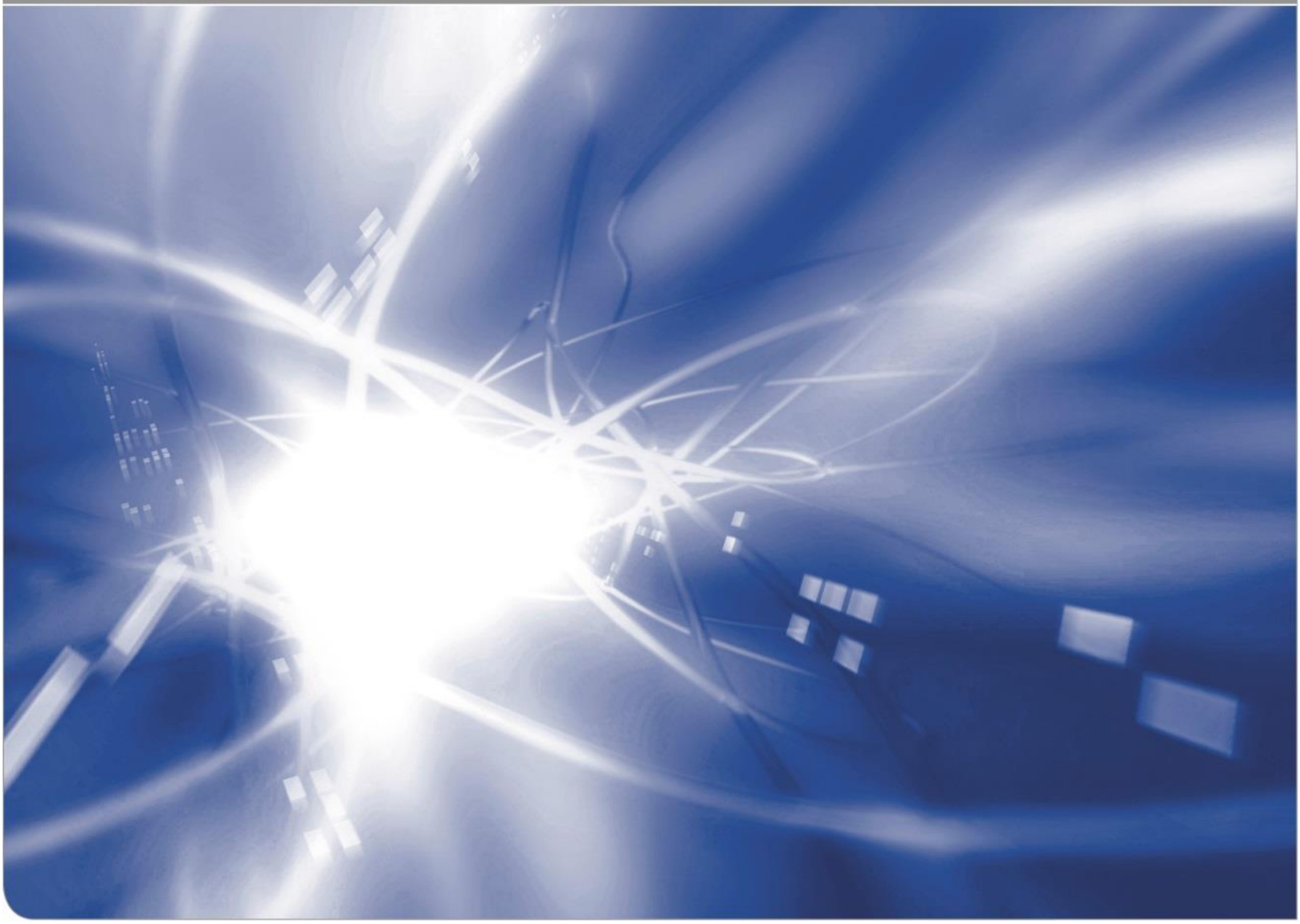
Karlsruhe Institute of Technology

Improved modelling of alpha-particle emission in nucleon induced reactions

A.Yu. Konobeyev[1], D. Leichtle[1], A.J. Koning[2]

KIT SCIENTIFIC WORKING PAPERS 176



[1] INR, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany

[2] Nuclear Data Section, International Atomic Energy Agency, A-1400 Vienna, Austria

Impressum

Karlsruher Institut für Technologie (KIT)
www.kit.edu

2021

ISSN: 2194-1629

Abstract

This report discusses the phenomenological approach proposed to estimate the contribution of direct processes to the emission of α-particles in nucleon induced reactions. Using available measured energy distributions, the values of the parameters required for the calculations are obtained. The analysis was performed using the TALYS code.

CONTENTS

1. Introduction

The modelling of α-particle energy distributions in nucleon induced reactions at intermediate primary energies remains a challenge, and it is too early to talk about a final solution. With caution, one can only say about the relative success of modeling the equilibrium and pre-equilibrium α-emission. The calculation or estimation of the contribution of direct processes in α-particle spectra is a special task that cannot be easy solved for most nuclei because of the lack of experimental data and complexity of theoretical analysis.

A paragon for calculating the spectra of α-particles produced in direct interactions is the works of Gadioli et al. [1-3], which combine the application of a rigorous theoretical approach with the use of detailed measured α-spectra. For most targets, the use of such a method, for obvious reasons, seems difficult.

In this work the question is raised whether it is possible to describe the hard part of the α-particle spectra using a less rigorous approach than that used in Refs.[1-3], but which, to a certain extent, would give acceptable or close results. Such a method would have to be more suitable for mass calculations and for improving the quality of predictions of existing models and codes. With a certain degree of caution this question is answered positively.

The phenomenological approach discussed and proposed in this work does not claim to be rigorous, but its use provides some advantages and increases, to a certain extent, the agreement between measured and predicted data.

The proposed method of calculation is used within the TALYS code [4,5] and, naturally, will profit from a combination of models already implemented in the code.

The approach is discussed in Section 2. Section 3 presents a comparison of the calculated and measured α-particle spectra and the discussion.

2. Brief description of method of calculation

The TALYS code implements the Kalbach model [6] for calculating the pre-equilibrium emission spectra of complex particles. The use of the model does not imply an explicit consideration of direct processes. The present work shows that the situation can be improved to some extent.

The simplest attempt to describe direct processes in some way without resorting to a rigorous theory is to use the approach from Refs.[7,8]. In spite of its formulation for a hybrid model [9], and as a possible phenomenological solution, it does not lead to contradictions when using the exciton model [10] to simulate the whole pre-equilibrium emission. Using results of Refs.[7,8] approach, the contribution of direct processes to α-particle emission can be estimated as follows

$$\frac{d\sigma^D}{d\varepsilon_\alpha} \sim \beta_1\, exp(-\beta_2(U-\beta_3)^2)\, \frac{\lambda_\alpha^e(\varepsilon_\alpha)}{\lambda_\alpha^e(\varepsilon_\alpha)+\lambda_\alpha^+(\varepsilon_\alpha)}\, g_\alpha, \qquad (1)$$

where $\lambda_\alpha^e(\varepsilon_\alpha)$ and $\lambda_\alpha^+(\varepsilon_\alpha)$ are emission and absorption rates of α-particles, which are calculated similarly to Ref.[7,8], β_i are parameters, other symbols are conventional.

There are three parameters in Eq.(1), the sensitivity of the calculations to which and which importance, can be checked by comparing the measured and calculated α-particle spectra.

In the TALYS code, the Kalbach continuum α-particle spectrum is “mapped” on discrete states, which aptly simulates the effect of real resolution of measurements. The study shows that the change of normalization coefficient of one of the corresponding values “fac1” or “fac2” in the TALYS subroutine “Spectra” together with the use of Eq.(1), can further improve the agreement with the experimental data.

The routines providing calculations using Eq.(1) from Refs.[11,12] were added to the TALYS code [4,5].

The next Section discusses the comparison of calculated α-particle spectra with experimental data, the use of parameters, and the problems associated with calculations.

3. Results and discussion

The available measured energy distributions of α-particles in neutron induced reactions for 38 target nuclei and in proton induced reactions for 43 target nuclei from ^{12}C to ^{238}U [1,3,13-72] have been analysed.

Not all experimental data, or rather a smaller part of them, are suitable for studying the contribution of direct processes to the α-particle energy distributions. Such a study requires detailed information about the hard part of the spectra, which was not always obtained in the measurements.

The parameters were chosen to achieve the best visible agreement with the experimental data. If possible, the parameters were taken to be the same for different targets or, practically, were not used, as in the case of the β_3 parameter.

The study shows that in most cases, when suitable experimental information is available, the use of discussed phenomenological model for calculations significantly improves the agreement between the calculated and measured data.

Figures 1-68 show examples of calculated α-particle energy distributions together with measured data. The results for neutron induced reactions are shown in Figs.1-51 and for proton induced reactions in Figs.52-68.

The resulting value of the β_2 parameter for all reactions except (n,xα) on ^{95}Mo, ^{142,143,144}Nd, and ^{144,149}Sm was taken equal to 0.3, assuming that subroutines from Refs.[11,12] are used for calculations with Eq.(1). The β_3 value is equal to zero for all considered reactions except n+^{60,61,62,63}Ni. The value of β_1 varies from 10^{-5} to 10^{-2} with a general trend that heavier target nuclei have lower β_1 values.

The normalization coefficient C_f for "fac2" ranges from 1 (no changes), to 10. The number of cases of coefficient value 2 is 25%, value 5 is 47%, and 10 is 10%.

All parameters β_i and C_f were treated as independent of incident nucleon energy.

The results indicate the principal possibility of using the discussed phenomenological approach to improve the agreement between the calculated and experimental α-particle energy distributions. In most cases, as mentioned above, it is necessary to know only the values of β_1 and C_f parameters. Of course, in the absence of necessary experimental information, it is possible to use global or systematic values of these parameters.

Obviously, the use of discussed method cannot replace the rigorous theoretical calculations of the α-particle spectra. However, even in this case the experimental information is necessary to obtain the absolute values of the spectra [1].

The described approach can apparently be extended to describe the emission of other complex particles using the models implemented in the TALYS code.

Hopefully, new measurements of α-particle spectra will provide more information necessary to improve and refine this approach, and will create the possibility of a detailed theoretical analysis of the spectra.

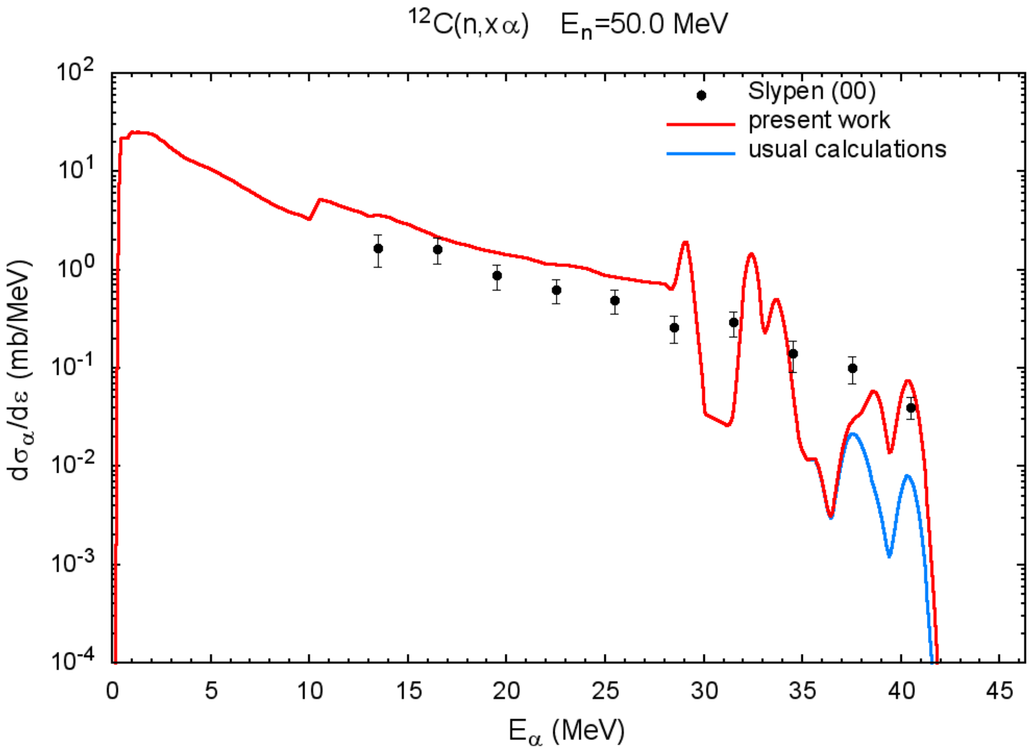


Fig.1 Comparison between experimental α-particle energy distributions and calculations using the TALYS code [4,5] without (blue line) and using (red line) the discussed phenomenological model for the estimation of contribution of direct processes to the α-particle emission for the n+^{12}C reaction at the primary neutron energy equal to 50 MeV.

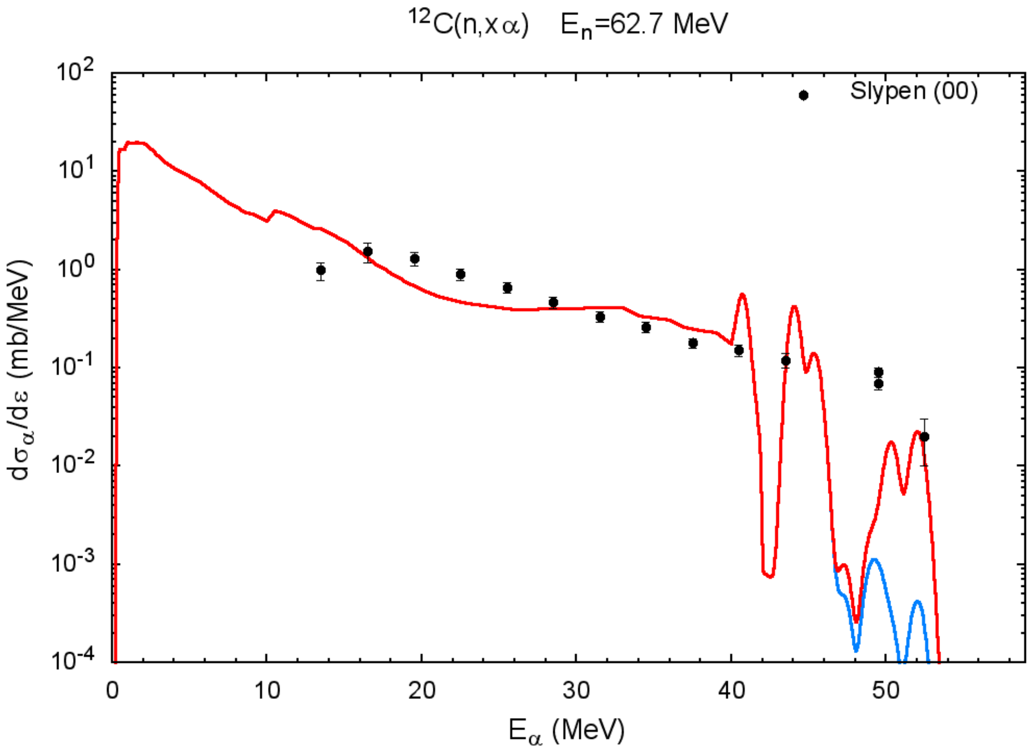


Fig.2 The same as in Fig.1 but for the n+^{12}C reaction at E_n=62.7 MeV.

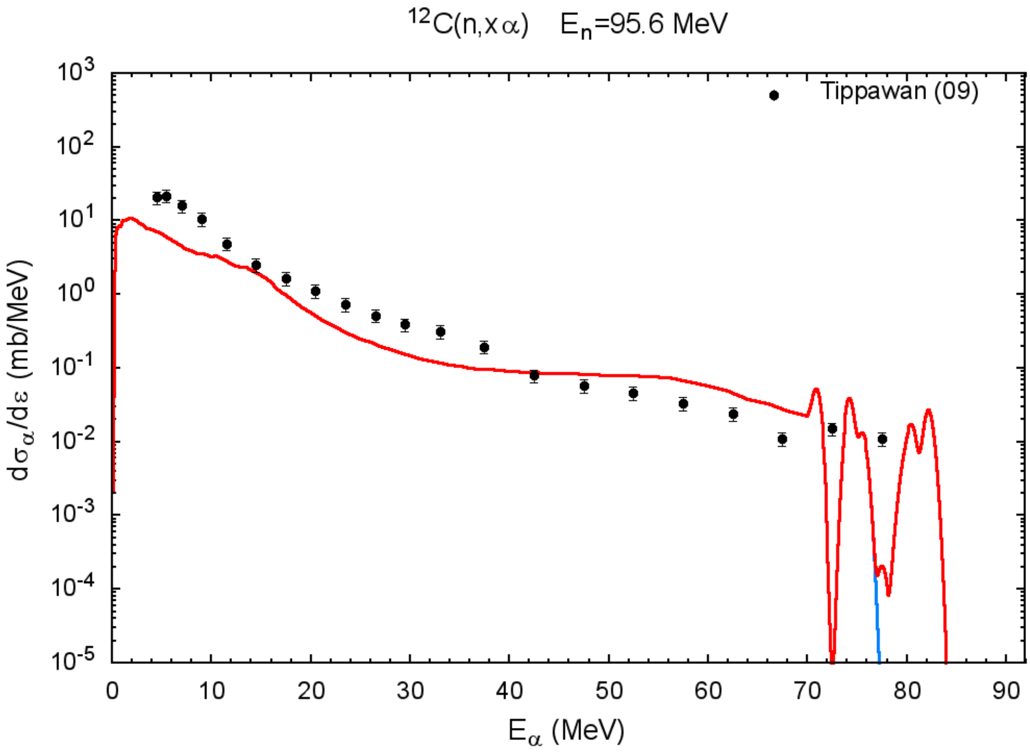


Fig.3 The same as in Fig.1 but for the n+^{12}C reaction at E_n=95.6 MeV.

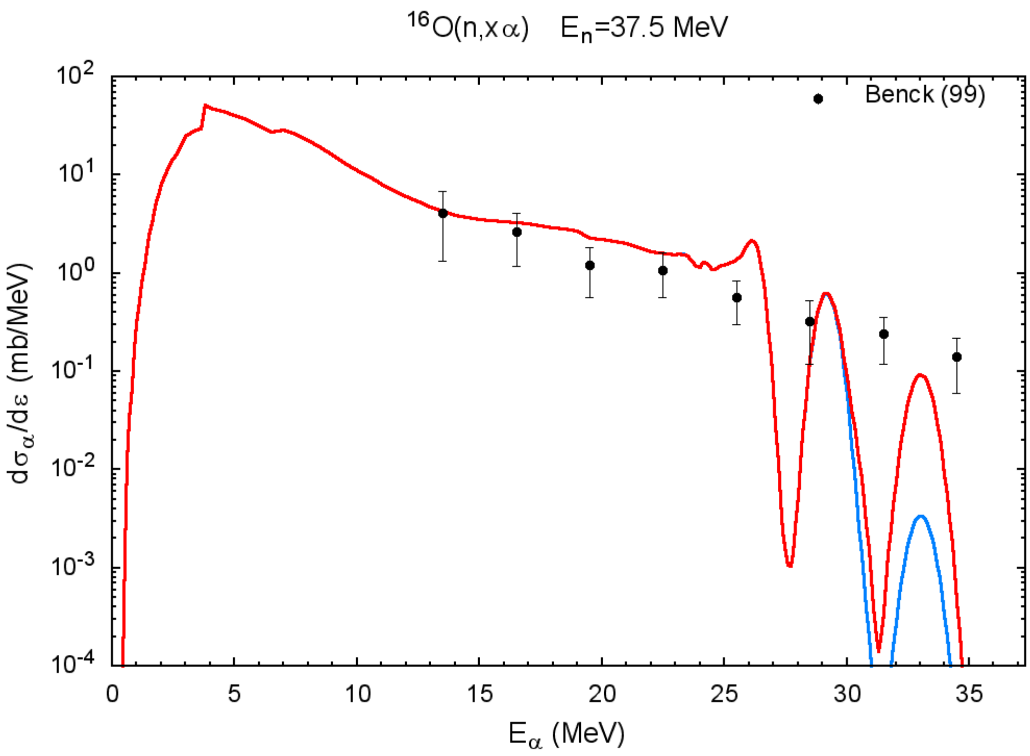


Fig.4 The same as in Fig.1 but for the n+^{16}O reaction at E_n=37.5 MeV.

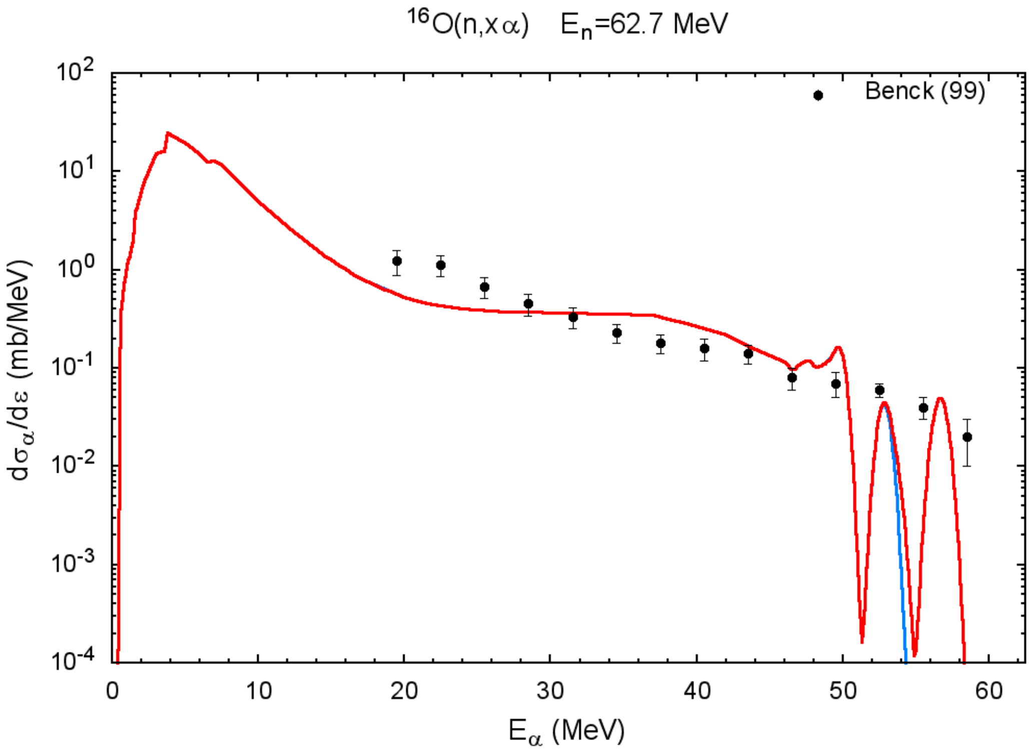


Fig.5 The same as in Fig.1 but for the n+^{16}O reaction at E_n=62.7 MeV.

