cu-isotope
b natural copper

Table XII. Recommended values of cross sections for $^{63}Cu\ (p,2n)\ ^{62}Zn$ reaction for natural copper and copper enriched 100 percent in ^{63}Cu-isotope

Ep (MeV)	Cross section (mb)[a]	Cross section (mb)[b]
24.0	92.1	63.6
22.5	83.8	57.9
21.0	71.9	49.7
19.5	68.5	47.3
18.5	67.0	46.3
17.5	64.1	44.3
16.5	51.1	35.6
15.5	31.7	21.9
14.5	8.7	6.0

a 100 percent enriched copper in ^{63}Cu-isotope
b natural copper

Table XIII. Recommended values of cross sections for $^{65}Cu(p,n)$ ^{65}Zn reaction for natural copper and copper enriched 100 percent in ^{63}Cu-isotopes

Ep(MeV)	Cross section (mb)[a]	Cross Section(mb)[b]
21.4	64.0	19.8
20.4	76.1	22.9
19.4	94.2	29.1
18.4	103.8	32.1
17.4	127.3	39.3
16.4	166.0	51.3
15.4	223.4	69.0
14.4	305.7	94.5
13.4	422.8	130.7
12.4	570.1	176.2
11.4	708.7	219.0
10.4	746.1	230.6
9.4	690.3	213.3
8.4	614.0	189.7
7.4	520.7	160.9
6.4	414.3	128.0
5.4	295.3	91.3
4.4	166.5	51.5
3.4	55.5	17.2

a 100 percent enriched copper in ^{65}Cu-isotope
b natural copper

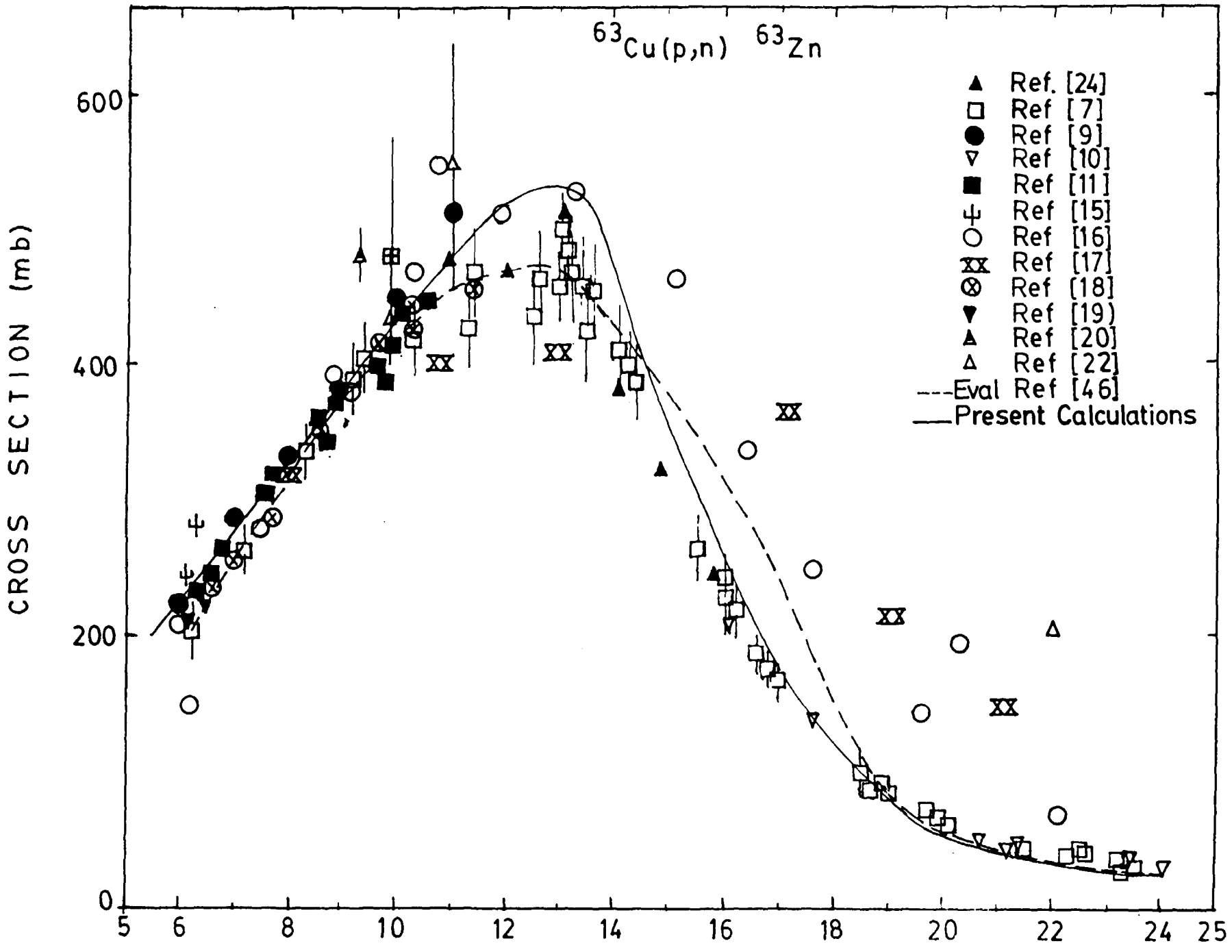
$^{63}Cu(p,n)\ ^{63}Zn$
Ref. [24]
Ref [7]
Ref [9]
Ref [10]
Ref [11]
Ref [15]
Ref [16]
Ref [17]
Ref [18]
Ref [19]
Ref [20]
Ref [22]
---Eval Ref [46]
——Present Calculations
CROSS SECTION (mb)
0
200
400
600
5
6
8
10
12
14
16
18
20
22
24
25
PROTON ENERGY (MeV)

