ANALYSIS OF FAST-NEUTRON-INDUCED (n,α) REACTION CROSS SECTIONS AND ANGULAR DISTRIBUTIONS FOR MEDIUM MASS NUCLEI

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1. Introduction

Investigation of (n,α) reactions induced by fast neutrons is important for both nuclear reactor technology and the understanding of basic nuclear physics problems. For example, the (n,α) reaction leads to a buildup of residual radioactivity and radiation damage due to helium production in the structural materials. On the other hand, systematic study of such reactions depending on neutron energy allows the contributions of compound, pre-equilibrium and direct mechanisms of the studied reactions to be determined. However, for neutron energy of several MeV, where the thresholds of many of the (n,α) reactions lie, the experimental data base is rather scarce and there are significant discrepancies between the available results of various authors. In addition, essential deviations among evaluated nuclear data libraries for fast neutron induced (n,α) reaction cross sections exist, also.

In connection with this situation, during the last ~20 years in the several MeV energy range of neutrons we studied the (n,α) reaction for broad mass of nuclei ($6 \leq A \leq 149$).

In this work from the unified view point using the TALYS-1.6 code [1] we analyzed our experimental (n,α) cross sections and angular distributions for medium mass nuclei including 11 isotopes from ^{39}K to ^{95}Mo [2-16]. Our results are compared to other existing experimental data [17-48] and the evaluated nuclear data libraries [49], also.

2. Total (n,α) Cross Sections

Our experimental total (n,α) cross sections in the several MeV energy range of neutrons for 11 nuclei from ^{39}K to ^{95}Mo [2-16] are compared to other existing experimental data [17-48], evaluated nuclear data libraries [49] and TALYS-1.6 [1] calculations with default optical potential parameters in Figs.1,2. It can be seen from the Figs.1,2 that for total (n,α) cross sections existing experimental data of medium mass nuclei are very scanty and evaluated nuclear data libraries give essential different results for the same nucleus.