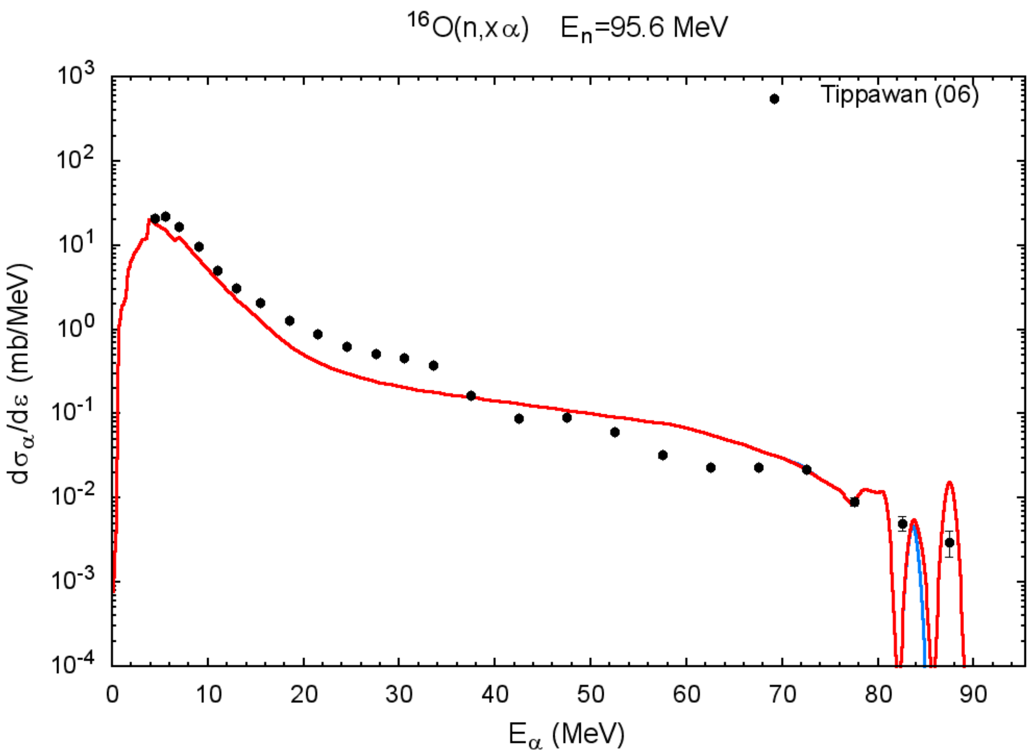


Fig.6 The same as in Fig.1 but for the n+^{16}O reaction at E_n=95.6 MeV.

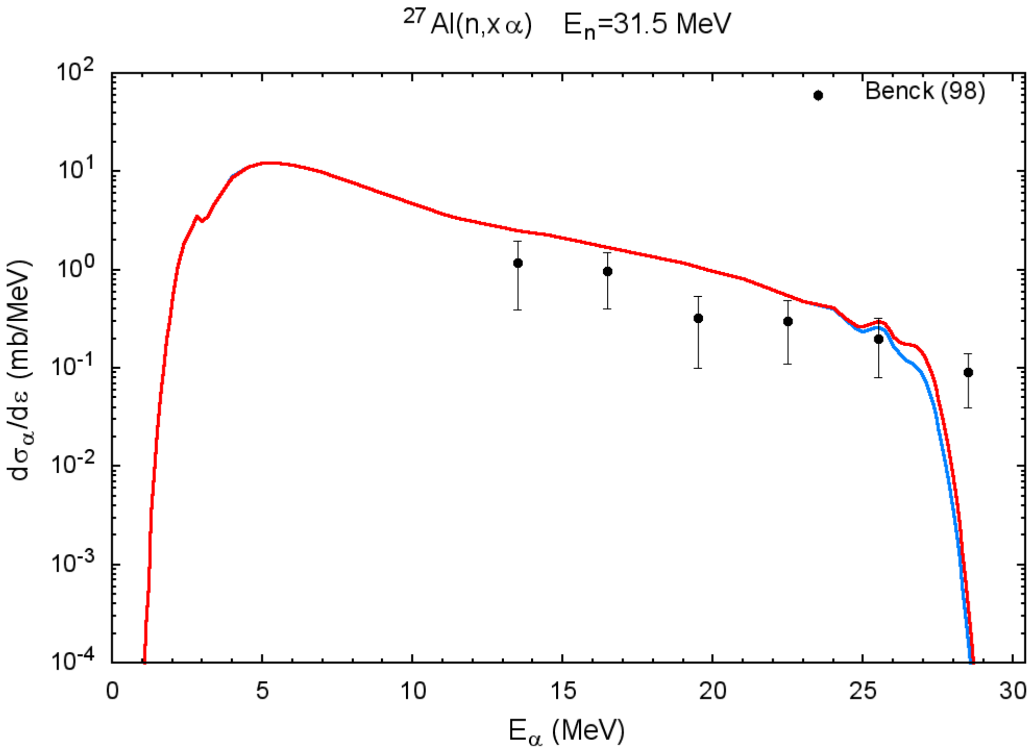


Fig.7 The same as in Fig.1 but for the n+^{27}Al reaction at E_n=31.5 MeV.

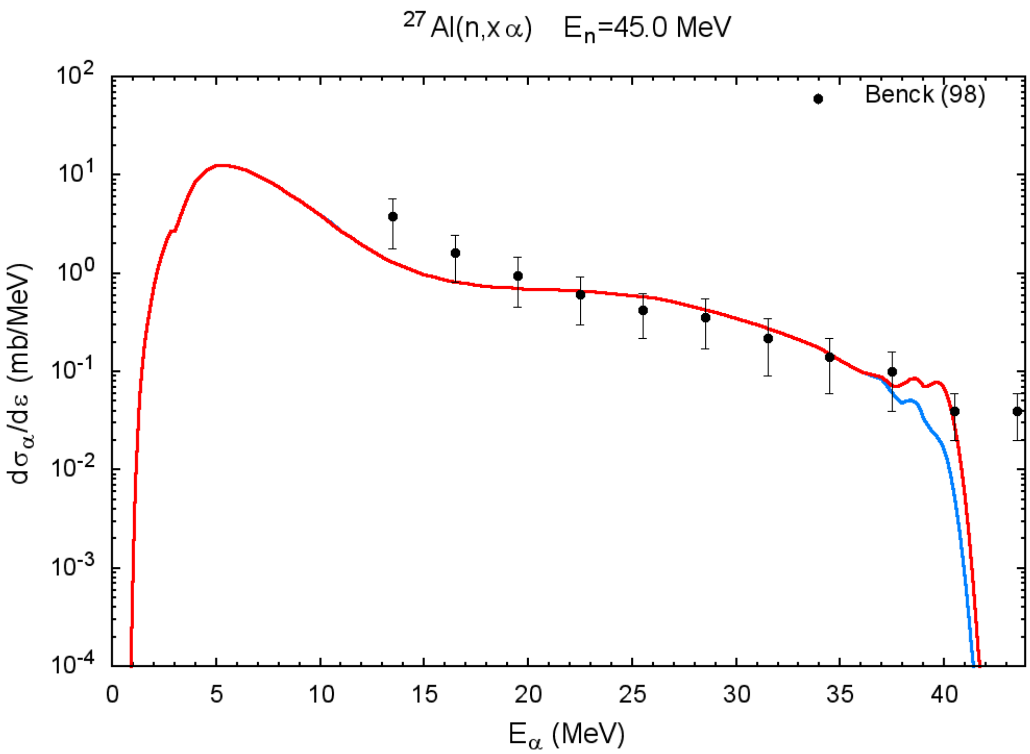


Fig.8 The same as in Fig.1 but for the n+^{27}Al reaction at E_n=45 MeV.

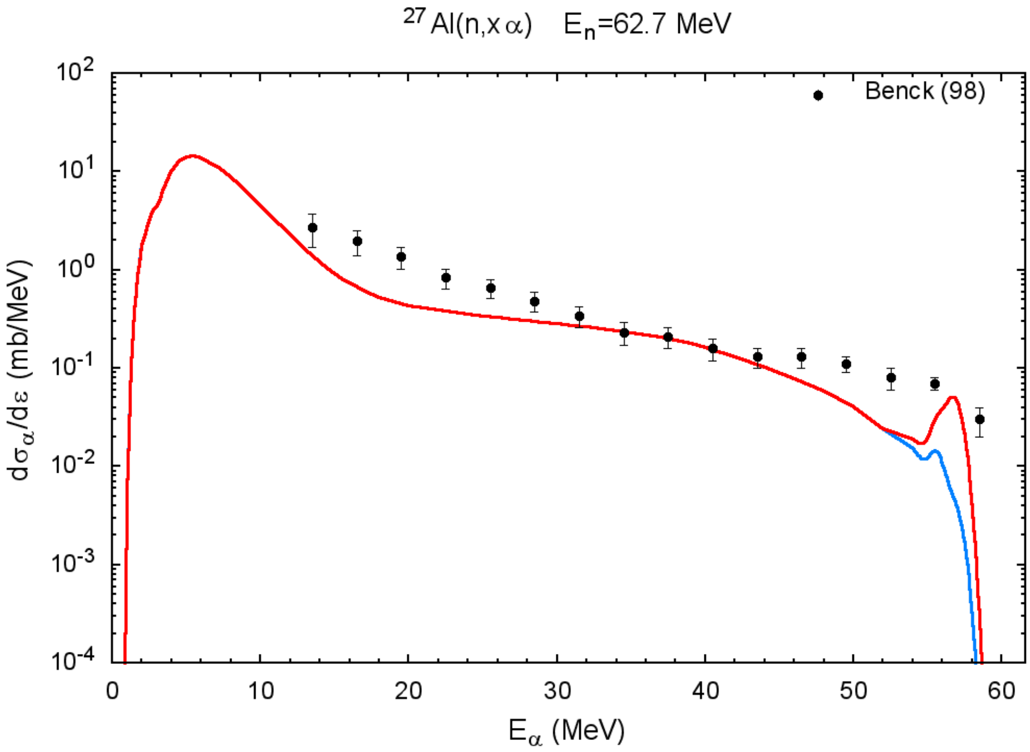


Fig.9 The same as in Fig.1 but for the n+^{27}Al reaction at E_n=62.7 MeV.

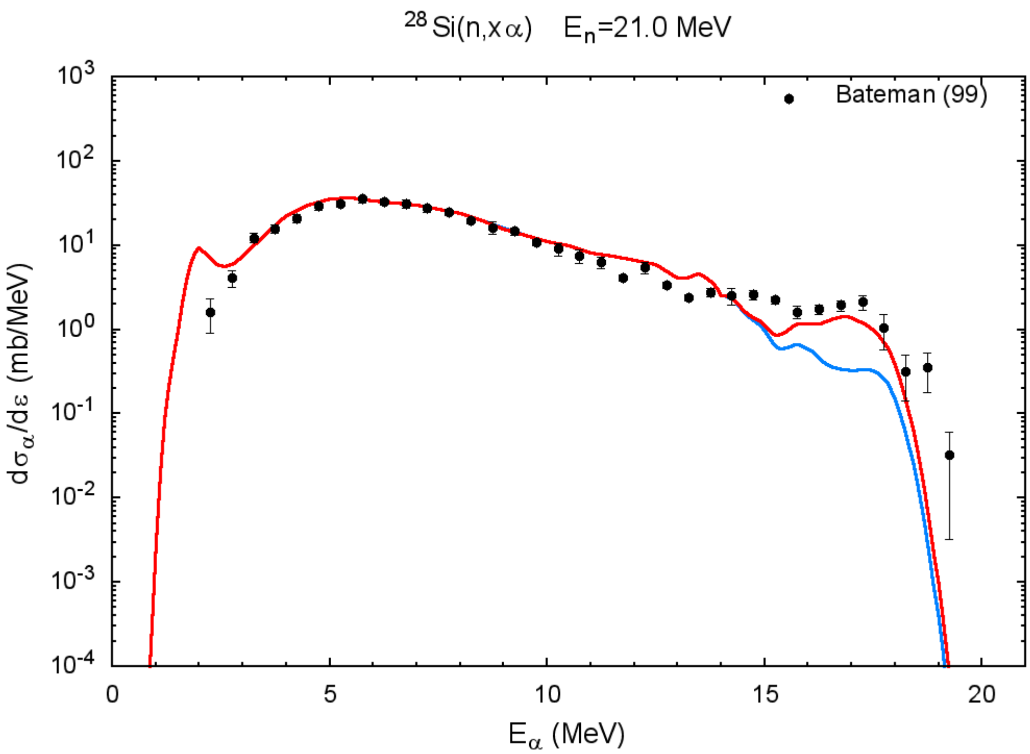


Fig.10 The same as in Fig.1 but for the n+^{28}Si reaction at E_n=21 MeV.

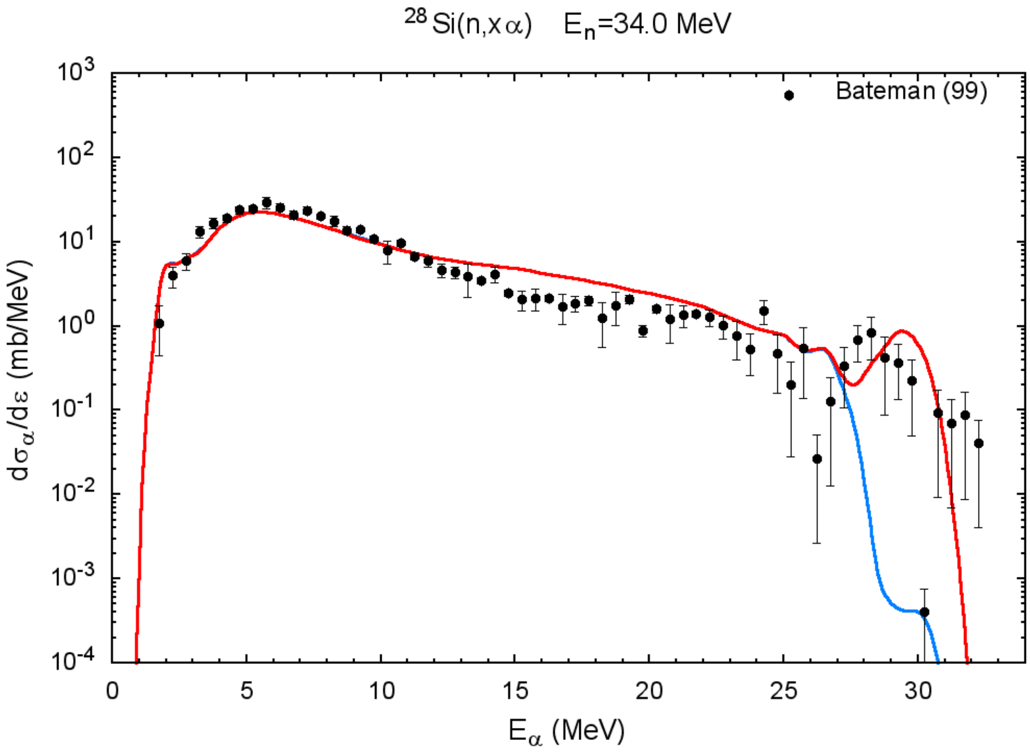


Fig.11 The same as in Fig.1 but for the n+^{28}Si reaction at E_n=34 MeV.

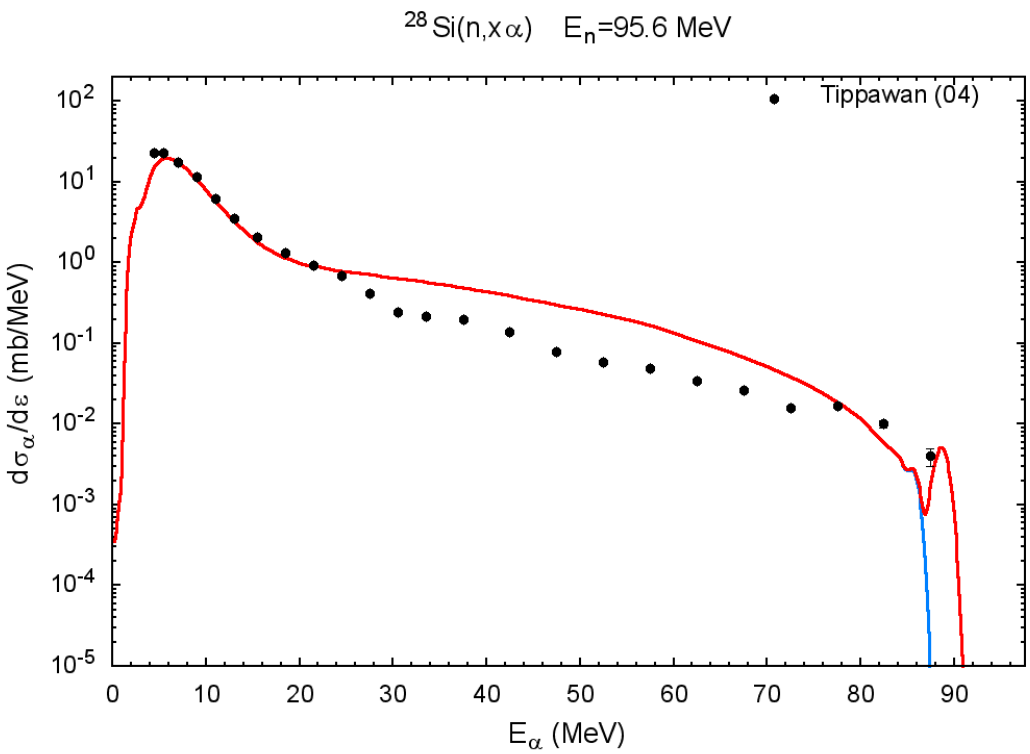


Fig.12 The same as in Fig.1 but for the n+^{28}Si reaction at E_n=95.6 MeV.

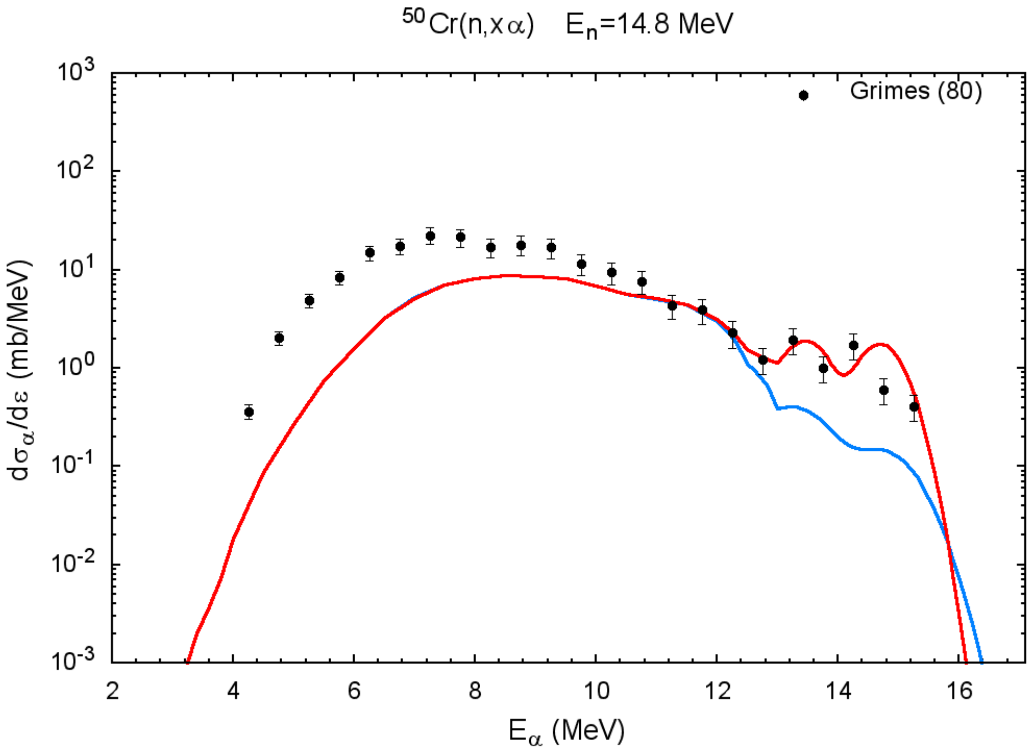


Fig.13 The same as in Fig.1 but for the n+^{50}Cr reaction at E_n=14.8 MeV.

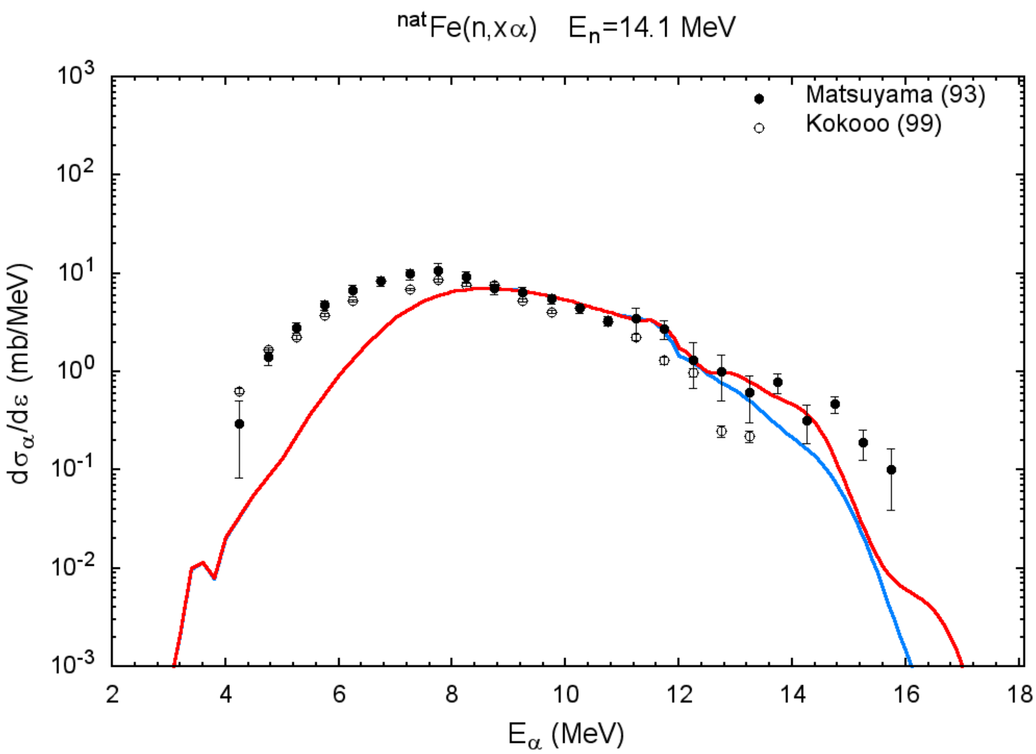


Fig.14 The same as in Fig.1 but for the n+Fe reaction at E_n=14.1 MeV.

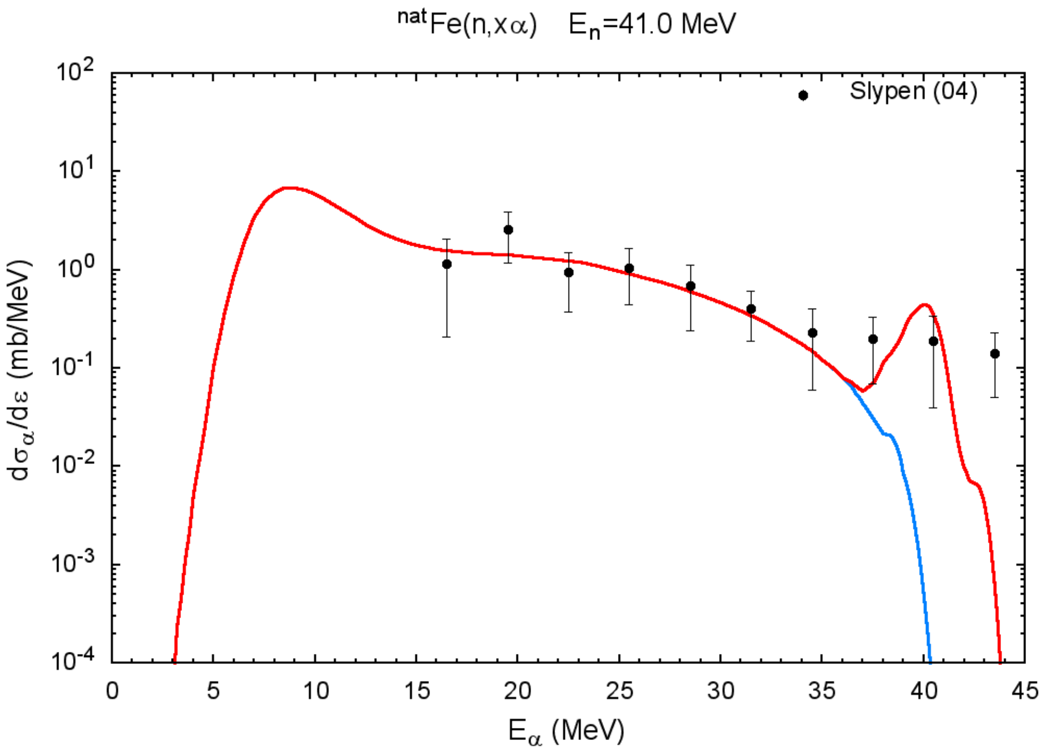


Fig.15 The same as in Fig.1 but for the n+Fe reaction at E_n=41 MeV.