FIG.1

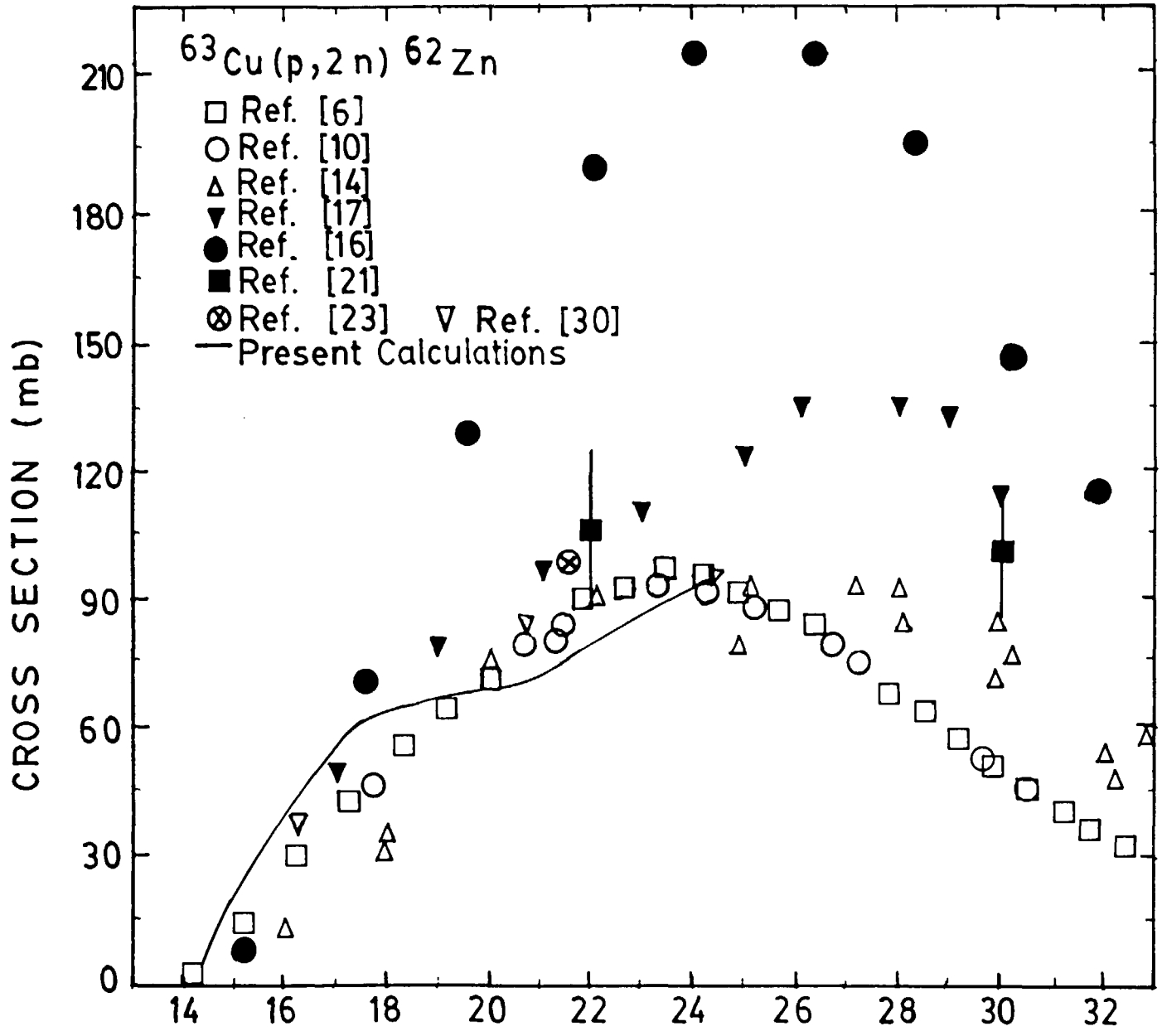
$^{63}Cu(p,2n)^{62}Zn$
Ref. [6]
Ref. [10]
Ref. [14]
Ref. [17]
Ref. [16]
Ref. [21]
Ref. [23]
Ref. [30]
Present Calculations
CROSS SECTION (mb)
0
30
60
90
120
150
180
210
14
16
18
20
22
24
26
28
30
32
PROTON ENERGY (MeV)