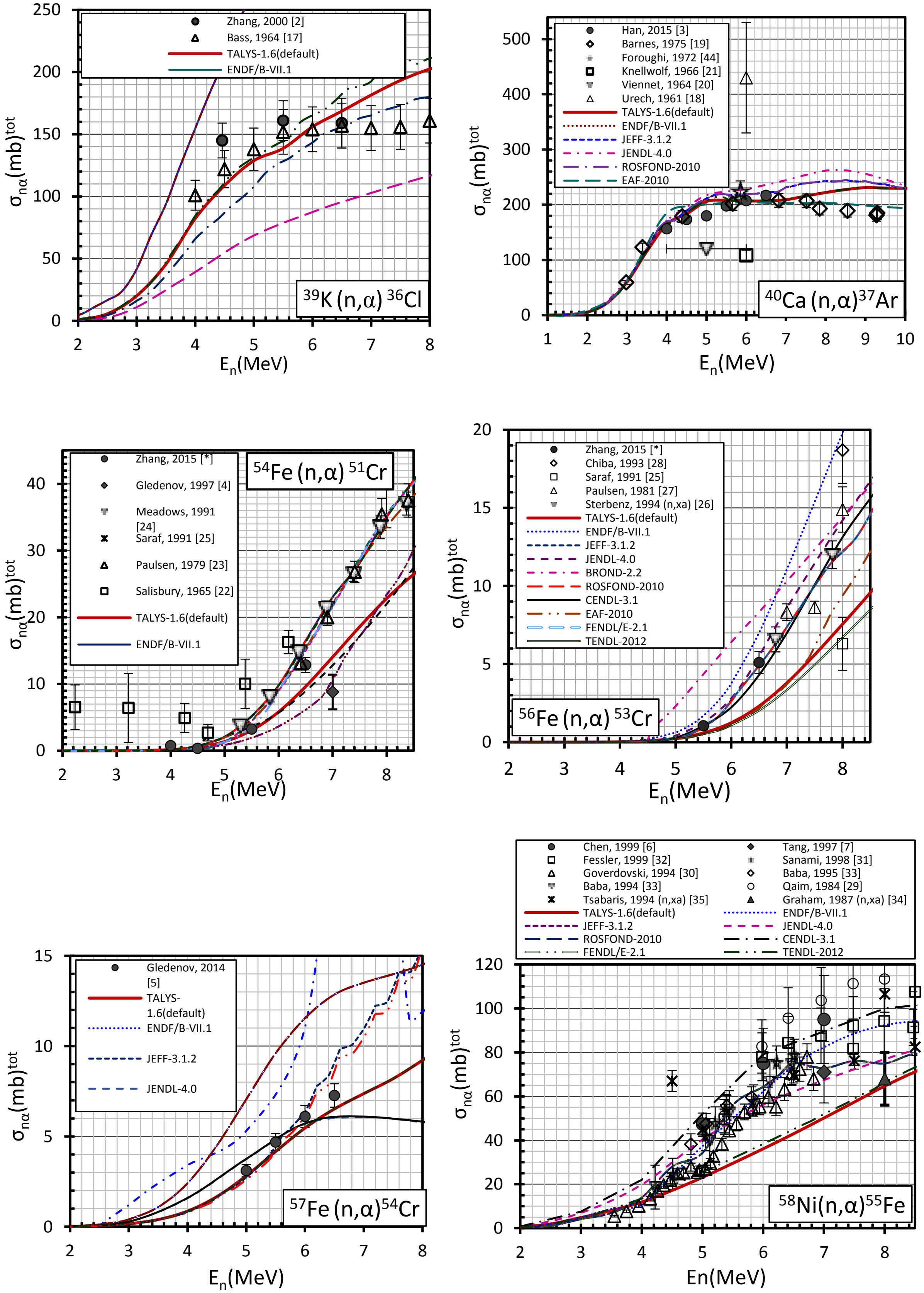
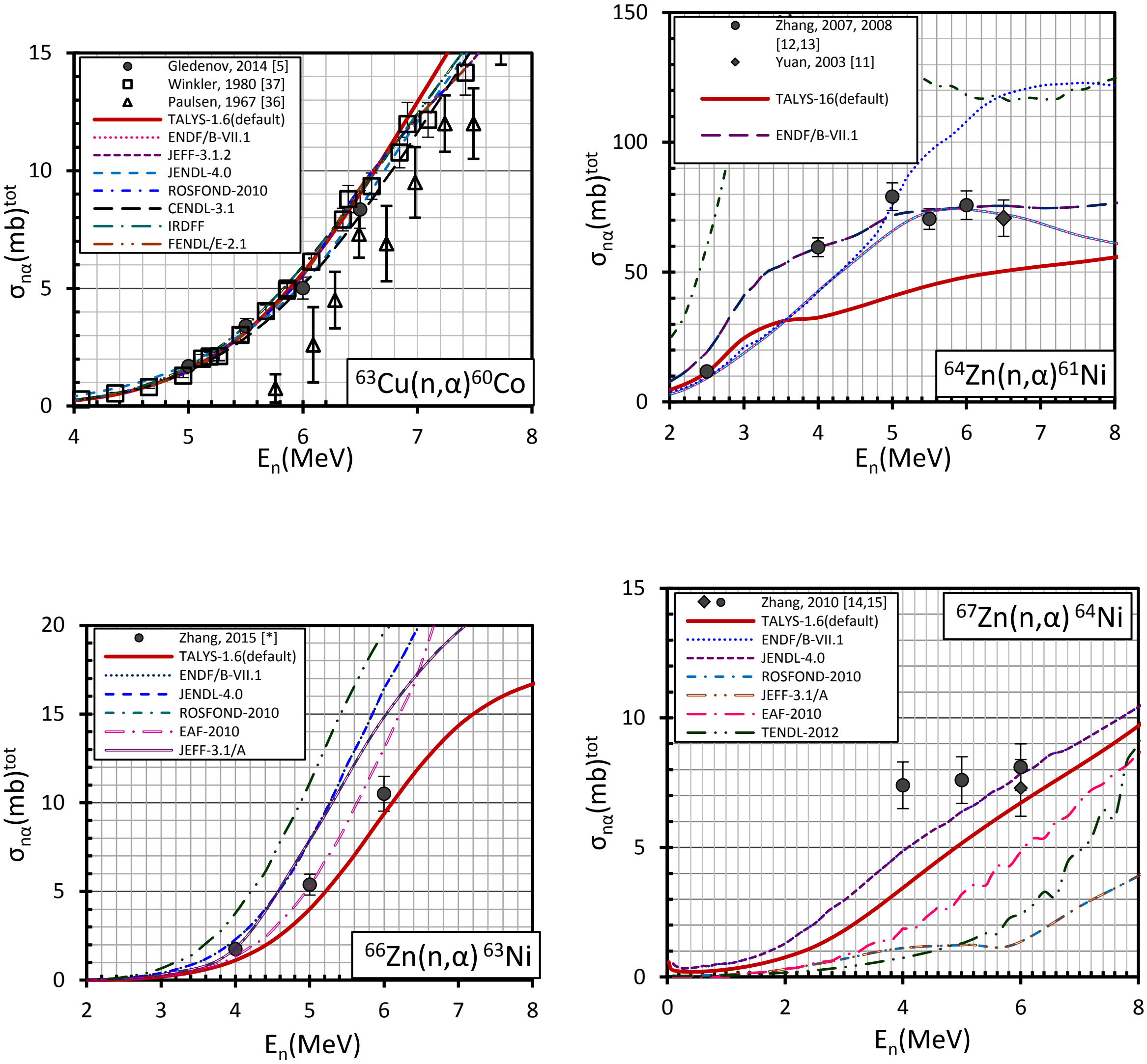