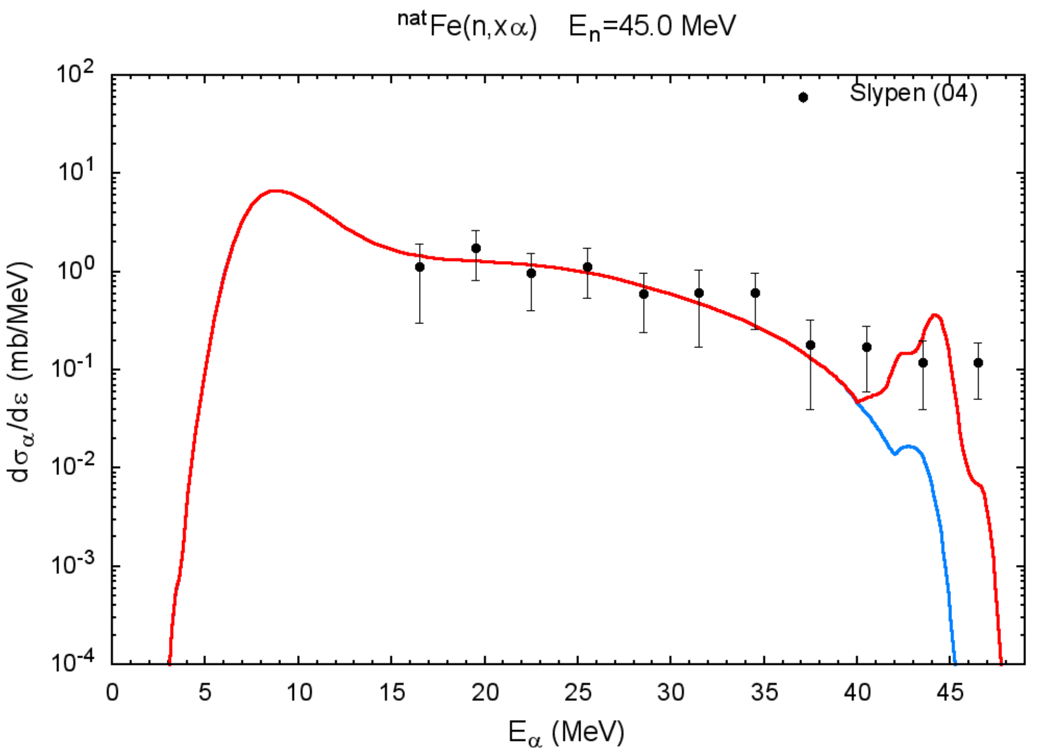


Fig.16 The same as in Fig.1 but for the n+Fe reaction at E_n=45 MeV.

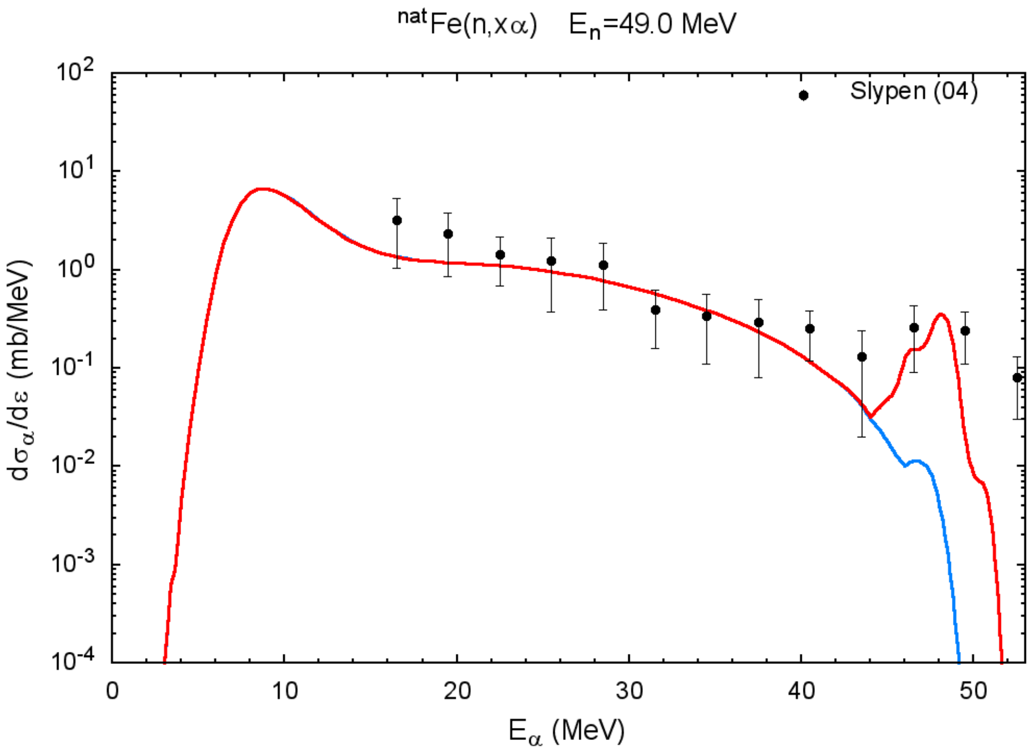


Fig.17 The same as in Fig.1 but for the n+Fe reaction at E_n=49 MeV.

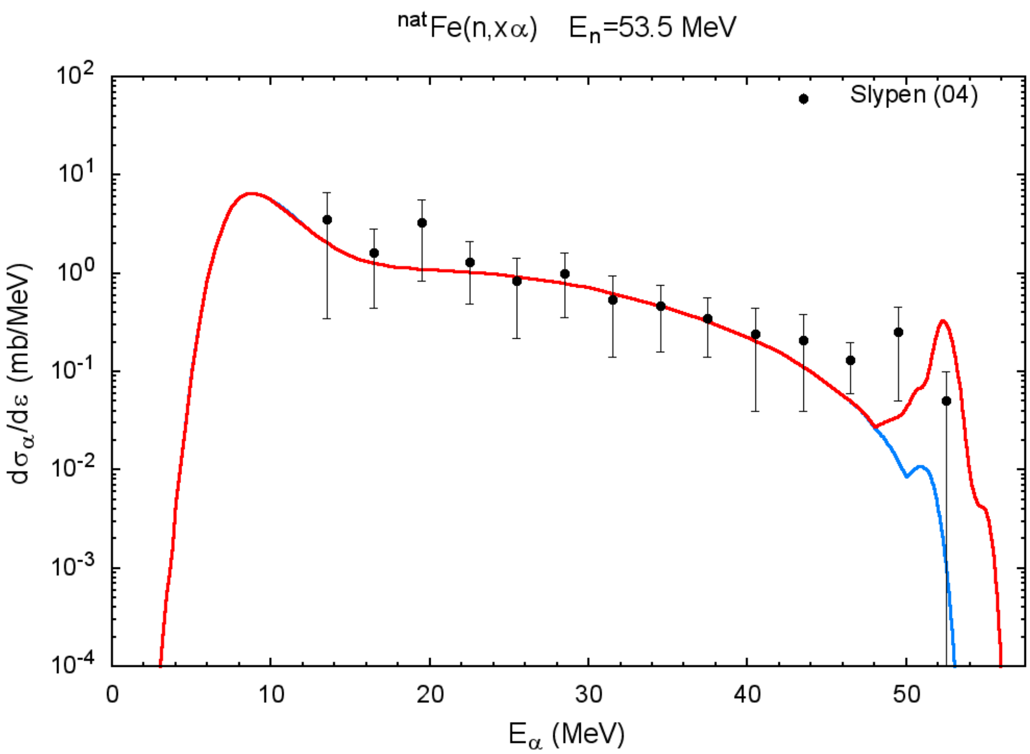


Fig.18 The same as in Fig.1 but for the n+Fe reaction at E_n=53.5 MeV.

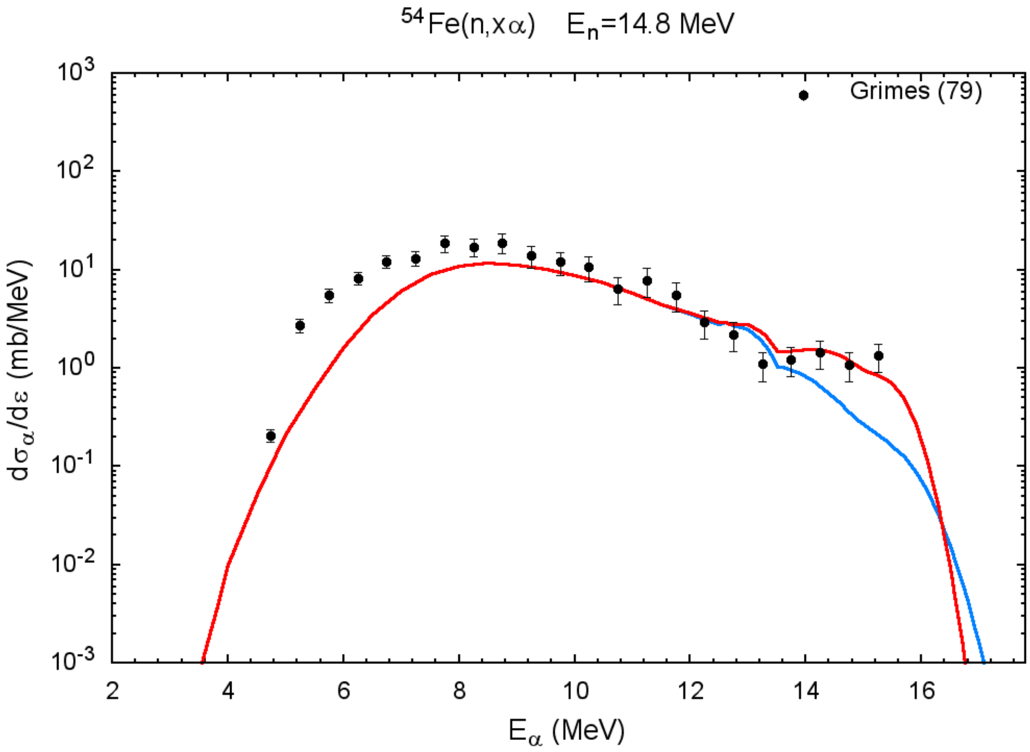


Fig.19 The same as in Fig.1 but for the n+^{54}Fe reaction at E_n=14.8 MeV.

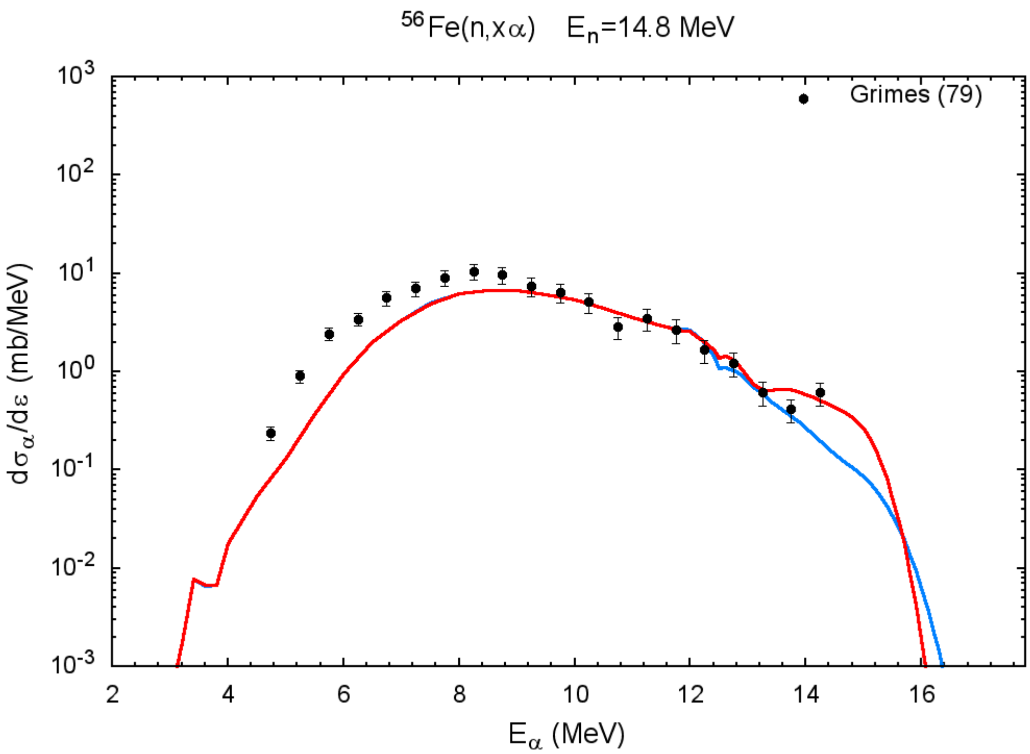


Fig.20 The same as in Fig.1 but for the n+^{56}Fe reaction at E_n=14.8 MeV.

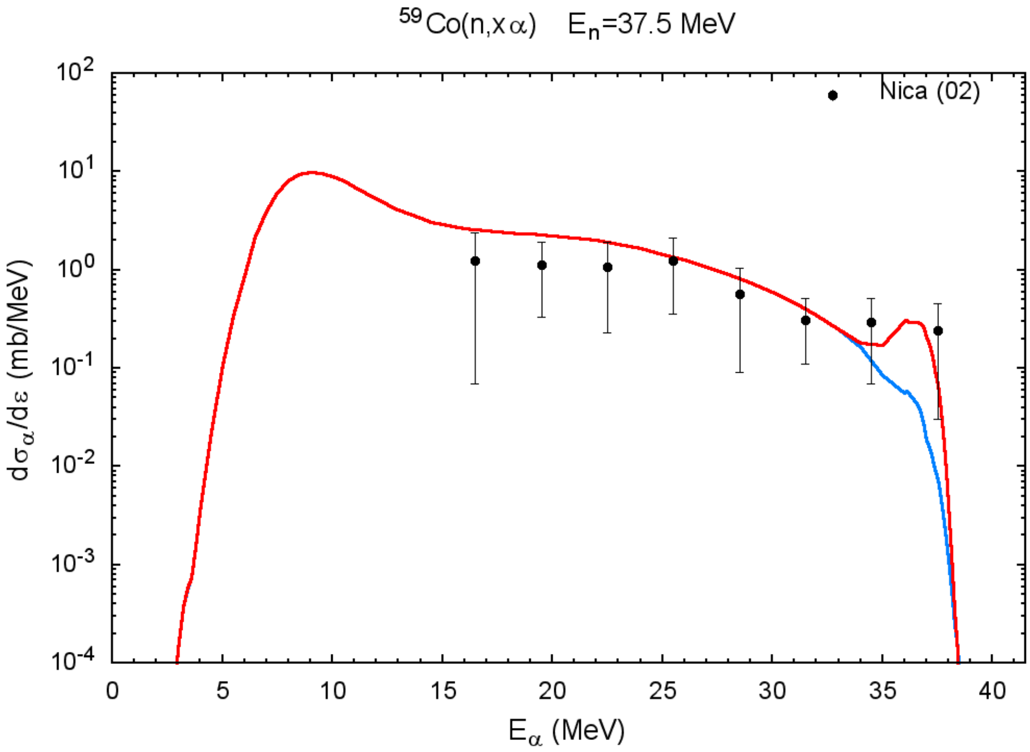


Fig.21 The same as in Fig.1 but for the n+^{59}Co reaction at E_n=37.5 MeV.

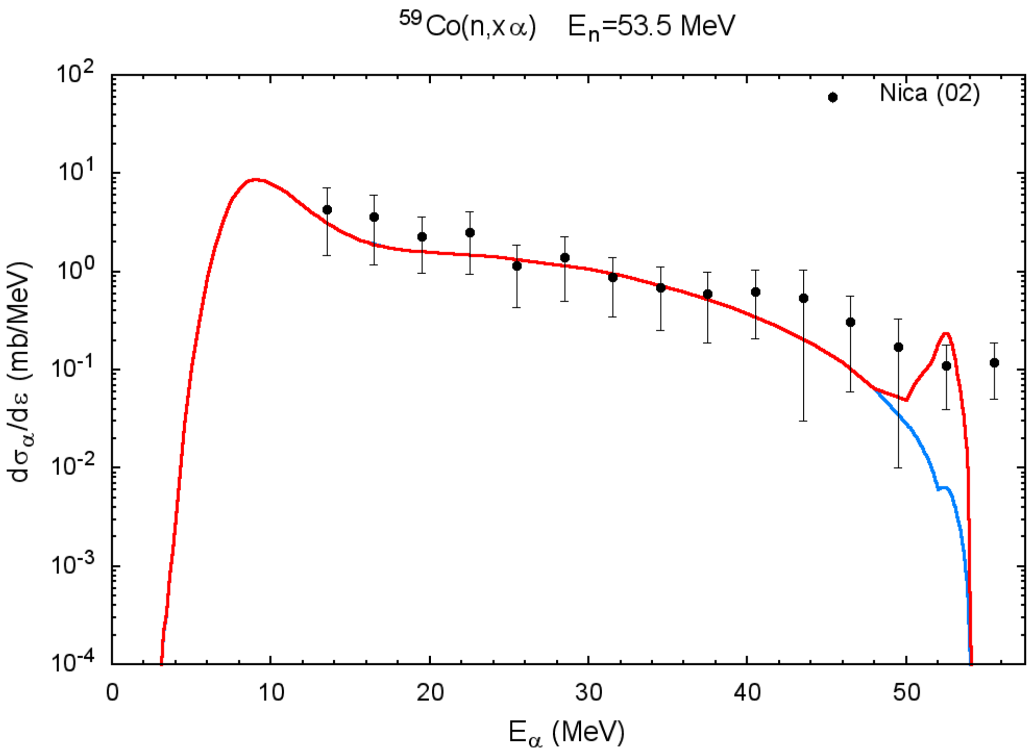


Fig.22 The same as in Fig.1 but for the n+^{59}Co reaction at E_n=53.5 MeV.

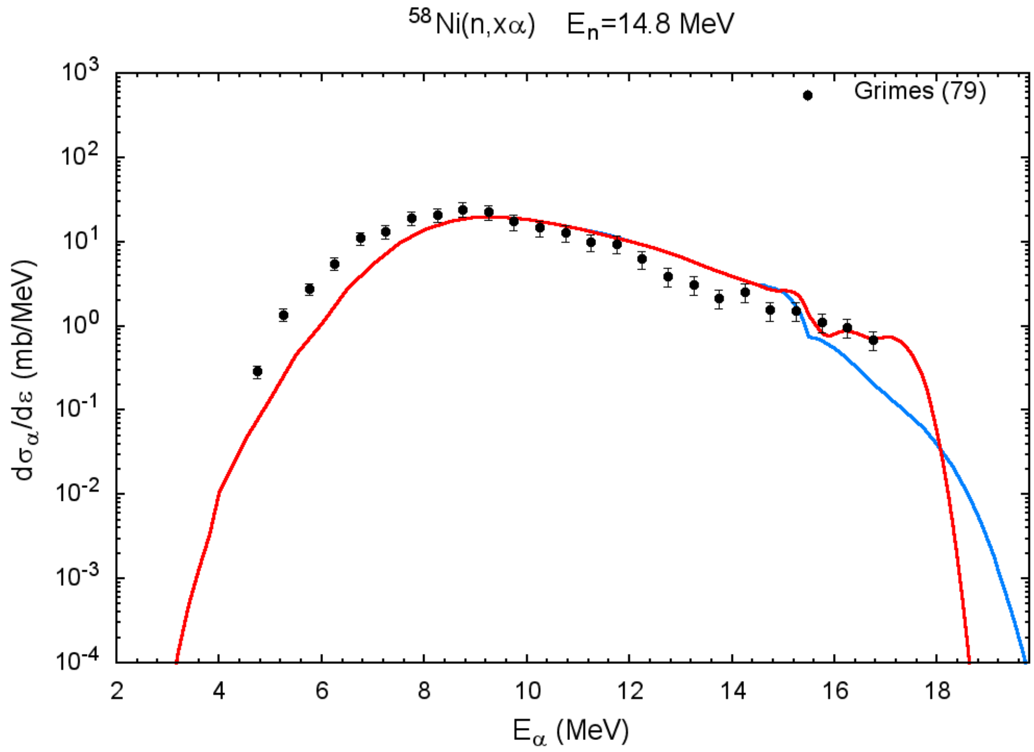


Fig.23 The same as in Fig.1 but for the n+^{58}Ni reaction at E_n=14.8 MeV.

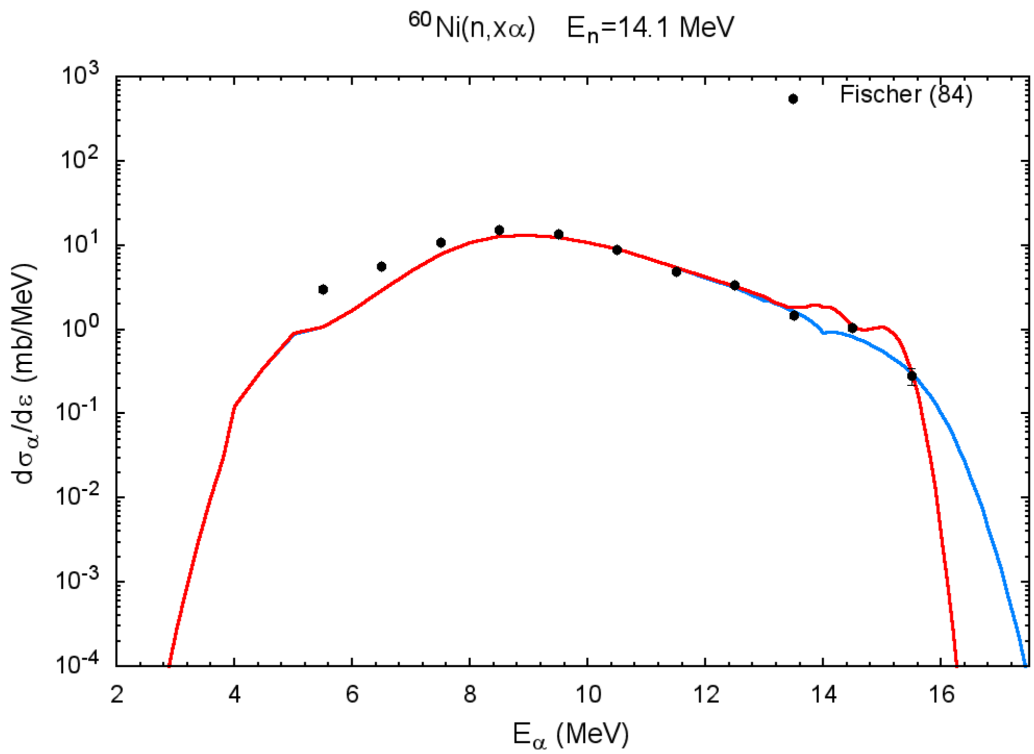


Fig.24 The same as in Fig.1 but for the n+^{60}Ni reaction at E_n=14.1 MeV.