FIG. 2

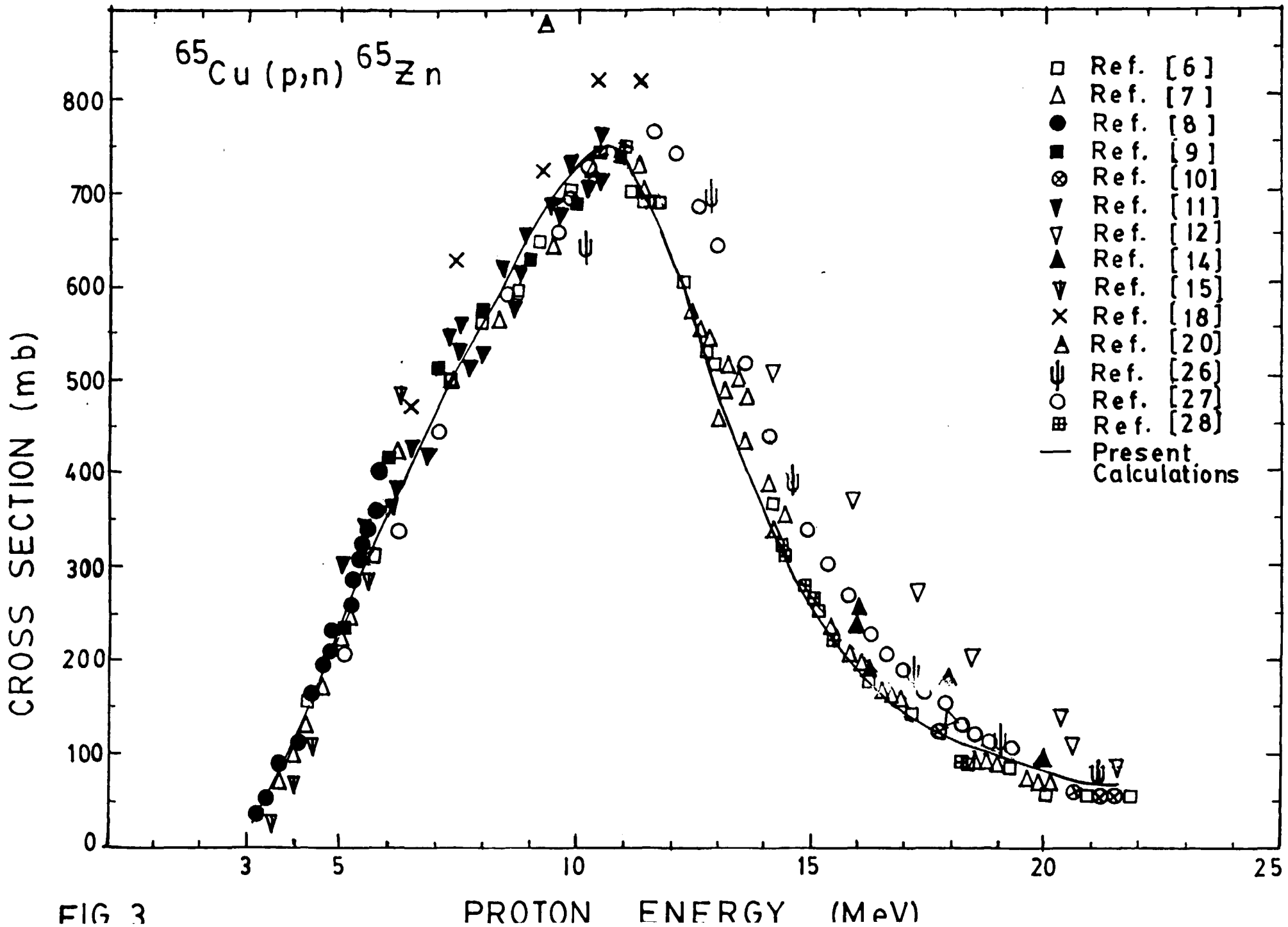
$^{65}Cu(p,n)^{65}Zn$
Ref. [6]
Ref. [7]
Ref. [8]
Ref. [9]
Ref. [10]
Ref. [11]
Ref. [12]
Ref. [14]
Ref. [15]
Ref. [18]
Ref. [20]
Ref. [26]
Ref. [27]
Ref. [28]
Present Calculations
CROSS SECTION (mb)
PROTON ENERGY (MeV)
0
100
200
300
400
500
600
700
800
3
5
10
15
20
25

FIG 3

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