Fig.1. Total (n,α) cross sections for ^{39}K, ^{40}Ca, ^{54}Fe, ^{56}Fe, ^{57}Fe and ^{58}Ni.



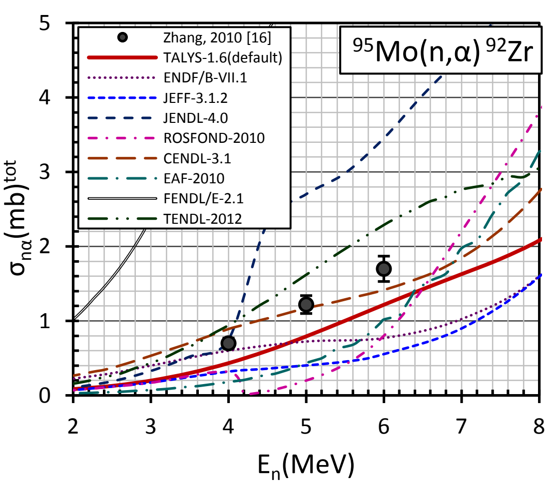


Fig.2. The same as in Fig.1 for ^{63}Cu, ^{64}Zn, ^{66}Zn, ^{67}Zn and ^{95}Mo.

$^{39}K(n,\alpha)^{36}Cl$. For this reactionour experimental cross sections at the neutron energies of 4.5, 5.5 and 6.5 MeV [2] are satisfactorily in agreement with data of Ref. [17], evaluation of EAF-2010 and calculations by TENDL-2012 and TALYS-1.6. At the same time, our results are in disagreement with the evaluated data of JEFF-3.1/A, ENDF/B-VII.1, JENDL-4.0 and ROSFOND-2010.

$^{40}Ca(n,\alpha)^{37}Ar$. In this case our experimental cross sections at the neutron energies of 4.0, 4.5, 5.0, 5.5, 6.0 and 6.5 MeV [3] are in agreement with the experimental data of Refs. [19,44] and all evaluated nuclear data libraries [49]. Our results are in essential disagreement with data of Refs. [18,20,21].

$^{54}Fe(n,\alpha)^{51}Cr$. In this reaction our preliminary results of the cross sections for neutron energy of 4.0, 4.5, 5.5 and 6.5 MeV [4] are in agreement with experimental data of Refs. [23,24] and the evaluated nuclear data libraries of JENDL-4.0, EAF-2010, ENDF/B-VII.1, JENDL-4.0, CENDL-3.1, IRDFF and FENDL/E-2.1.

However, our results are in disagreement with experimental data of [22], TENDL-2012, TALYS-1.6 calculations, evaluated nuclear data libraries of ROSFOND-2010, BROND-2.2 and JEFF-3.1.2.

$^{56}Fe(n,\alpha)^{53}Cr$.For this reactionour preliminary experimental cross sections at neutron energies of 5.5 and 6.5 MeV are in agreement with the evaluated nuclear data libraries of CENDL-3.1, ROSFOND-2010, JENDL-4.0, FENDL/E-2.1 and JEFF-3.1.2.