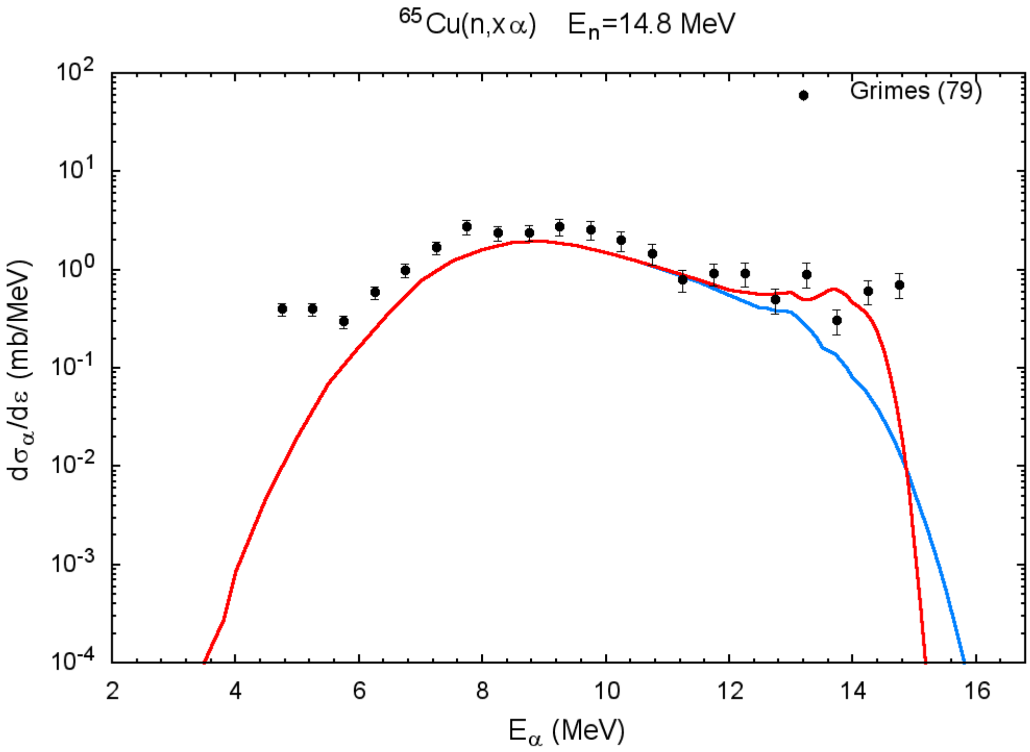


Fig.25 The same as in Fig.1 but for the n+^{65}Cu reaction at E_n=14.8 MeV.

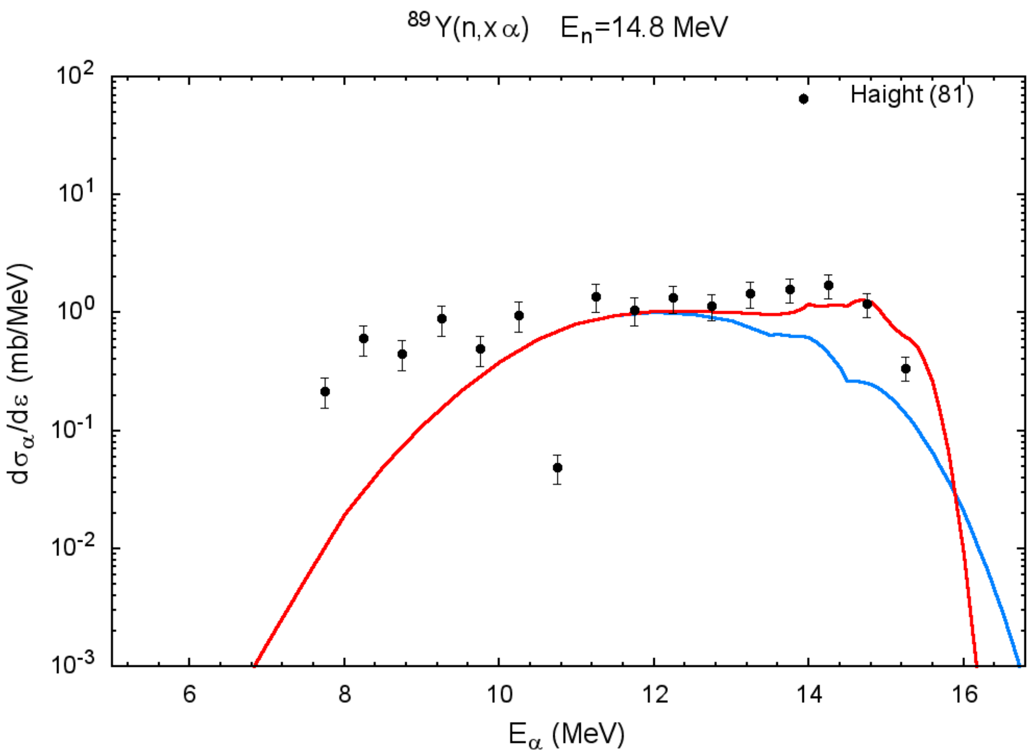


Fig.26 The same as in Fig.1 but for the n+^{89}Y reaction at E_n=14.8 MeV.

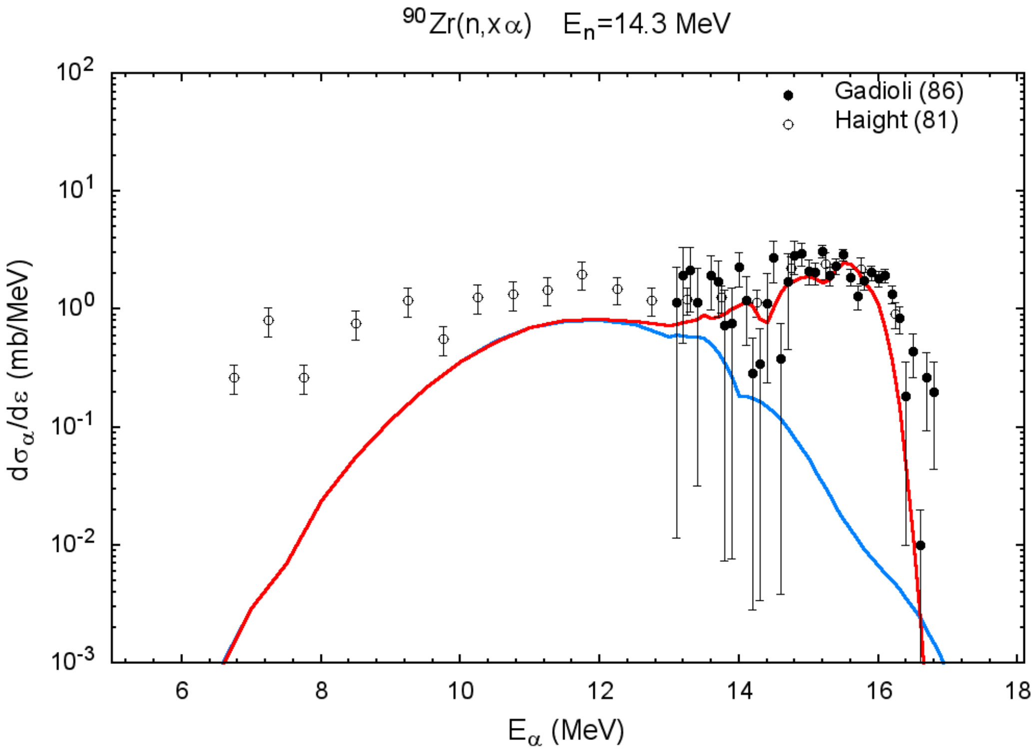


Fig.27 The same as in Fig.1 but for the n+^{90}Zr reaction at E_n=14.3 MeV.

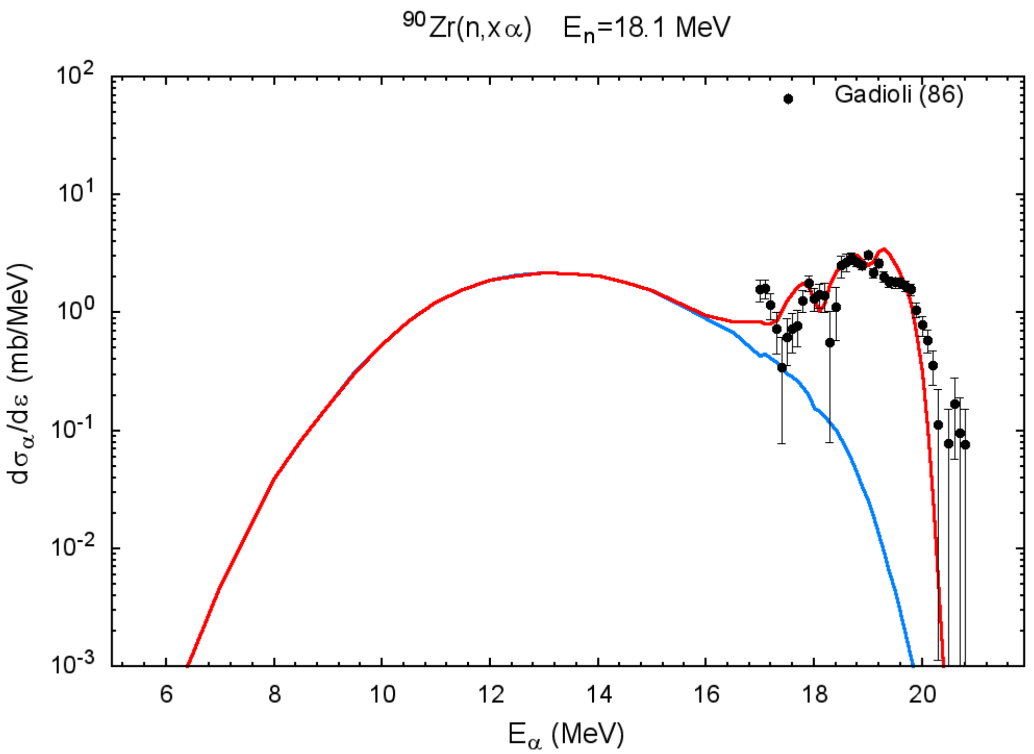


Fig.28 The same as in Fig.1 but for the n+^{90}Zr reaction at E_n=18.1 MeV.

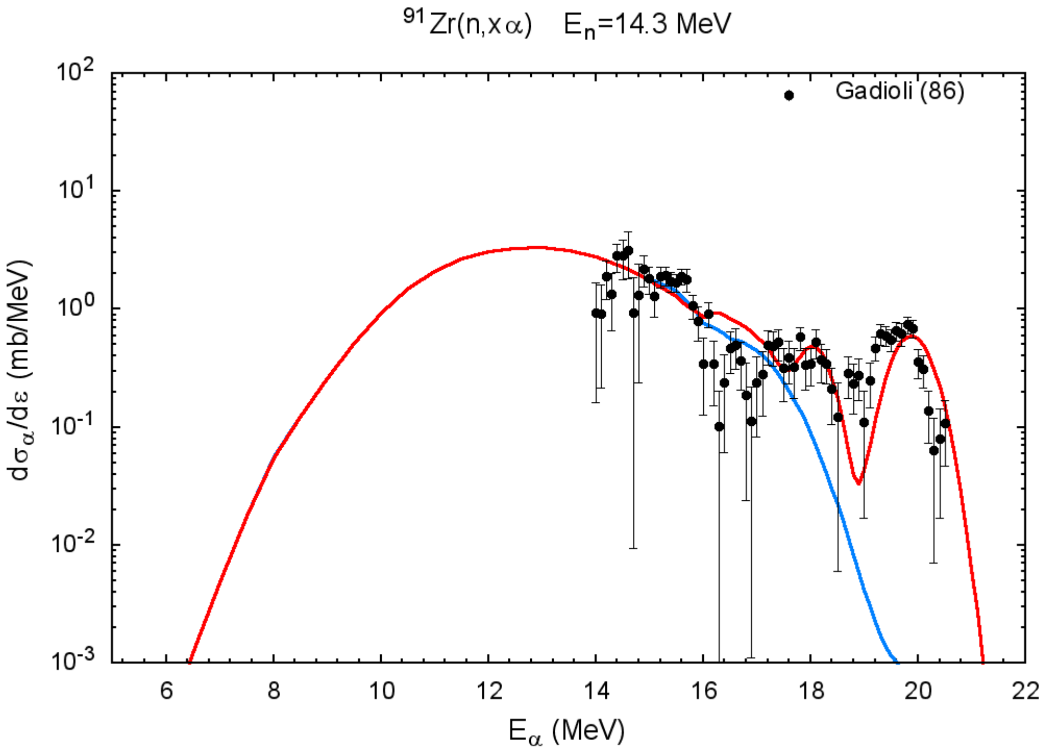


Fig.29 The same as in Fig.1 but for the n+^{91}Zr reaction at E_n=14.3 MeV.

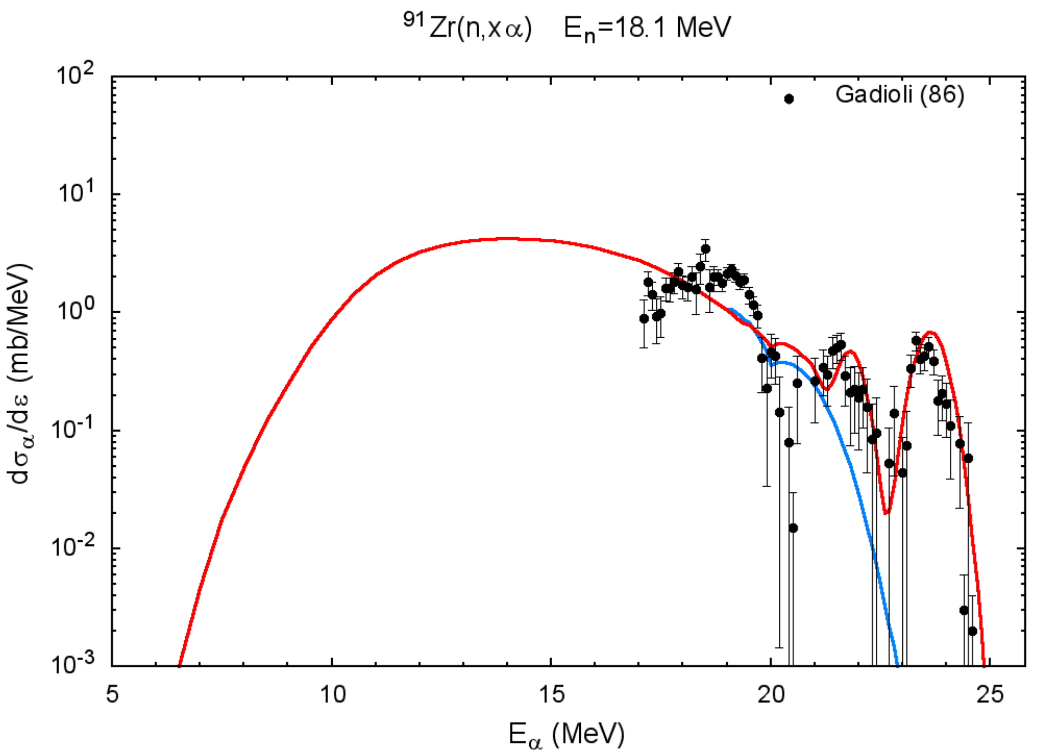


Fig.30 The same as in Fig.1 but for the n+^{91}Zr reaction at E_n=18.1 MeV.

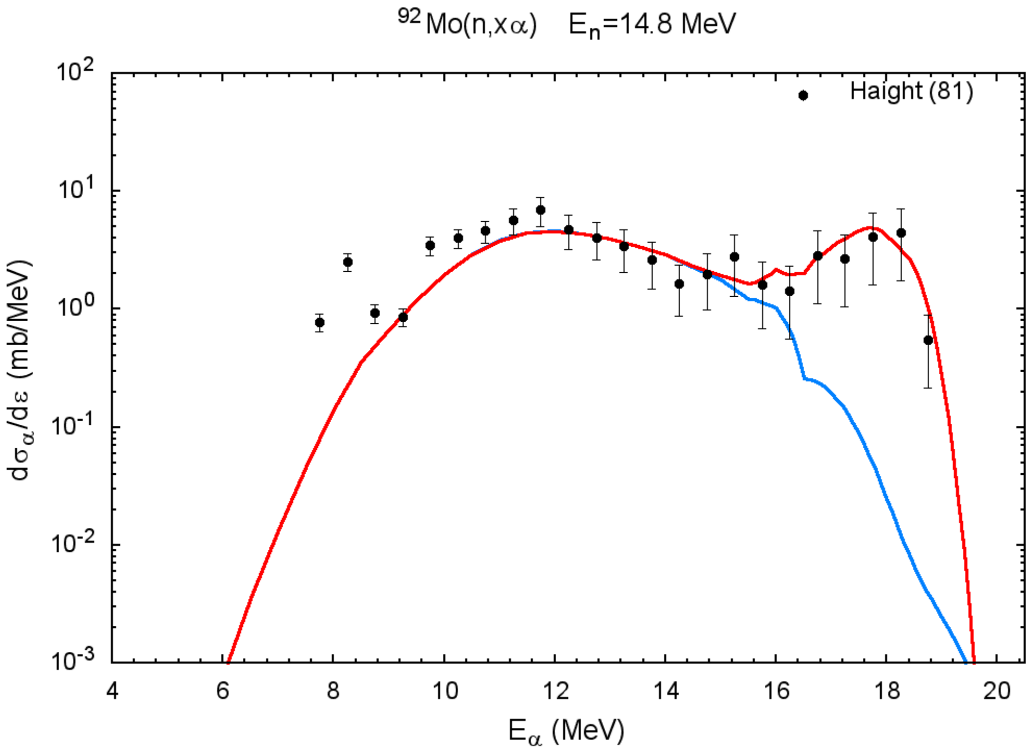


Fig.31 The same as in Fig.1 but for the n+^{92}Mo reaction at E_n=14.8 MeV.

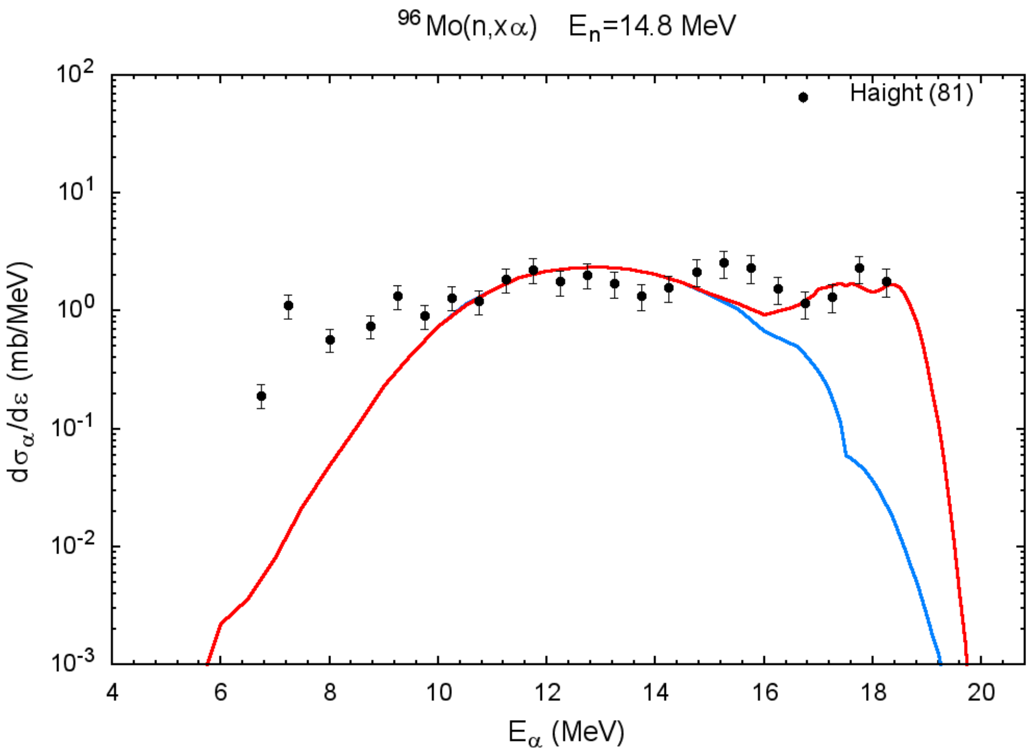


Fig.32 The same as in Fig.1 but for the n+^{96}Mo reaction at E_n=14.8 MeV.

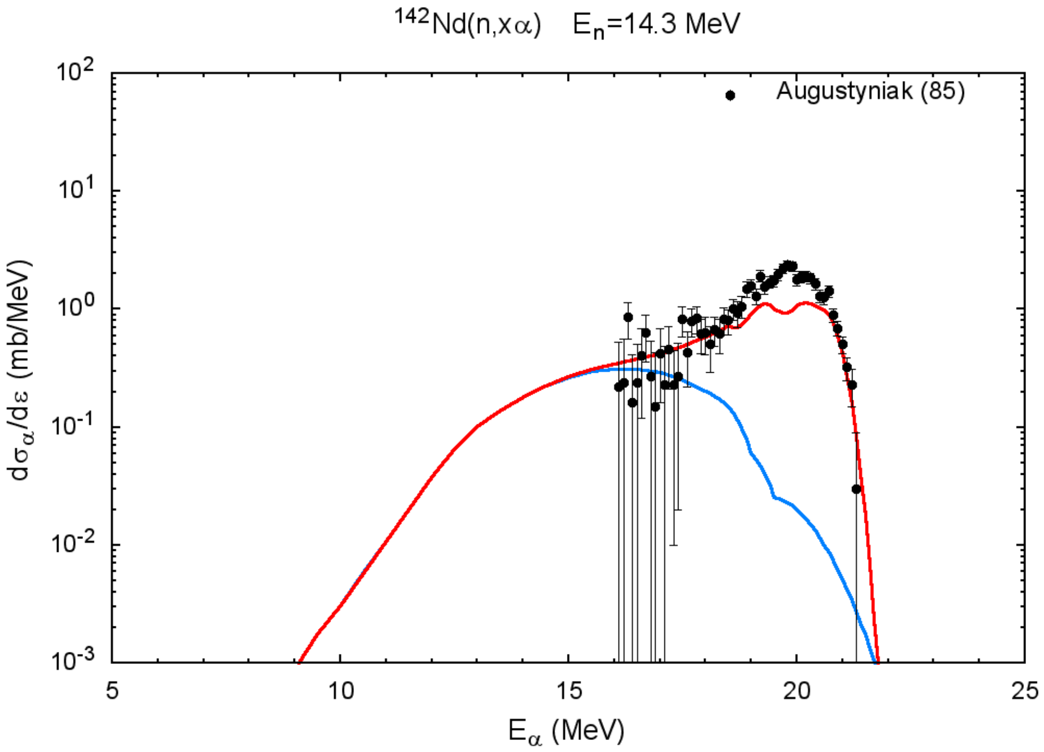


Fig.33 The same as in Fig.1 but for the n+^{142}Nd reaction at E_n=14.3 MeV.

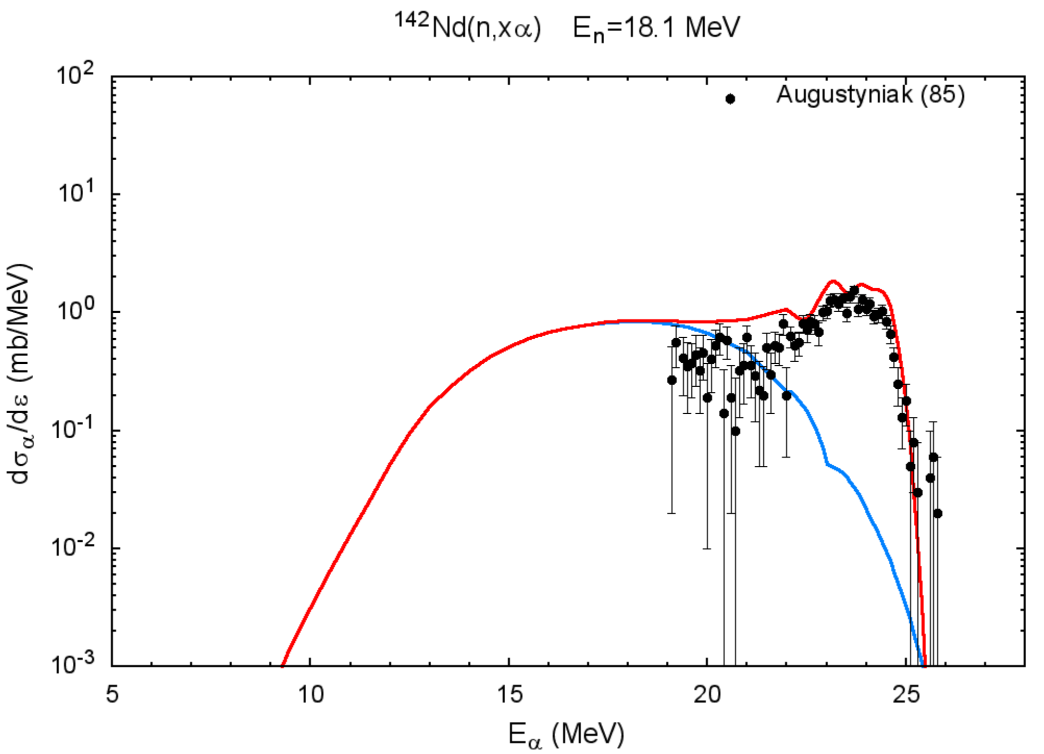


Fig.34 The same as in Fig.1 but for the n+^{142}Nd reaction at E_n=18.1 MeV.

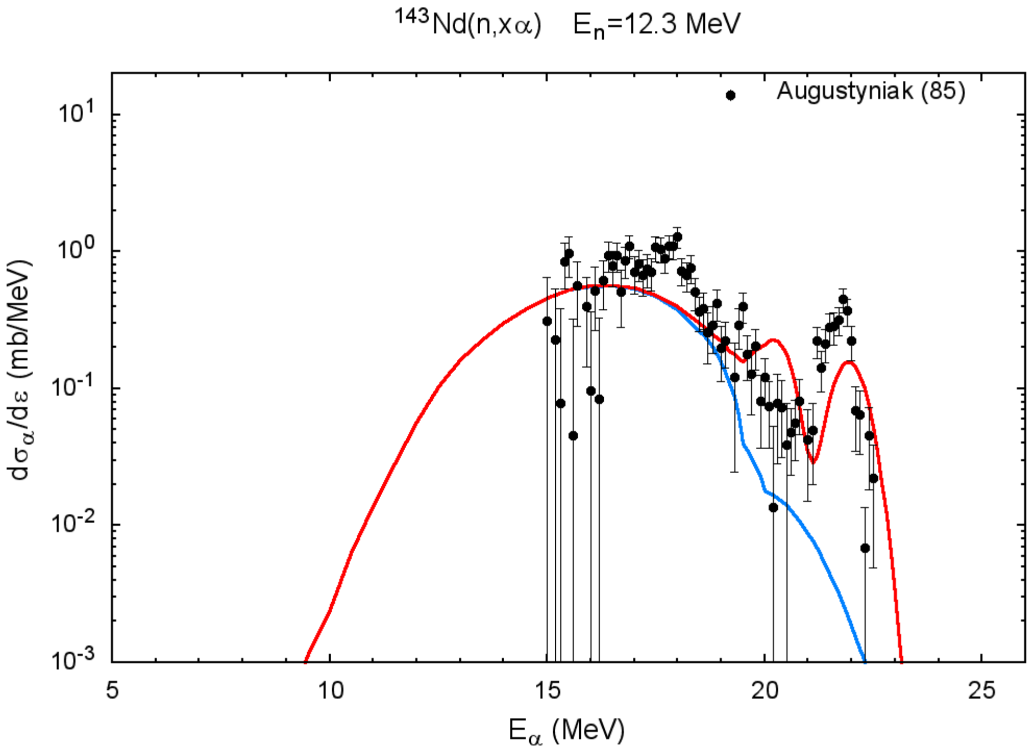


Fig.35 The same as in Fig.1 but for the n+^{143}Nd reaction at E_n=12.3 MeV.

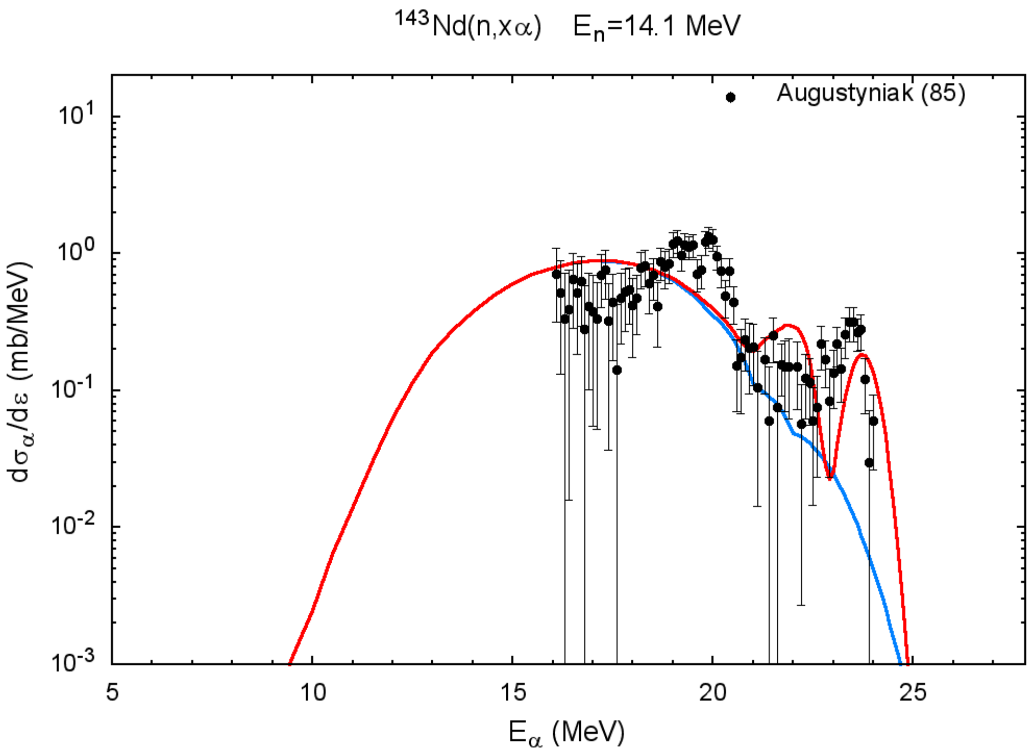


Fig.36 The same as in Fig.1 but for the n+^{143}Nd reaction at E_n=14.1 MeV.

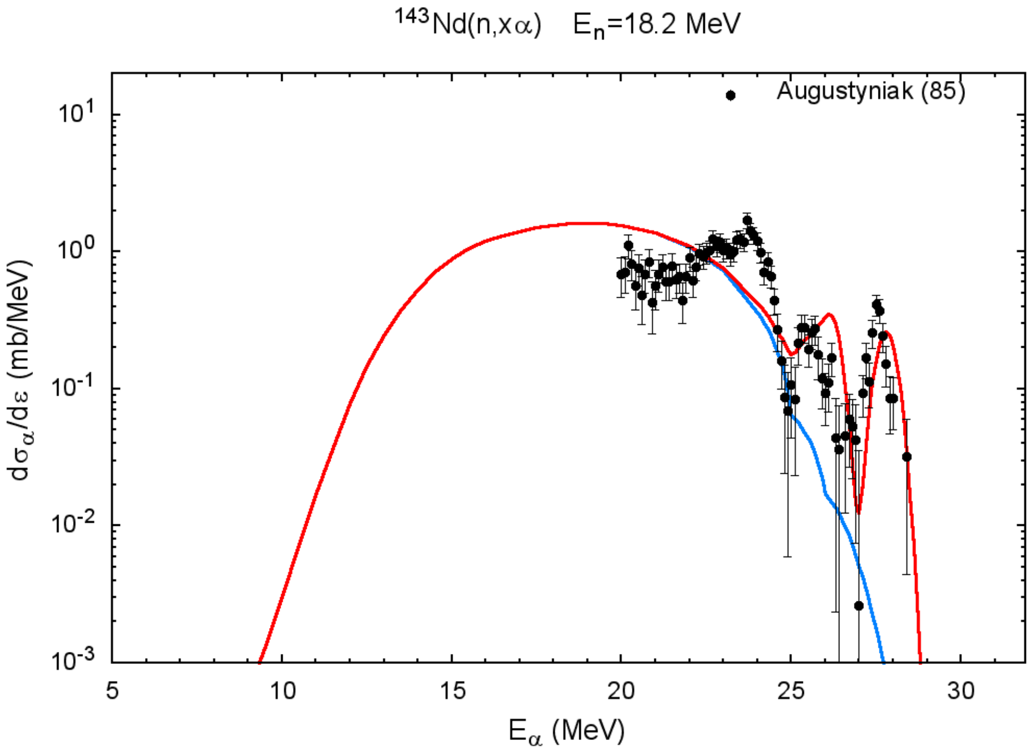


Fig.37 The same as in Fig.1 but for the n+^{143}Nd reaction at E_n=18.2 MeV.

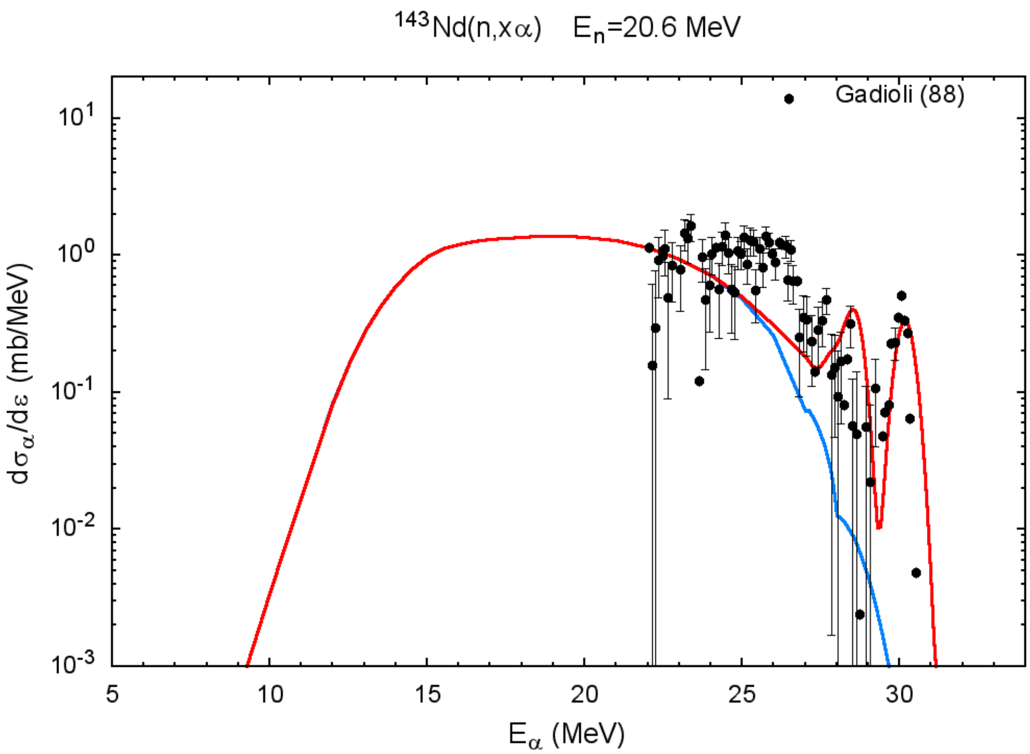


Fig.38 The same as in Fig.1 but for the n+^{143}Nd reaction at E_n=20.6 MeV.

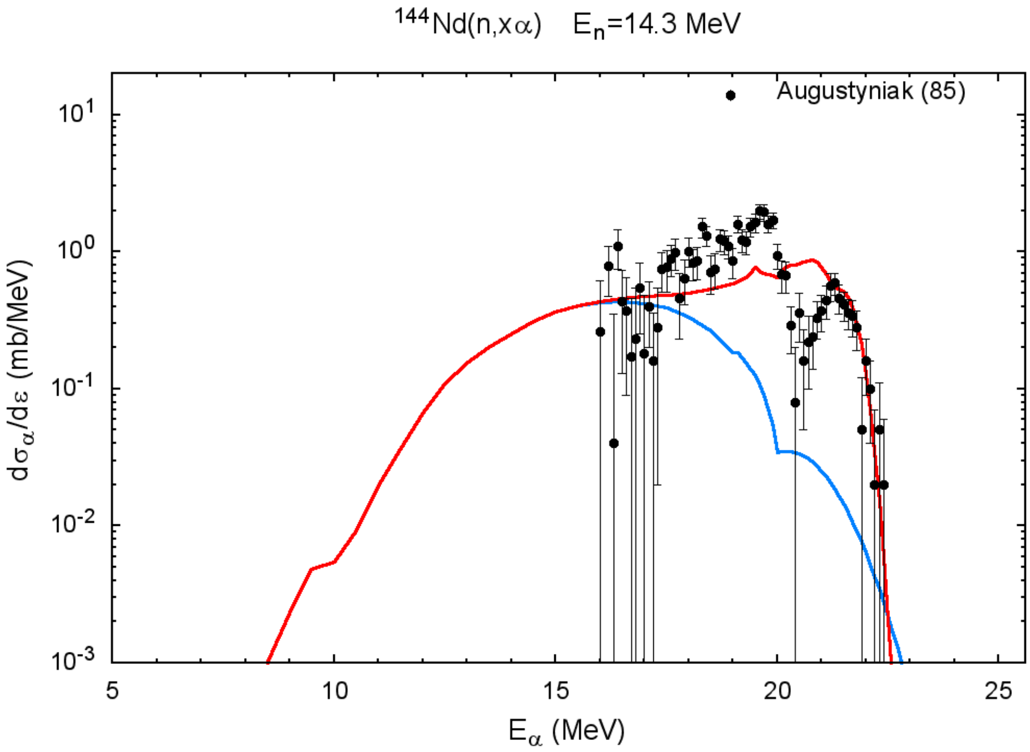


Fig.39 The same as in Fig.1 but for the n+^{144}Nd reaction at E_n=14.3 MeV.

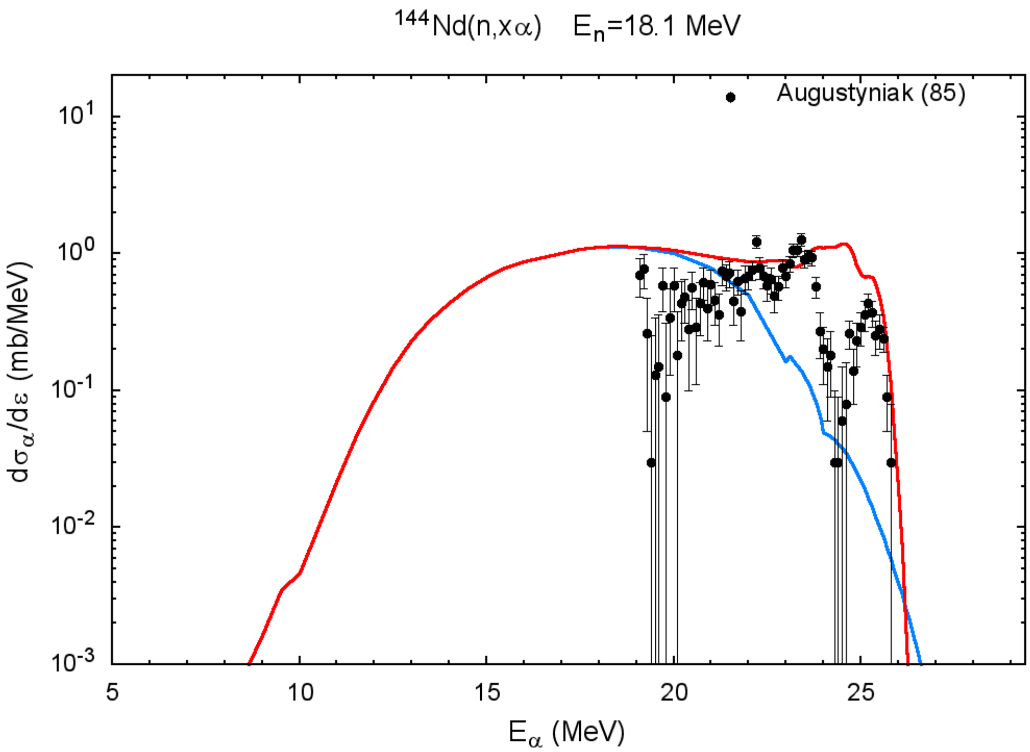


Fig.40 The same as in Fig.1 but for the n+^{144}Nd reaction at E_n=18.1 MeV.

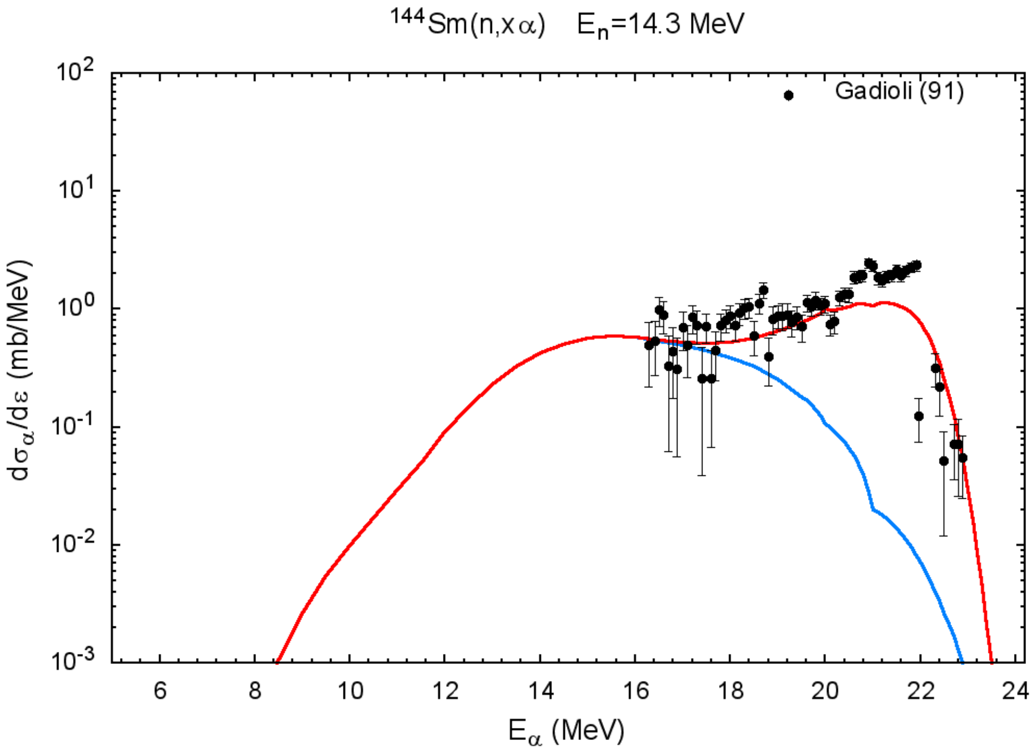


Fig.41 The same as in Fig.1 but for the n+^{144}Sm reaction at E_n=14.3 MeV.

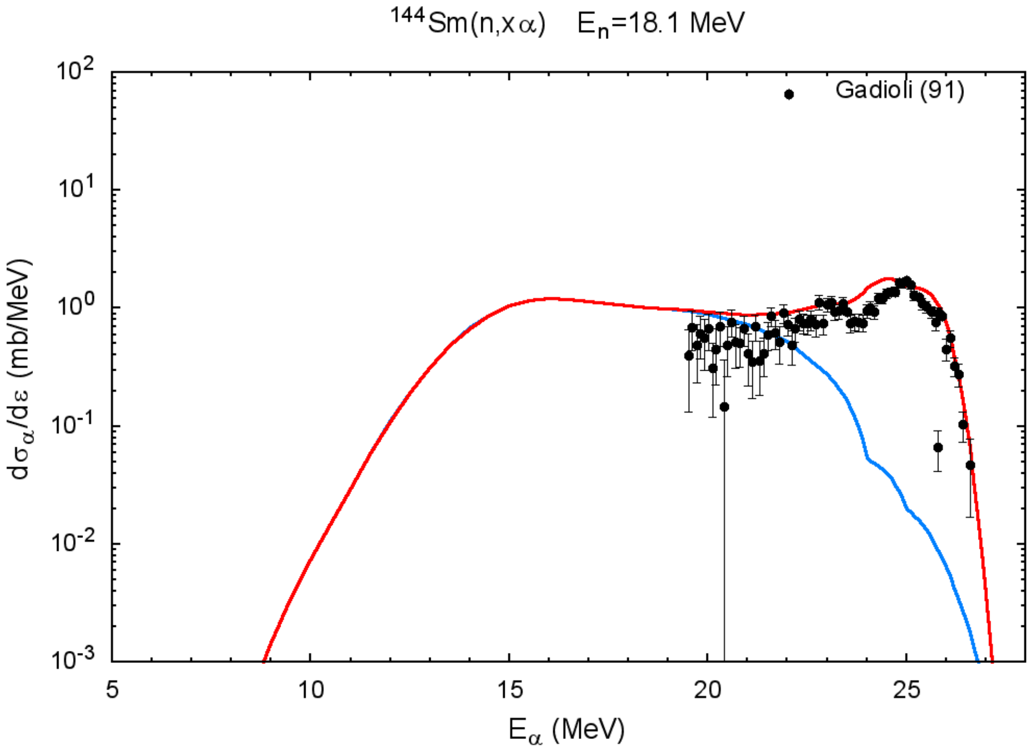


Fig.42 The same as in Fig.1 but for the n+^{144}Sm reaction at E_n=18.1 MeV.

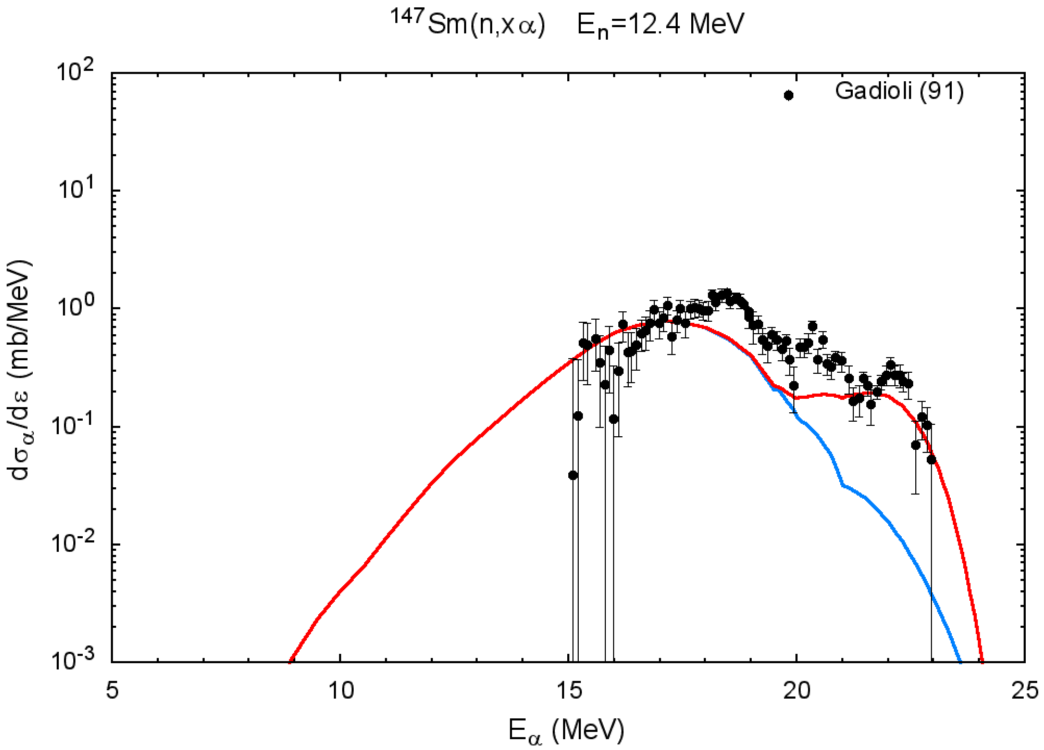


Fig.43 The same as in Fig.1 but for the n+^{147}Sm reaction at E_n=12.4 MeV.