But, our results are in disagreement with the evaluated nuclear data libraries of BROND-2.2, EAF-2010, ENDF/B-VII.1 and TENDL-2012 and TALYS-1.6 calculations.

In addition, it can be seen that trend of dependence of our experimental cross sections on neutron energy is in agreement with experimental data of Refs. [26,27] and is different from data of Refs. [25,28].

$^{57}Fe(n,\alpha)^{54}Cr$.Our experimental cross sections of this reaction for neutron energy of 5.0, 5.5, 6.0 and 6.5 MeV [5] are satisfactorily in agreement with TENDL-2012, TALYS-1.6 calculations and EAF-2010, JEFF-3.1.2 evaluations. At the same time, our results are in disagreement with evaluations of FENDL/E-2.1, ROSFOND-2010, ENDF/B-VII.1, CENDL-3.1 and JENDL-4.0.

$^{58}Ni(n,\alpha)^{55}Fe$.For this reaction our experimental cross sections at neutron energies of 5.0, 6.0 and 7 MeV [6] are in agreement with experimental data of Refs. [31,32,33] and are in disagreement with data of Refs. [30,29]. Our results are in agreement with evaluations of CENDL-3.1 and are in disagreement with all other evaluations and TENDL-2012, TALYS-1.6 calculations.

$^{63}Cu(n,\alpha)^{60}Co$. Our experimental cross sections of this reaction at neutron energy of 5.0, 5.5, 6.0 and 6.5 MeV [5] are in good agreement with experimental data of Ref. [37], all evaluations and TALYS-1.6 calculations. At the same time our results are in essential disagreement with data of Ref. [36].

$^{64}Zn(n,\alpha)^{61}Ni$.For this reaction our experimental total cross sections at energies of 2.5, 4.0, 5.0, 5.5, 6.0 and 6.5 MeV [11-13] are satisfactorily in agreement with the evaluated data of JENDL-4.0 and ENDF/B-VII.1. But, most of our results are in essential disagreement with

TENDL-2012, TALYS-1.6 calculations with default parameters and evaluated nuclear data libraries of EAF-2012, JEFF-3.1/A and ROSFOND-2012.

^{66}Zn(n,α)^{63}Ni.Our preliminary results for total cross section of this reaction are satisfactorily in agreement with calculation by TALYS-1.6 and evaluation of EAF-2012. At the same time our results are in disagreement with other evaluations of JEFF-3.1/A, ROSFOND-2010, JENDL-4.0 and ENDF/B-VII.1. In addition, it should be noted that TALYS-1.6 and TENDL-2012 (Talys-based Evaluated Nuclear Data Library) calculations give essential different results for this reaction.

^{67}Zn(n,α)^{64}Ni. For this reaction our total cross section is satisfactorily in agreement with TALYS-1.6 calculation and JENDL-4.0 evaluation at neutron energy of 6 MeV [14], only, and our results at E_n=4 and 5 MeV [15] are in disagreement with all evaluations and TALYS-1.6 calculation.

^{95}Mo(n,α)^{92}Zr.In this case trend of dependence of our experimental cross sections [16] on neutron energy are satisfactorily in agreement with the CENDL-3.1 evaluation and are in disagreement with other evaluations and TALYS-1.6 calculation.

So, it can be concluded from these analyses that our experimental total (n,α) cross sections are in agreement with TALYS-1.6 calculations with default parameters for ^{40}Ca, ^{57}Fe, ^{63}Cu and ^{66}Zn. At the same time our experimental results are in disagreement with TALYS-1.6 calculations for ^{56}Fe, ^{58}Ni, ^{64}Zn, ^{67}Zn and ^{95}Mo. In addition, for ^{54}Fe and ^{39}Ktrend of dependenceof the experimental total (n,α) cross sections on neutron energy are roughly described by TALYS-1.6 calculations.

Also, Figs.1,2 show that various evaluated nuclear data libraries give essentially different total cross sections for these reactions except ^{40}Ca and ^{63}Cu. Moreover, the total (n,α) cross sections calculated by TALYS-1.6 with default parameters and Talys-based Evaluated Nuclear Data Library TENDL-2012 for the same reaction have visible discrepancy for ^{64}Zn, ^{66}Zn, ^{67}Zn and ^{95}Mo.

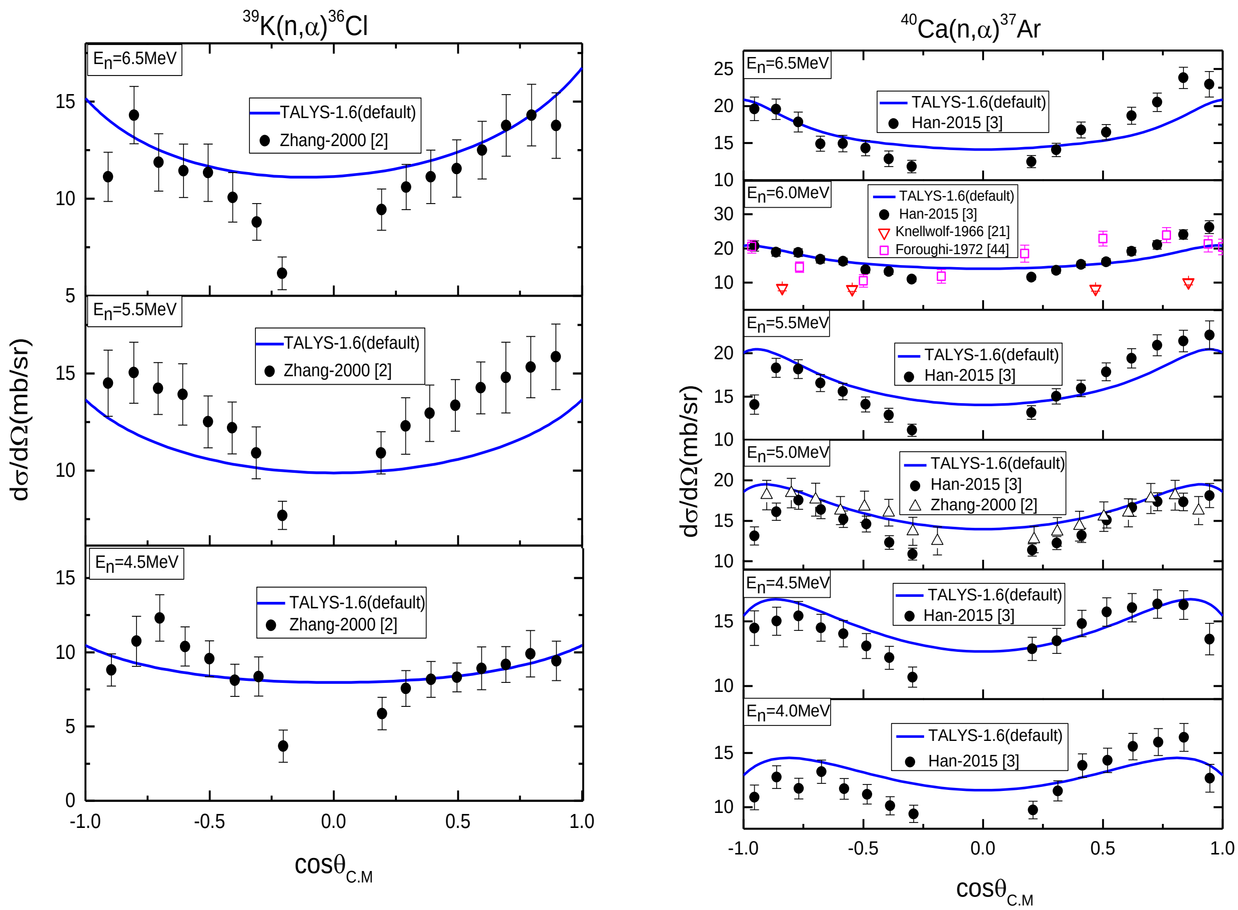
3. Angular Distribution

The angular distributions of emitted α-particles from (n,α) reaction induced by fast neutrons were measured for five target nuclei: ^{39}K, ^{40}Ca, ^{54}Fe, ^{58}Ni and ^{64}Zn (Figs.3,4).These angular distributions are nearly symmetrical with respect to θ_{cm}=90º. This fact indicates that compound mechanism predominates over the pre-equilibrium and direct reaction mechanisms in these reactions. At the same time, it should be noted that for the ^{54}Fe(n,α)^{51}Cr reaction the angular distribution at neutron energy 7 MeV is slightly forward picked which maybe shows presence of some non-statistical effect in this reaction.