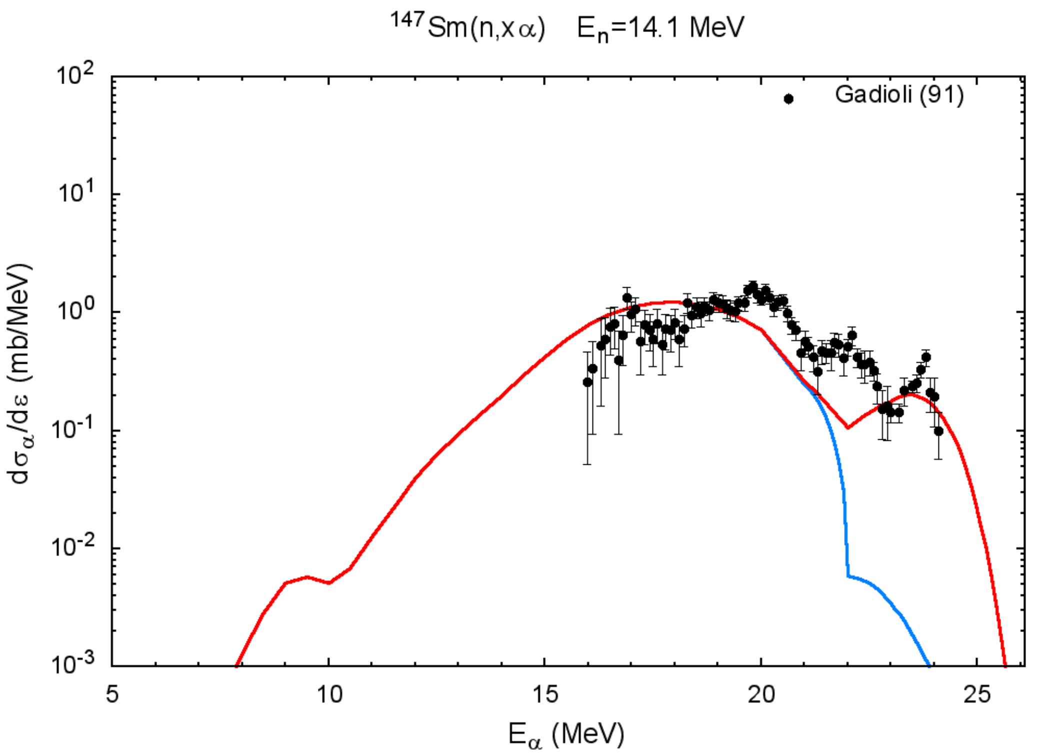


Fig.44 The same as in Fig.1 but for the n+^{147}Sm reaction at E_n=14.1 MeV.

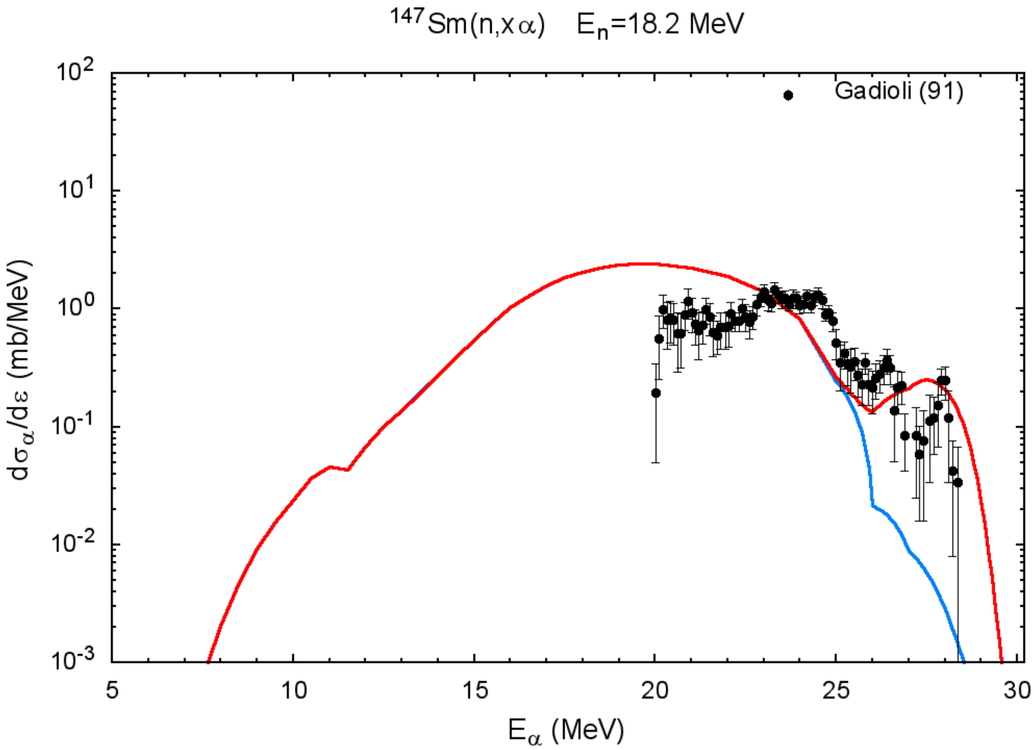


Fig.45 The same as in Fig.1 but for the n+^{147}Sm reaction at E_n=18.2 MeV.

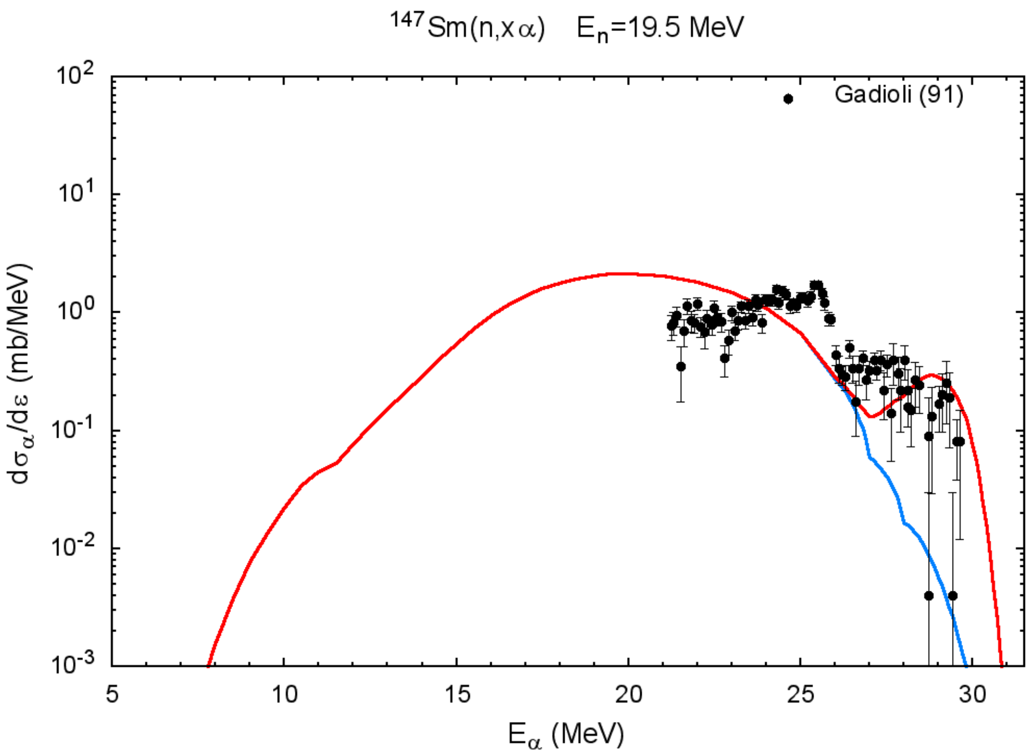


Fig.46 The same as in Fig.1 but for the n+^{147}Sm reaction at E_n=19.5 MeV.

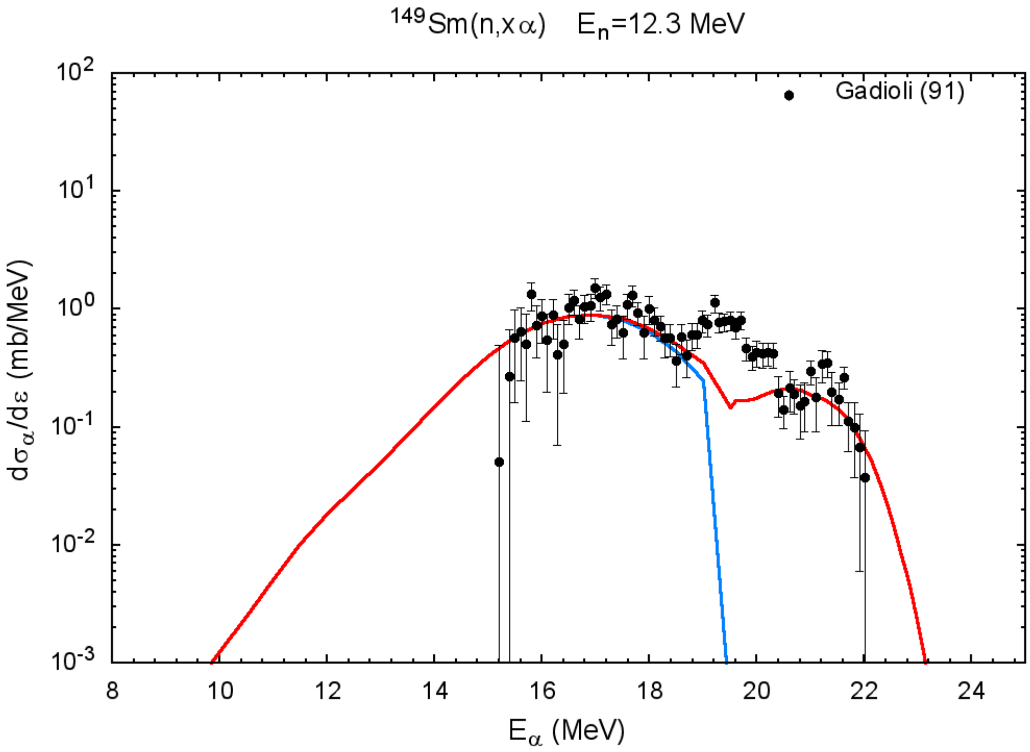


Fig.47 The same as in Fig.1 but for the n+^{149}Sm reaction at E_n=12.3 MeV.

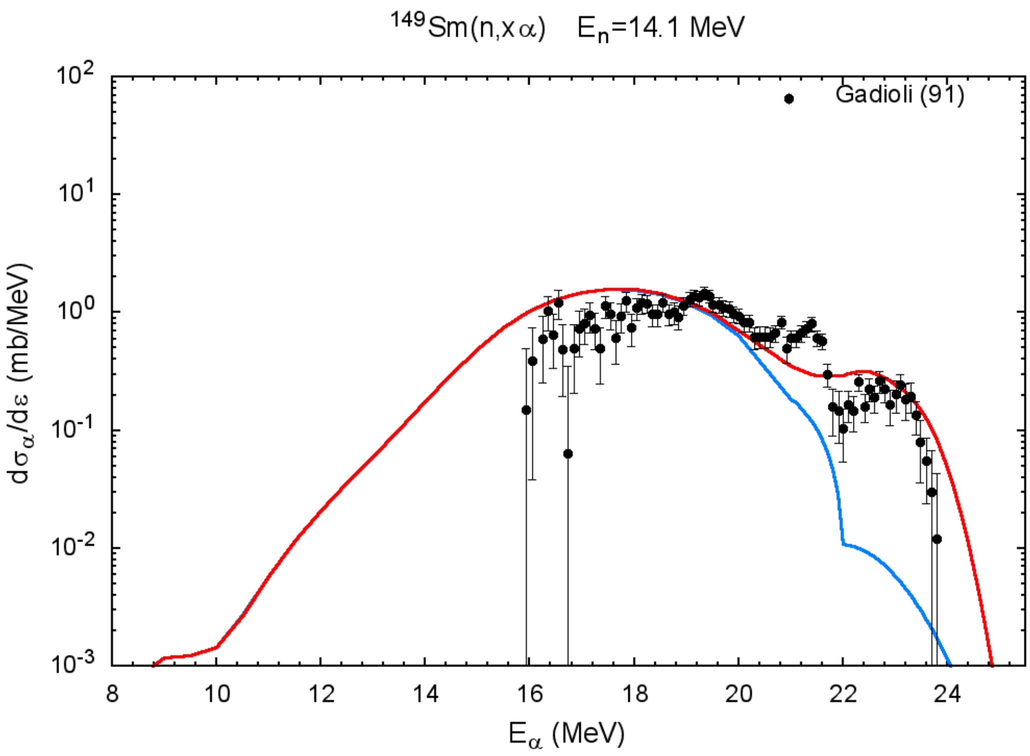


Fig.48 The same as in Fig.1 but for the n+^{149}Sm reaction at E_n=14.1 MeV.

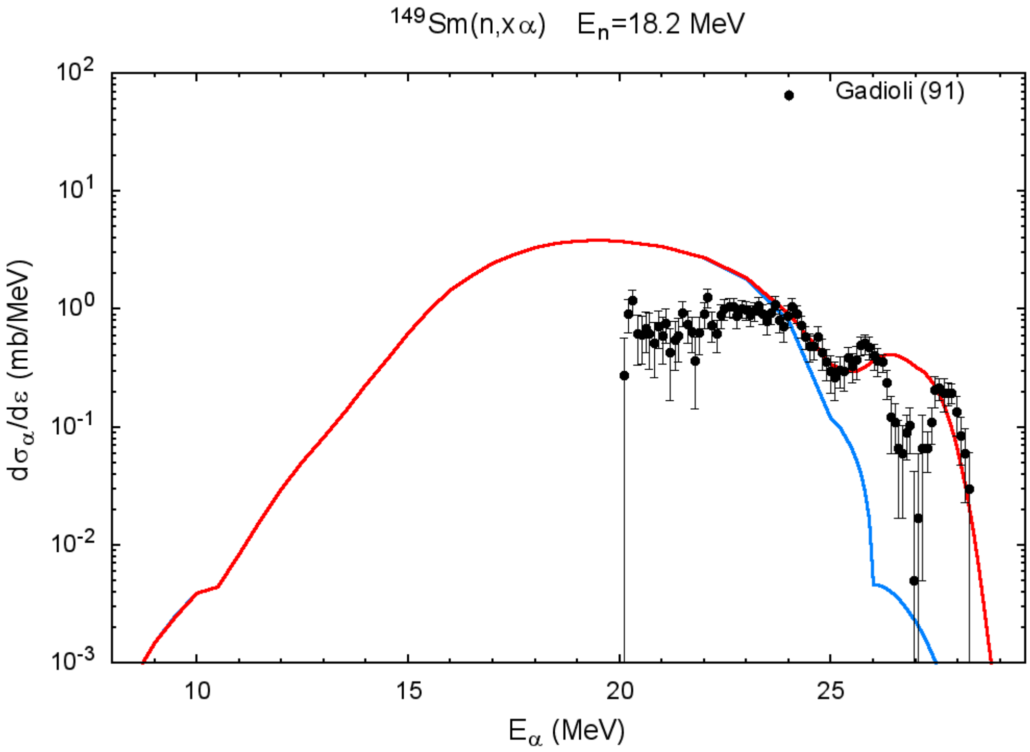


Fig.49 The same as in Fig.1 but for the n+^{149}Sm reaction at E_n=18.2 MeV.

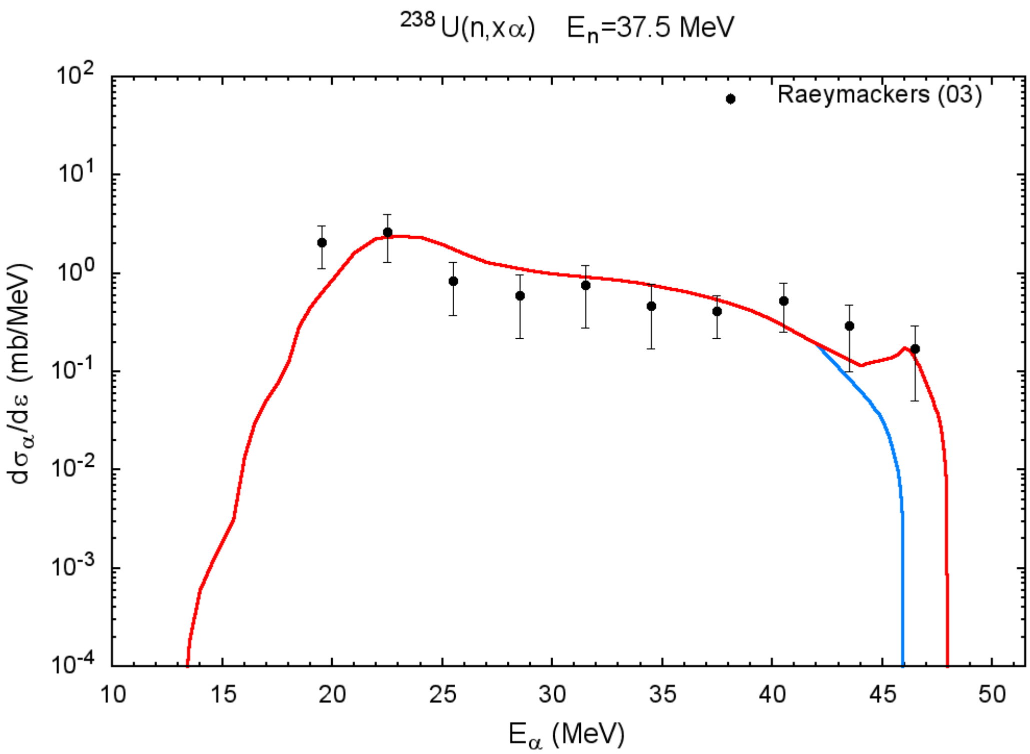


Fig.50 The same as in Fig.1 but for the n+^{238}U reaction at E_n=37.5 MeV.

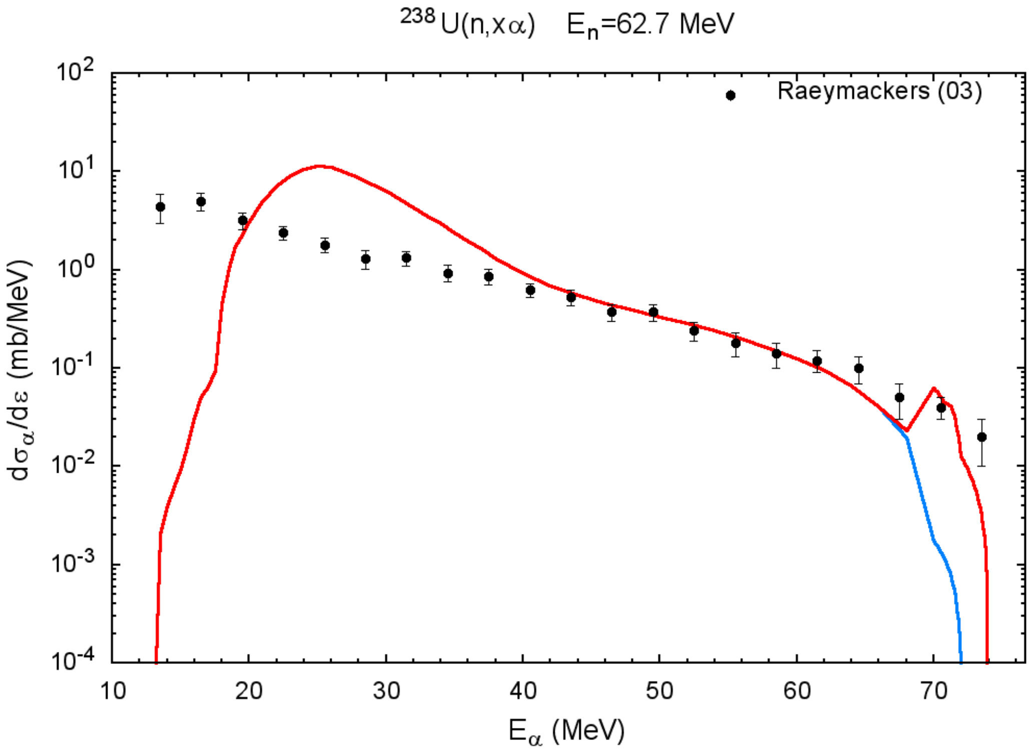


Fig.51 The same as in Fig.1 but for the n+^{238}U reaction at E_n=62.7 MeV.

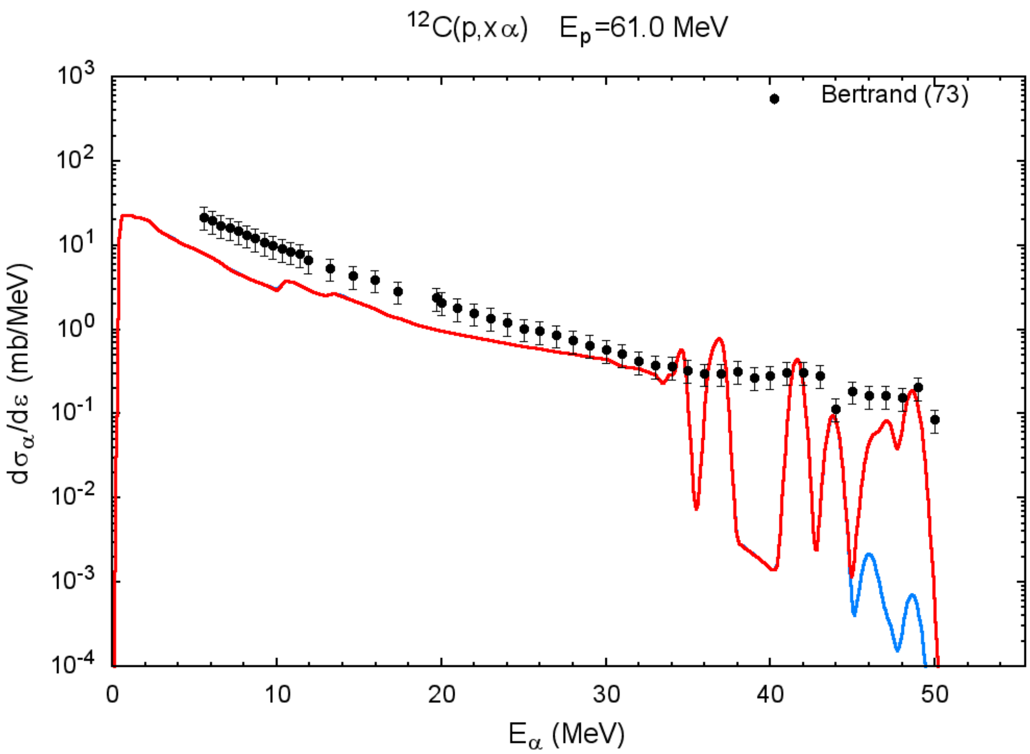


Fig.52 The same as in Fig.1 but for the p+^{12}C reaction at E_p=61 MeV.

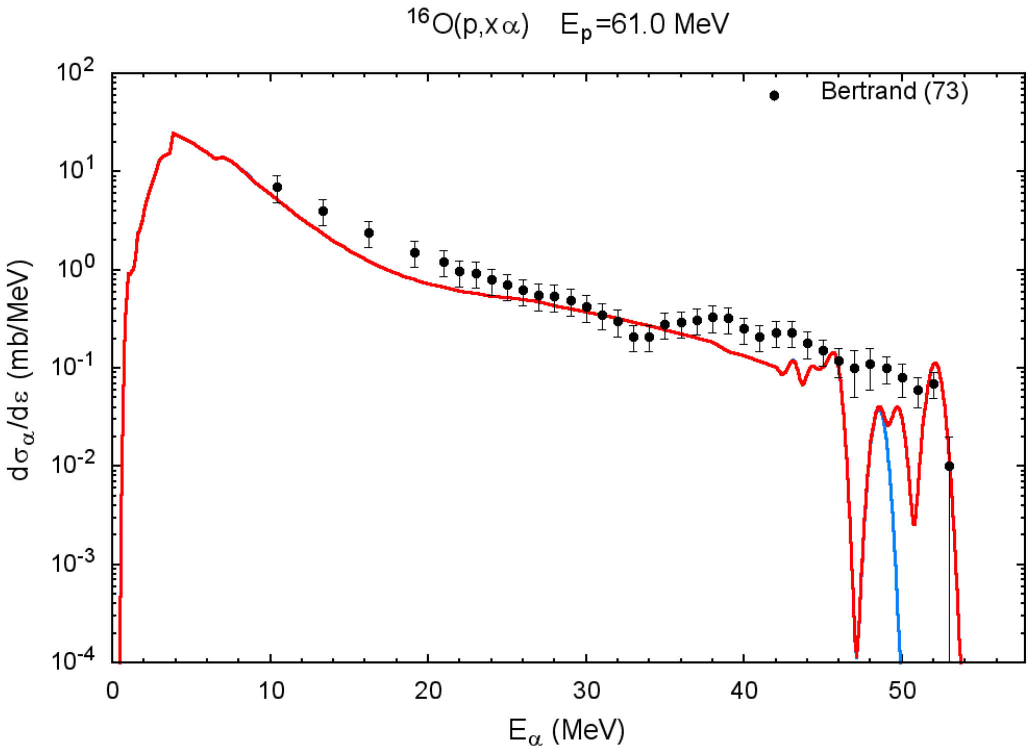


Fig.53 The same as in Fig.1 but for the p+^{16}O reaction at E_p=61 MeV.

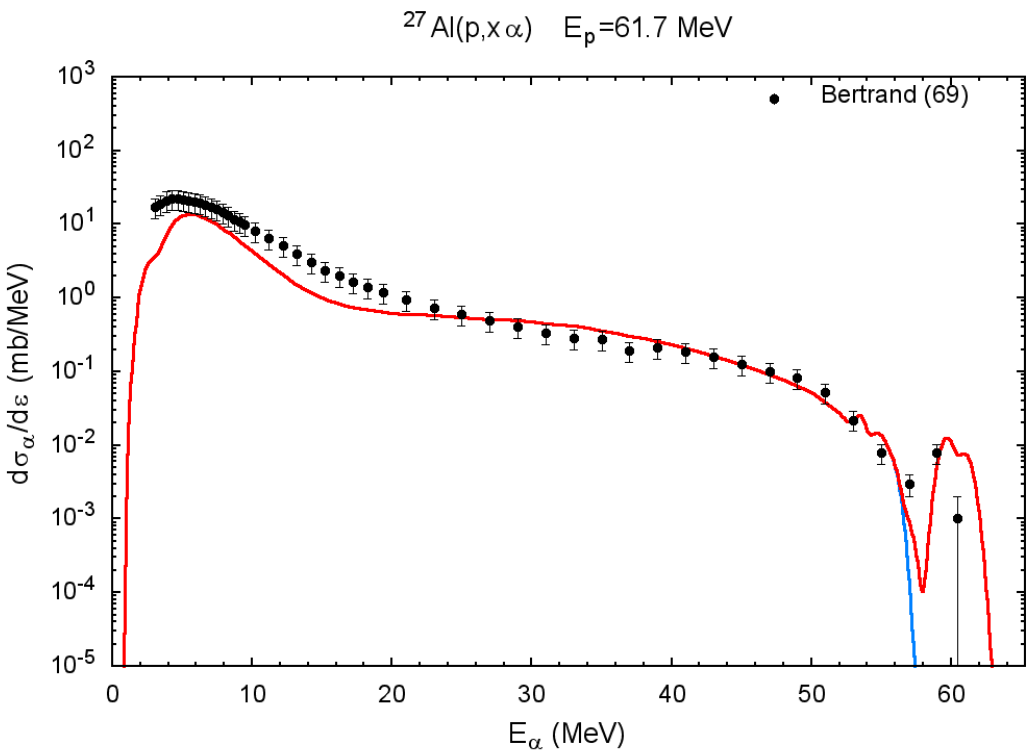


Fig.54 The same as in Fig.1 but for the p+^{27}Al reaction at E_p=61.7 MeV.

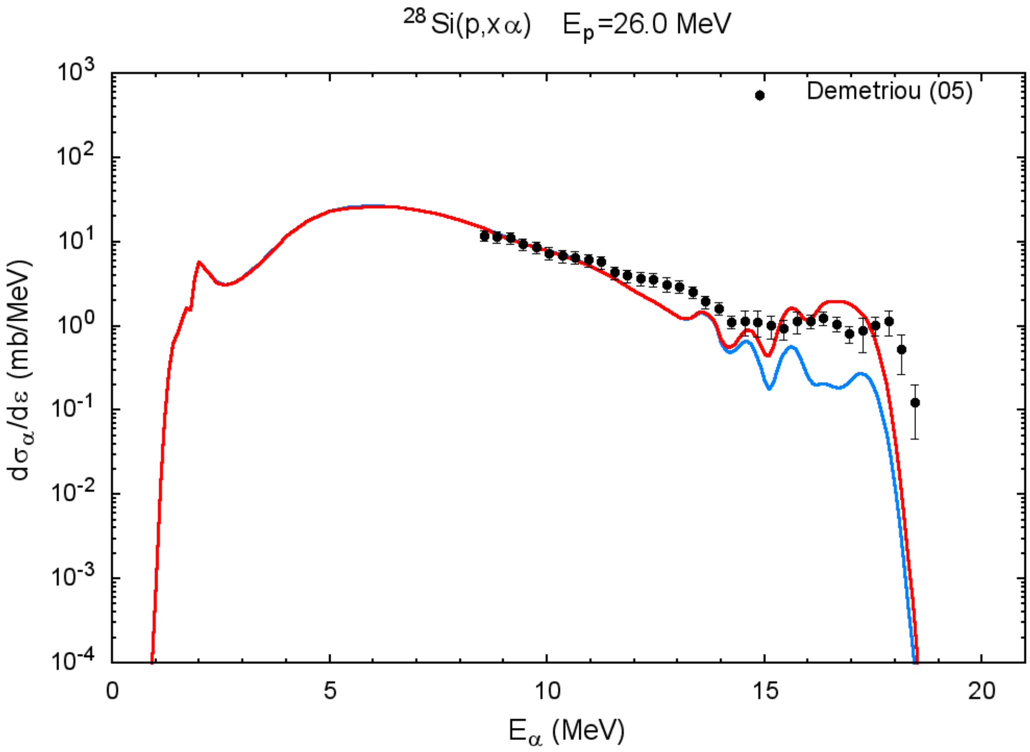


Fig.55 The same as in Fig.1 but for the p+^{28}Si reaction at E_p=26 MeV.

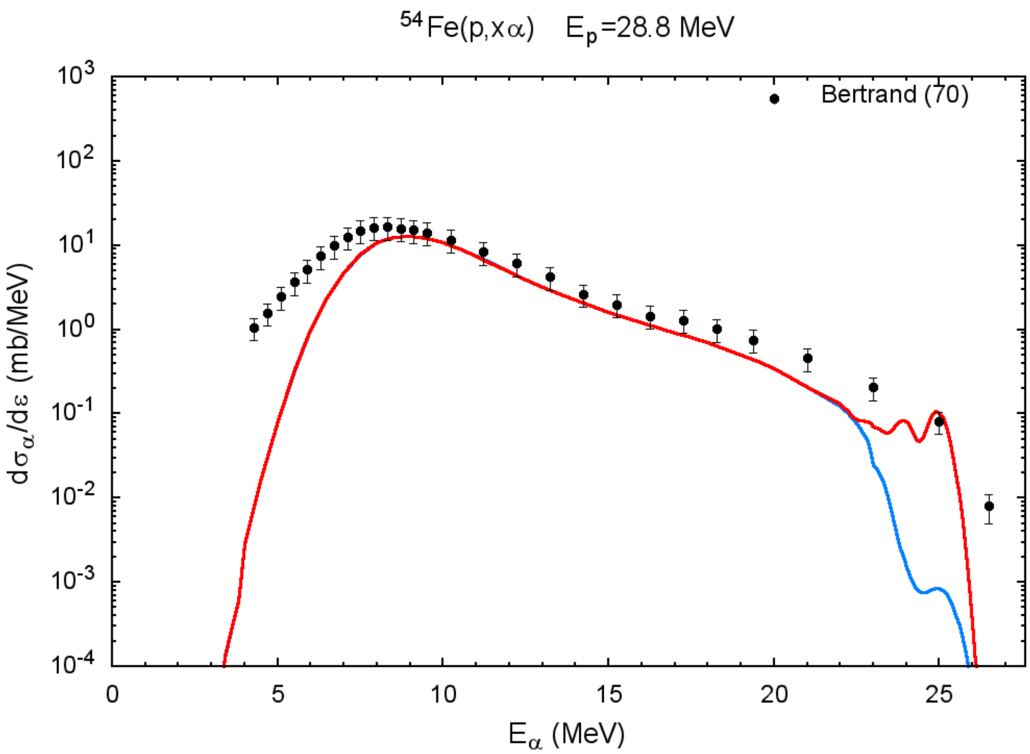


Fig.56 The same as in Fig.1 but for the p+^{54}Fe reaction at E_p=28.8 MeV.

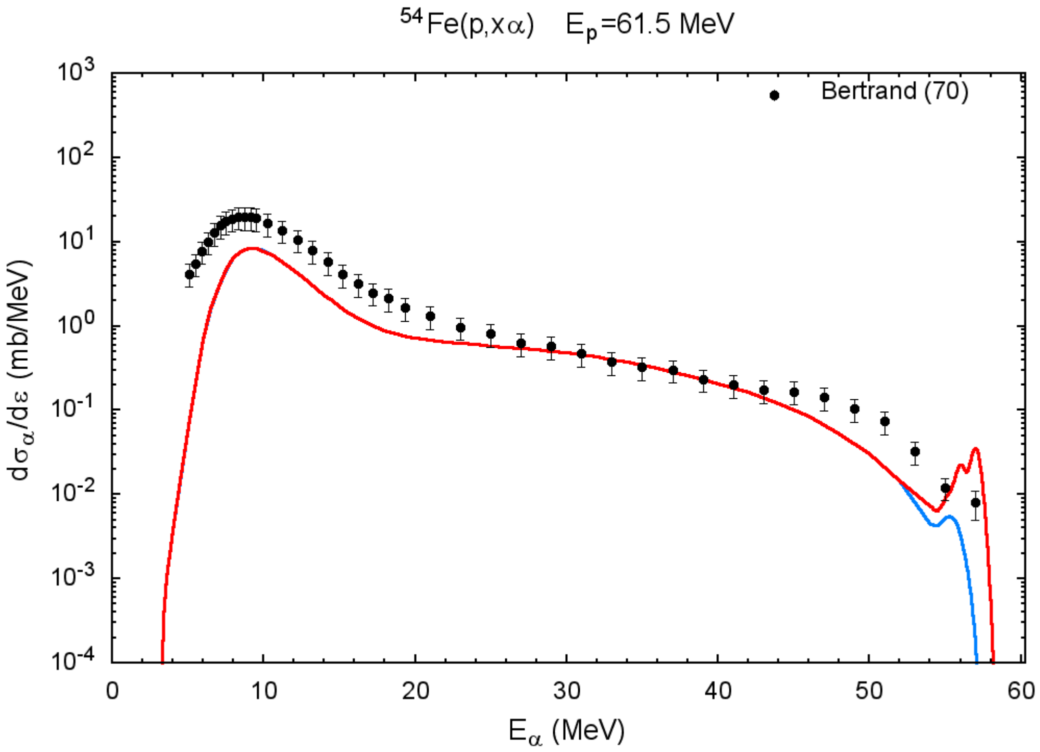


Fig.57 The same as in Fig.1 but for the p+^{54}Fe reaction at E_p=61.5 MeV.

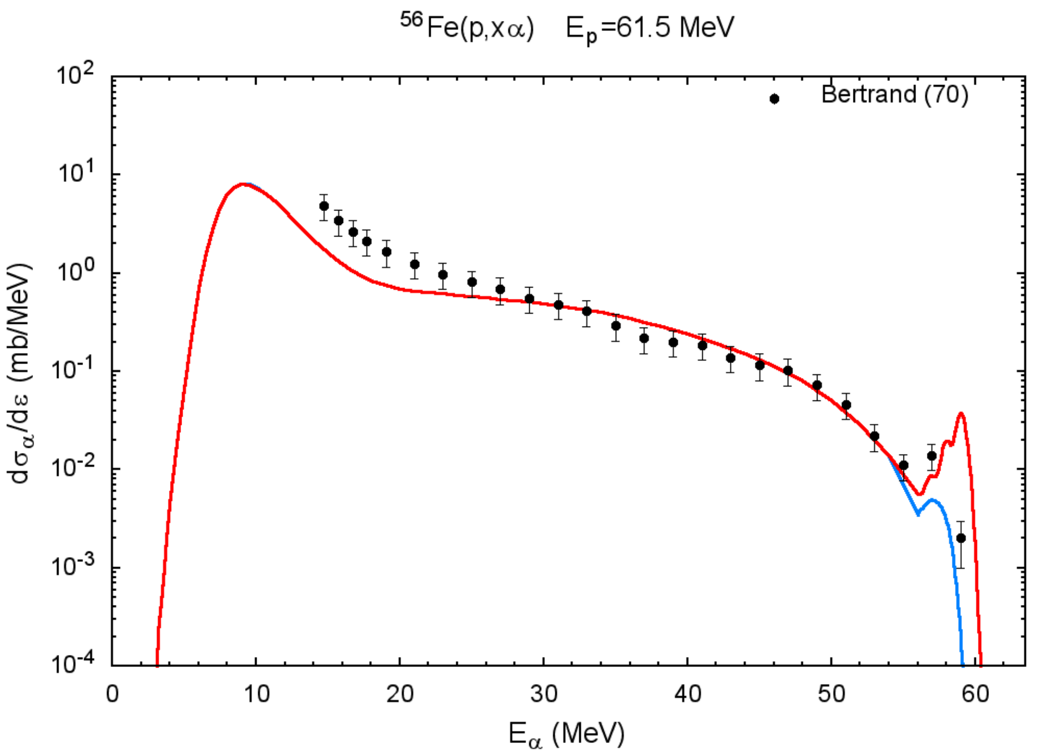


Fig.58 The same as in Fig.1 but for the p+^{56}Fe reaction at E_p=61.5 MeV.

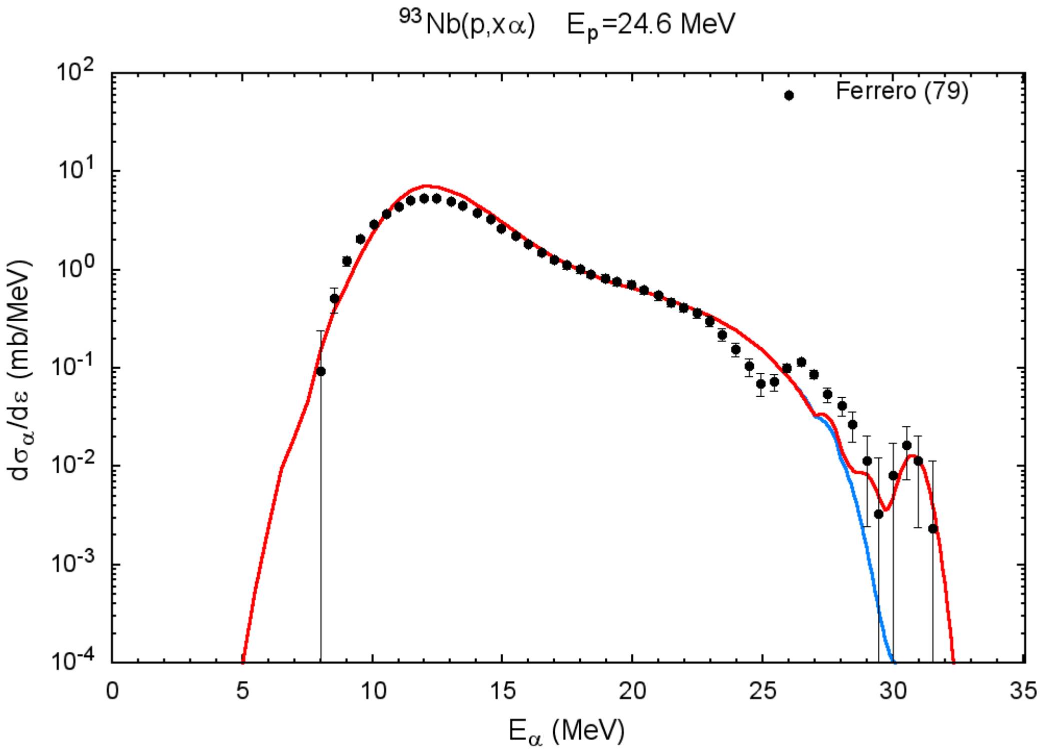


Fig.59 The same as in Fig.1 but for the p+^{93}Nb reaction at E_p=24.6 MeV.

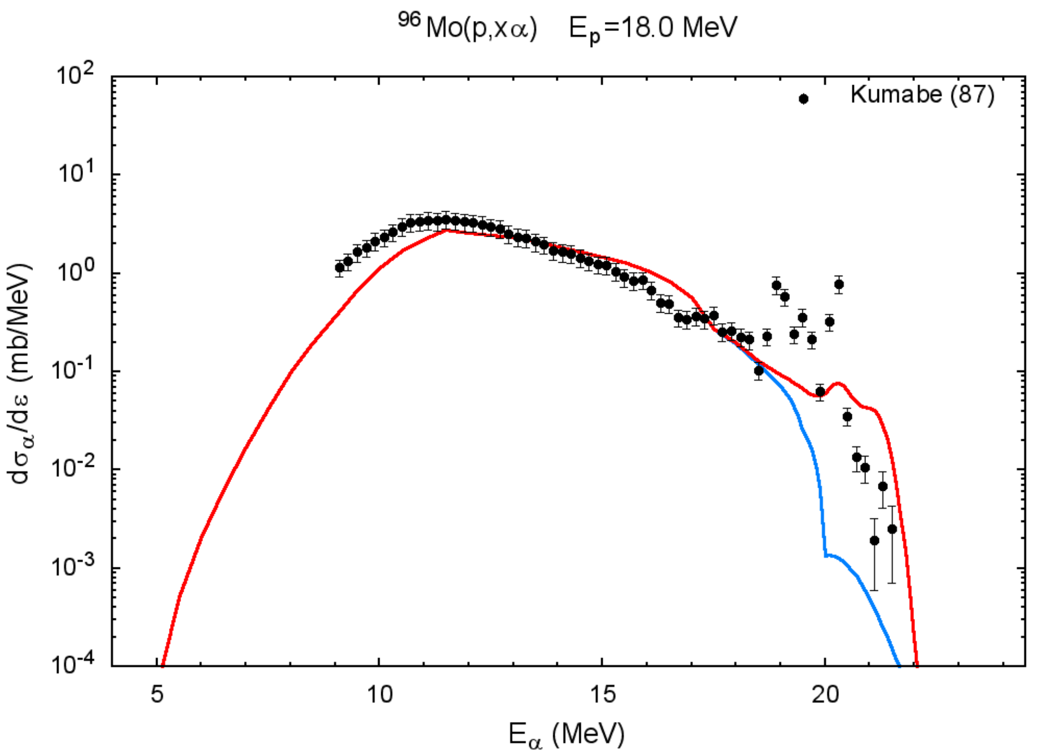


Fig.60 The same as in Fig.1 but for the p+^{96}Mo reaction at E_p=18 MeV.

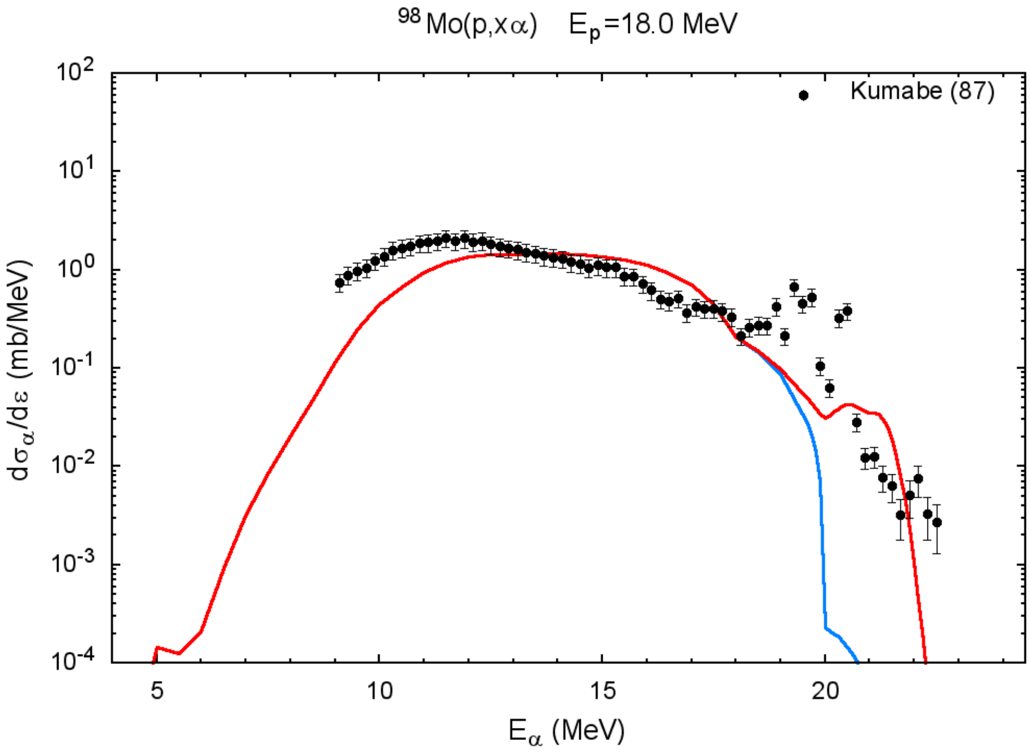


Fig.61 The same as in Fig.1 but for the p+^{98}Mo reaction at E_p=18 MeV.