Also, in Figs.3,4 our experimental angular distributions are compared with TALYS-1.6 calculations. In the case of angular distribution given in arbitrary units the results calculated by TALYS-1.6 are normalized to experimental data at the θ_{cm}=90º.It is seen that the experimental angular distributions are in agreement with TALYS-1.6 calculations for ^{39}K and ^{40}Ca. At the same time for ^{54}Fe, ^{58}Ni and ^{64}Zn there are visible discrepancies between the TALYS-1.6 calculations with default parameters and the experimental results.

In future, the TALYS code calculations should be done with different parameters from default one for those nuclei where there areessential discrepancies between the experimental data and calculated results. Namely, such calculations with the same optical model parameters should be simultaneously carried out for cross sections and angular distributions of the same reaction. Figs.3,4 show that our angular distribution for the $^{40}Ca(n,\alpha)^{37}Ar$ reaction at neutron energy 6 MeV is in disagreement with results of Refs. [21,44].

In these analyses partial (n,α) cross sections and angular distributions were not considered. Also, angular distributions of other authors given in arbitrary units were not included in our analyses.



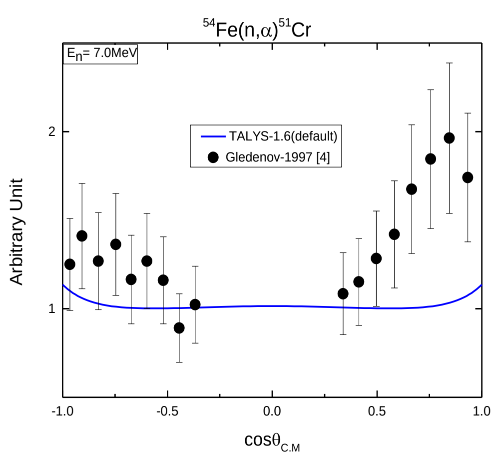


Fig.3. Angular distributions for the $^{39}K(n,\alpha)^{36}Cl$, $^{40}Ca(n,\alpha)^{37}Ar$ and $^{54}Fe(n,\alpha)^{51}Cr$ reactions.

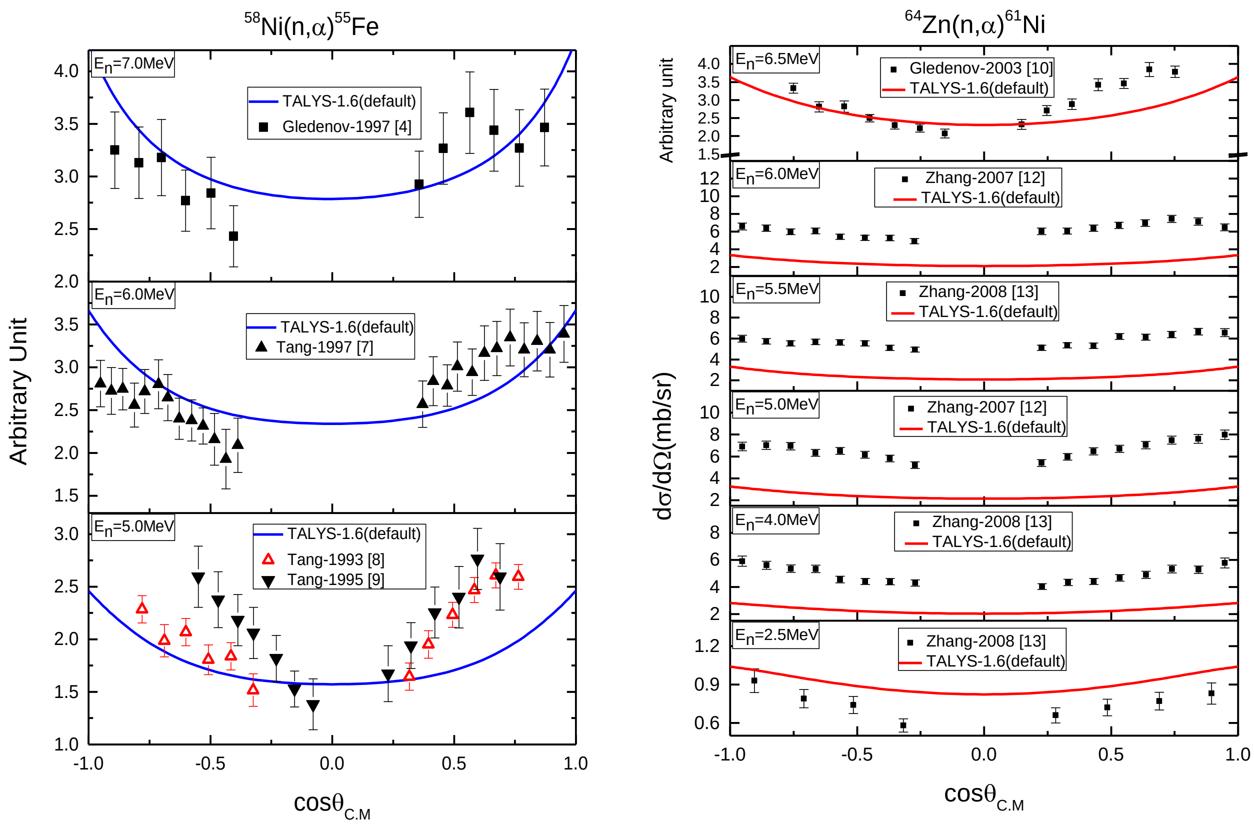


Fig.4. Angular distributions for the ^{58}Ni(n,α)^{55}Fe and ^{64}Zn(n,α)^{61}Ni reactions.

References

1. A.Koning, S.Hilaire and S.Goriely, TALYS-1.6, A Nuclear Reaction Program (User Manual), 2013, Petten, TheNederlands.
2. Xuemei Zhang *et al.*,Nucl. Sci. and Eng., v.134, N1, (2000), p.89
3. Jinhua Han, Jiaming Liu, Xiang Liu *et al.*, Eur. Phys. J., A, v.51, (2015), p.15012-5
4. Yu.M.Gledenov, M.V.Sedysheva, G.Khuukhenkhuu*et al.*,Prog. Intern. Conf. Nucl. Data for Sci. and Tech., (1997), Trieste, p.514
5. Yu.M.Gledenov, M.V.Sedysheva, V.A.Stolupin*et al.*, Phys. Rev. C, v.89, (2014), p.64607
6. Chen Zemin, Zhang Xuemei, Chen Yingtang*et al.*, Nuclear Physics Review, v.16, N1, (1999), p.31 (In Chinese)
7. Tang Guoyou, Fan Jihong, Chen Jinxiang*et al.*, Communication of Nuclear Data Progress, №17, (1997), p.1. China Nuclear Information Centre, Beijing.
8. Tang Guoyou, Bai Xinhua, Shi Zhaomin*et al.*, Communication of Nuclear Data Progress, N10, (1993), p.14
9. Tang Guoyou, Bai Xinhua, Shi Zhaomin*et al.*,Chinese Journal of Nuclear Physics, v.17, №1, (1995), p.45
10. Yu.M.Gledenov, M.V.Sedysheva, P.V.Sedyshev*et al.*,Izv.Akad.Nauk, ser.Fiz. T.67, N5, (2003), s.689
11. Jing Yuan, Zemin Chen, Guoyou Tang *et al.*,Nucl. Sci. and Eng., v.144, N1, (2003), p.108
12. Guohui Zhang, Rongtai Cao, Jinxian Chen *et al.*,Nucl. Sci. and Eng., v.156, (2007), p.115
13. Guohui Zhang, Jiaguo Zhang, Rongtai Cao *et al.*,Nucl. Sci. and Eng., v.160, (2008), p.123

14. Guohui Zhang, Hao Wu, Jiaguo Zhang *et al.*, Eur. Phys. J., A, v.43, (2010), p.1
15. Guohui Zhang, Yu.M.Gledenov, G.Khuukhenkhuu*et al.*, Phys. Rev.C, v.82, (2010), p.54619
16. Guohui Zhang, Hao Wu, Jiaguo Zhang *et al.*, Appl. Rad. and Isot., v.68, N1, (2010), p.180
17. R.Bass, U.Fanger and F.M.Saleh,Nucl. Phys., v.56, (1964), p.569
18. S.Urech, E,Jeannet and J.Rossel,Helv. Phys. Acta., v.34, N8, (1961), p.954
19. J.W.Barnes, B.P.Bayhurst, B.H.Erkkila*et al.*,J.Inorg. Nucl. Chem., v.37, N2, (1975), p.399
20. R.Viennet, T.Knellwolf and J.Rossel,Helv. Phys. Acta., v.37, N3, (1964), p.222
21. T.Knellwolf and J.Rossel,Helv. Phys. Acta., v.39, N4, (1966), p.376
22. S.R.Salysbury and R.A.Chalmers, Phys. Rev., v.140, N28, (1965), p.305
23. A.Paulsen, R.Widera, F.Arnotte and H.Liskien,Nucl. Sci. and Eng., v.72, N1, (1979), p.113
24. J.W.Meadows, D.L.Smith, L.R.Greenwood*et al.*,Prog. Intern. Conf. Nucl. Data for Sci. and Tech., Jülich, (1991), p.288
25. S.K.Saraf, C.E.Brient, P.M.Egun, S.M.Grimes*et al*.,Nucl.Sci. and Eng., v.107, N4, (1991), p.365
26. S.M.Sterbenz, F.B.Batman, T.M.Lee, R.C.Haight*et al.*,Prog. Intern. Conf. Nucl. Data for Sci. and Tech., Gatlinburg, (1994), v.1, p.314
27. A.Paulsen, H.Liskien, F.Arnotte and R.Widera,Nucl. Sci. and Eng., v.78, (1981), p.377
28. S.Chiba, N.Ito and M.Baba. (1993), in [21], Ref.9.
29. S.M.Qaim, R.Wölfle, M.M.Rahman and H.Ollig,Nucl. Sci. and Eng. v.88, N2, (1984), p.143
30. A.A.Goverdovski, V.A.Khryachkov, V.V.Ketlerov*et al.*,Prog. Intern. Conf. Nucl. Data for Sci. and Tech., Gatlinburg, (1994), v.1, p.117
31. T.Sanami, M.Baba, T.Kawano*et al.*,J.Nucl. Sci and Tech., v.35, N12, (1998), p.851
32. A.Fessler, J.RadiochimicaActa, v.84, N1, (1999), p.1
33. M.Baba, Proceedings of the International Seminar on Interaction of Neutrons with Nuclei, ISINN-3, JINR, E3-95-307, 1995, Dubna, p.191
34. S.L.Graham, M.Ahmad, S.M.Grimes*et al.*,Nucl. Sci. and Eng. v.95, N1, (1987), p.60
35. C.Tsabaris, E.Wattecamps and G.Rollin,Prog. Intern. Conf. Nucl. Data for Sci. and Tech., Gatlinburg, v.1, (1994), p.282
36. A.Paulsen and H.Liskien,Nucleonik, v.10, (1967), p.91
37. G.Winkler, D.L.Smith and J.W.Meadows,Nucl. Sci. and Eng., v.76, N.1, (1980), p.30
38. F.Cserpak,S.Sudar, J.Csikai and S.M.Qaim, Phys. Rev.C., v.49, N3, (1994), p.1525
39. G.Calvi, A.S.Figuera and R.Potenza,ComptesRendus du Congres International de Physique Nucleaire, (1964), v.2, Paris, p.724
40. S.Cavallaro and A.Rubbino, Phys.Lett., v.5, N4, (1963), p.265
41. H.Abaschi, B.Chambon, R.Salin and J.Depraz,ComptesRendus, T.265, N20, (1967), p.1127
42. C.M.Bartle, P.B.Johnson and N.G.Chapman,Nucl. Phys.A., v.220, N2, (1974), p.395
43. C.M.Bartle and P.A.Quin, Annals of Nuclear Energy, v.8, N1, (1981), p.43
44. F.Foroughi and J.Rossel,Helv. Phys. Acta., v.45, N3, (1972), p.439
45. R.Bass and F.Saleh, Progr. Report of Nucl. Data Research in the Euratom Community, EANDC 57 ‘U’, (1965), p.1
46. D.I.Garber, L.G.Stromberg, M.D.Goldberg*et al.*, Angular Distributions in Neutron-Induced Reactions, BNL-400, Brookhaven National Laboratory, Associated Universities, INC. USA, (1970).
47. E.Wattecamps, Proc. Intern. Conf. Nucl. Data for Sci. and Tech., (1991), Jülich, p.310
48. https://www-nds.iaea.org/exfor/exfor.htm
49. https://www-nds.iaea.org/exfor/endf.htm