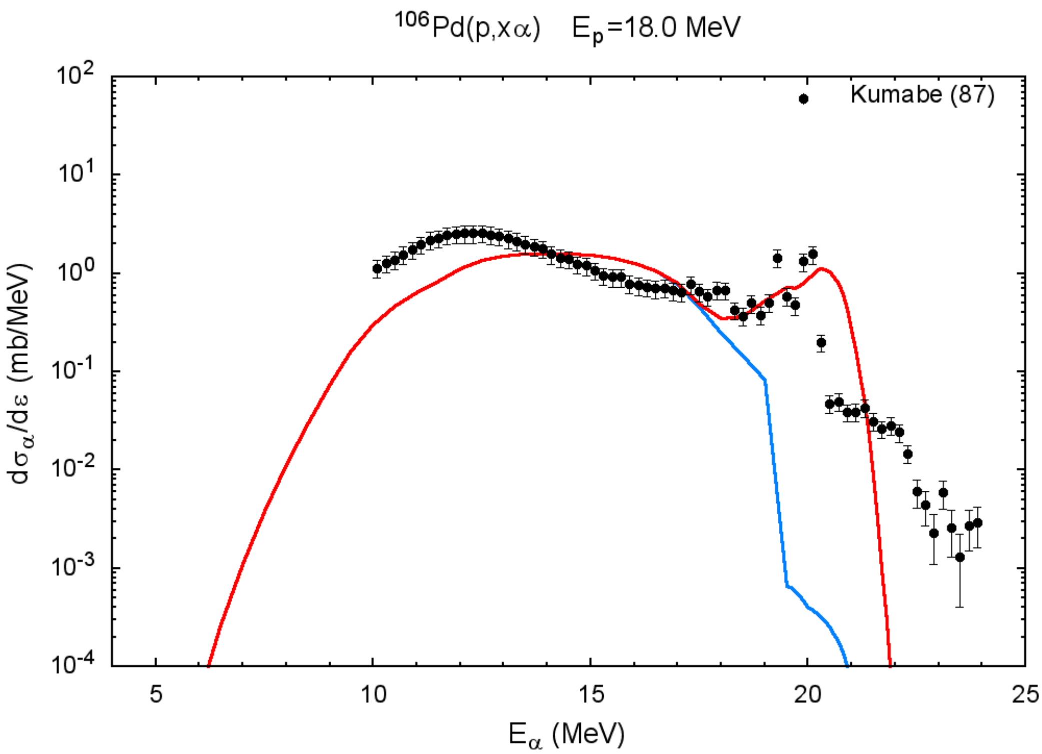


Fig.62 The same as in Fig.1 but for the p+^{106}Pd reaction at E_p=18 MeV.

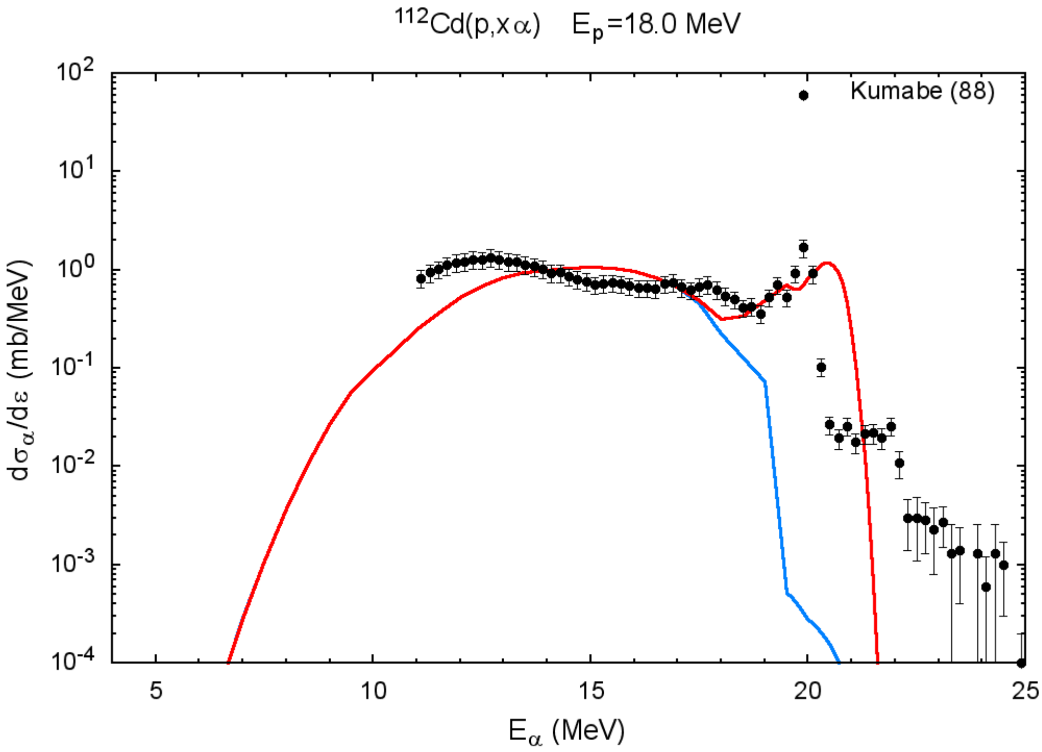


Fig.63 The same as in Fig.1 but for the p+^{112}Cd reaction at E_p=18 MeV.

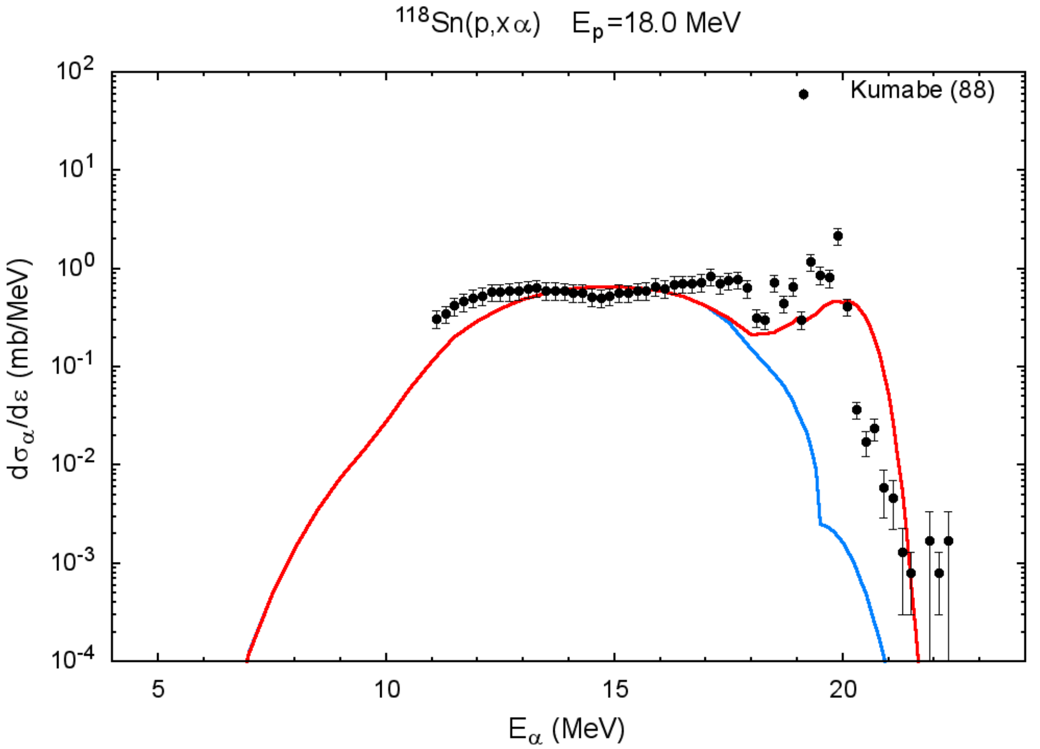


Fig.64 The same as in Fig.1 but for the p+^{118}Sn reaction at E_p=18 MeV.

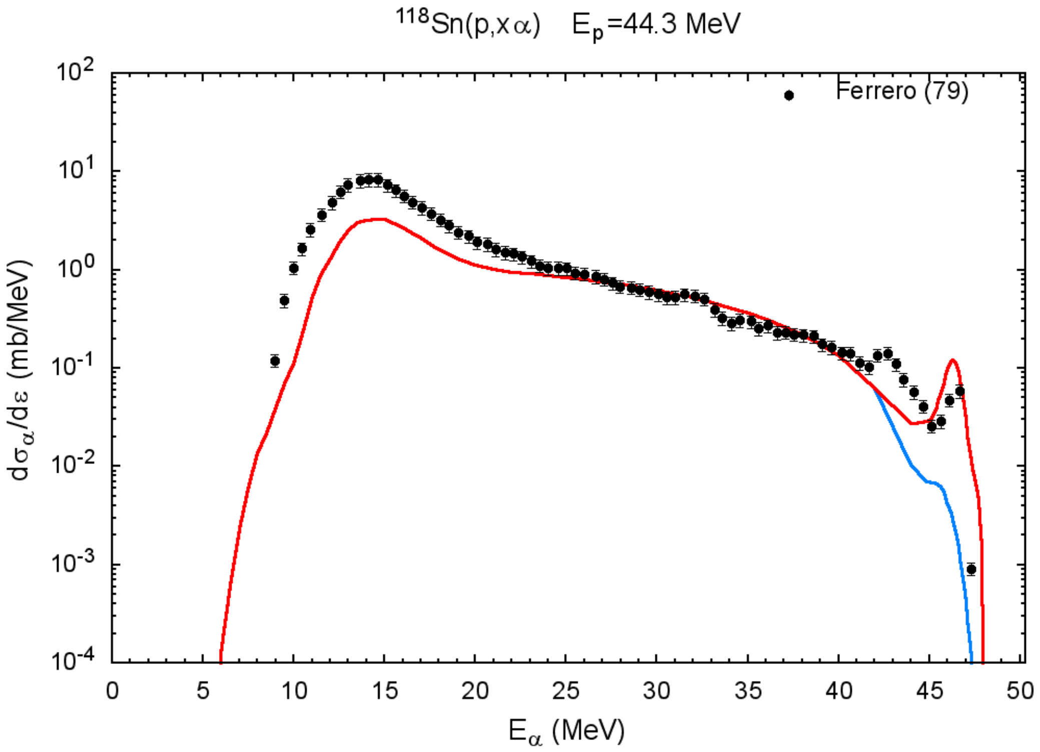


Fig.65 The same as in Fig.1 but for the p+^{118}C reaction at E_p=44.3 MeV.

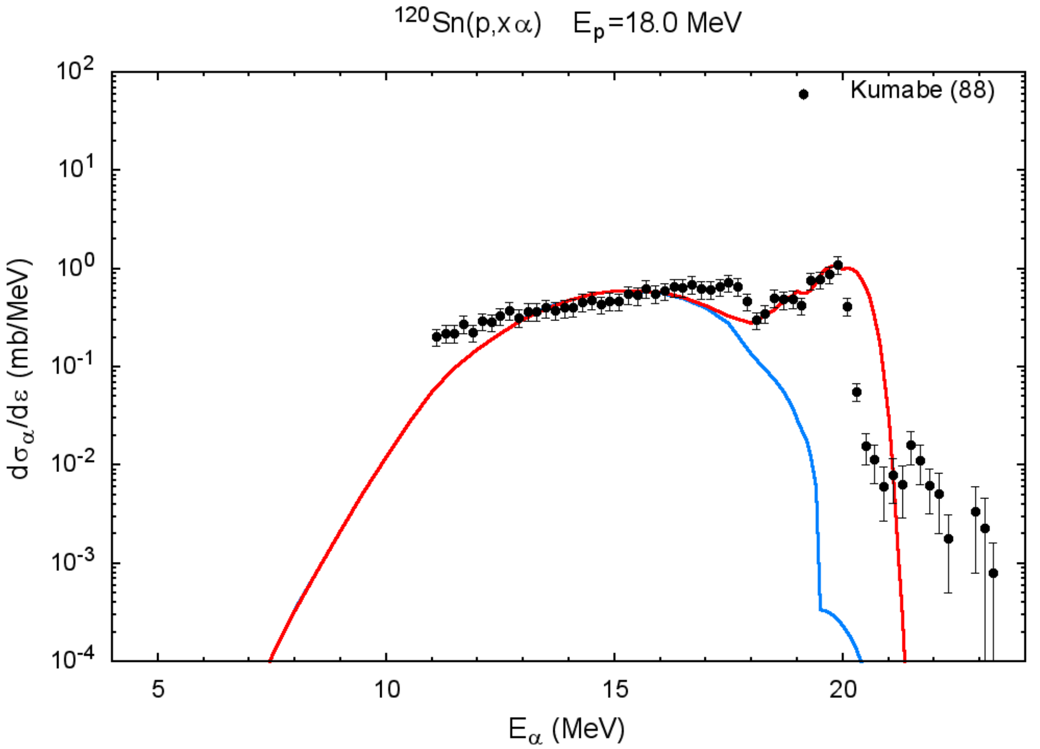


Fig.66 The same as in Fig.1 but for the p+^{120}Sn reaction at E_p=18 MeV.

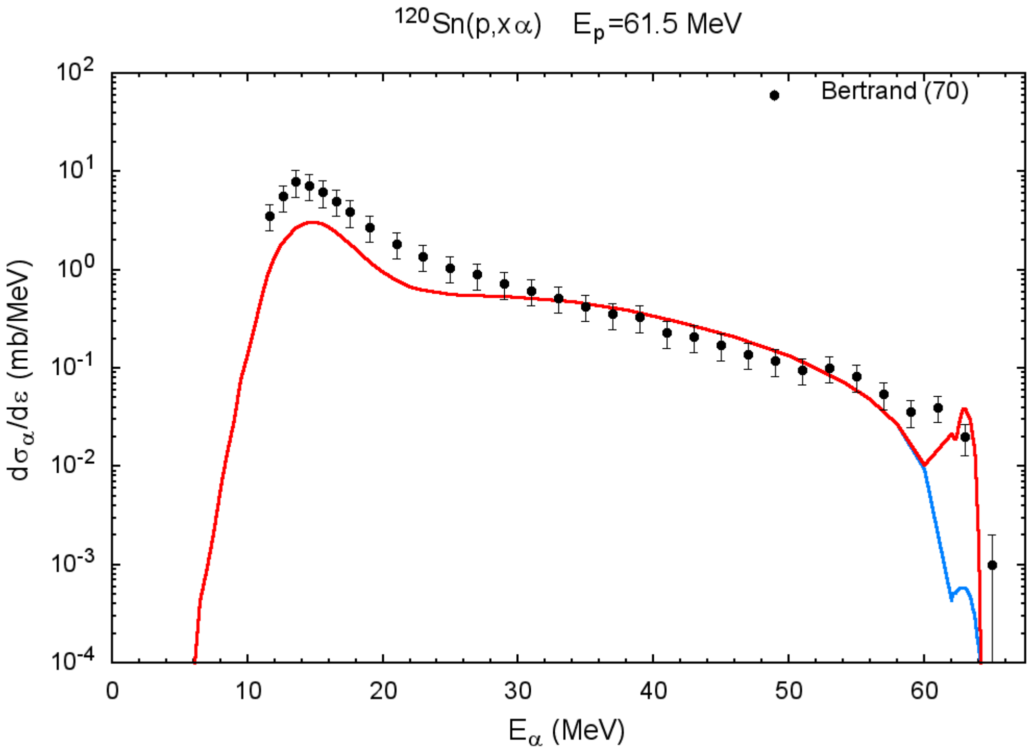


Fig.67 The same as in Fig.1 but for the p+^{120}Sn reaction at E_p=61.5 MeV.

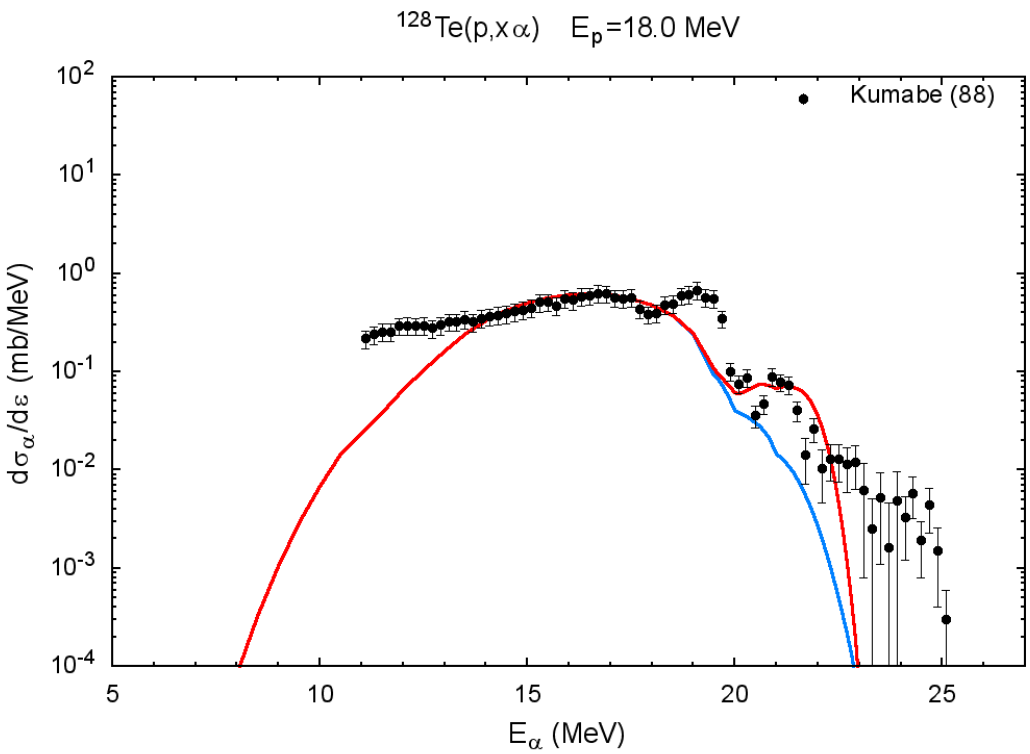


Fig.68 The same as in Fig.1 but for the p+^{128}Te reaction at E_p=18 MeV.

4. Conclusion

In this work, a simple phenomenological model is proposed for calculating the contribution of direct processes to the production of α-particles in reactions induced by nucleons. The calculated and experimental data for 38 target nuclei irradiated by neutrons and 44 target nuclei from ^{12}C to ^{238}U irradiated by protons are compared. The study shows that relative good agreement with the experimental data, in most cases, can be achieved using only two parameters. It is hoped that the proposed method will improve the quality of mass calculations of the spectra of α-particles.

Acknowledgement

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] E.Gadioli, E.Gadioli Erba, L.Glowacka, M.Jaskola, J.Turkiewicz, L.Zemlo, J.Dalmas, A.Chiadli, $^{90,91}Zr(n,\alpha)^{87,88}Sr$ reactions at 14.3 and 18.15 MeV incident neutron energy, Phys. Rev. C, Vol.34, Issue.6, p.2065 (1986).

[2] E.Gadioli, E.Gadioli Erba, W.Augustyniak, L.Glowacka, M.Jaskola, J.Turkiewicz, J.Dalmas, Alpha-particle emission from fast neutron-induced reactions on neodymium isotopes, Phys. Rev. C, Vol.38, p.1649 (1988).

[3] E.Gadioli, S.Mattioli, W.Augustyniak, L.Glowacka, M.Jaskola, J.Turkiewicz, A.Chiadli, Structure effects in the spectra of α-particles from the interaction of 12 to 20 MeV neutrons with samarium isotopes, Phys. Rev. C, Vol.43, p.1932 (1991).

[4] A.J. Koning, S. Hilaire, M.C. Duijvestijn, TALYS-1.0, Proc. International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, editors O. Bersillon, F. Gunsing, E. Bauge, R. Jacqmin, and S. Leray, EDP Sciences, 2008, p. 211

[5] A.J. Koning, S. Hilaire, S. Goriely, TALYS-1.95, A nuclear reaction program, December 24 (2019); https://tendl.web.psi.ch/tendl_2019/talys.html

[6] C. Kalbach, Preequilibrium reactions with complex particle channels, Phys. Rev. C 71, 034606 (2005).

[7] C.H.M. Broeders, A.Yu. Konobeyev, Phenomenological model for non-equilibrium deuteron emission in nucleon induced reactions, Kerntechnik, 70, 260 (2005).

[8] A.Yu.Konobeyev, U.Fischer, P.E.Pereslavtsev, M.Blann, Improved simulation of the pre-equilibrium triton emission in nuclear reactions induced by nucleons, Nuclear Data Sheets, v. 118, 280 (2014).

[9] M. Blann, H.K. Vonach, Global test of modified precompound decay models, Phys. Rev. C 28, 1475 (1983).

[10] A.J. Koning, M.C.Duijvestijn, A global pre-equilibrium analysis from 7 to200 MeV based on the optical model potential, Nucl. Phys. A744, 15 (2004).

[11] M. Blann, ALICE-91: Statistical model code system with fission competition, RSIC Code Package PSR-146, 1991.

[12] A.Yu. Konobeyev, U. Fischer, P.E. Pereslavtsev, A.J. Koning, M. Blann, Implementation of GDH model in TALYS-1.7 code, KIT Scientific Working Papers 45, (2016), https://publikationen.bibliothek.kit.edu/1000052543; A.J. Koning, M. Blann, J. Bisplinghoff, C.H.M. Broeders et al, TALYS-G: TALYS with implemented GDH model (2020), http://www.inr.kit.edu/940.php

[13] R.Arlt, G.Musiol, P.Schneider, D.Seeliger, W.Wagner, Measurement of the alpha-spectrum of the reaction Al-27(n,α)Na-24, Zentralinst. f. Kernforschung Rossendorf Reports, No.350, p.7 (1978).

[14] W.Augustyniak, L.Glowacka, M.Jaskola, J.Turkiewicz, L.Zemlo, Differential cross-sections for the (n,a)reactions induced by fast neutrons in Sm-149 and

Nd-143 nuclei., Inst. Badan Jadr. (Nucl.Res.), Swierk+Warsaw,Repts, No.1702/I/PL/A, p.11 (1977).
[15] W.Augustyniak, L.Glowacka, M.Jaskola, J.Turkiewicz, L.Zemlo, J.Dalmas, E.Gadioli, E.Gadioli Erba, Structure effects in (n,α) reactions on Nd isotopes, Lettere al Nuovo Cimento, Vol.42, p.425 (1985).
[16] F.B.Bateman, R.C.Haight, M.B.Chadwick, S.M.Sterbenz, S.M.Grimes, H.Vonach, Light charged-particle production from neutron bombardment of siliconup to 60 MeV: role of level densities and isospin, Phys. Rev. C, Vol.60, p.064609 (1999).
[17] S.Benck, I.Slypen, J.P.Meulders, V.Corcalciuc, M.B.Chadwick, P.G.Young, A.J.Koning, Light charged particle production in neutron-induced reactions on aluminum at En = 62.7 MeV, Phys. Rev. C, Vol.58, Issue.3, p.1558 (1998).
[18] S.Benck, I.Slypen, J.P.Meulders, V.Corcalciuc, Experimental cross sections for light-charged particle production induced by neutrons with energies between 25 and 65 MeV incident on oxygen, Atomic Data and Nuclear Data Tables, Vol.72, p.1 (1999).
[19] S.Benck, I.Slypen, J.-P.Meulders, V.Corcalciuc, Secondary light charged particle emission from the interaction of 25-to 65-MeV neutrons on silicon, Nucl. Sci. Eng., Vol.141, Issue.1, p.55 (2002).
[20] F.E.Bertrand, R.W.Peelle, Complete hydrogen and helium particle spectra from 30- to 60-MeV proton bombardment of nuclei with a = 12 to 209 and comparison with the intranuclearcascade model, Phys. Rev. C, Vol.8, p.1045 (1973).
[21] F.E.Bertrand, R.W.Peelle, Tabulated cross sections for hydrogen and helium particles produced by 62 and 29 MeV protons on 120-Sn, Oak Ridge National Lab. Reports, No.4471 (1970).
[22] F.E.Bertrand, R.W.Peelle, Tabulated cross sections for hydrogen and helium particles produced by 62 and 39 MeV protons on 209-Bi, Oak Ridge National Lab. Reports, No.4638 (1971).
[23] F.E.Bertrand, R.W.Peelle, Tabulated cross sections for hydrogen and helium particles produced by 62, 39 and 29 MeV protons on 54-Fe, Oak Ridge National Lab. Reports, No.4469 (1970).
[24] F.E.Bertrand, R.W.Peelle, Tabulated cross sections for hydrogen and helium particles produced by 62 MeV and 29 MeV protons on 27-Al, Oak Ridge National Lab. Reports, No.4455 (1969).
[25] F.E.Bertrand, R.W.Peelle, Tabulated cross sections for hydrogen and helium particles produced by 62 MeV protons on 89-Y, Oak Ridge National Lab. Reports, No.4450 (1969).
[26] F.E.Bertrand, R.W.Peelle, Tabulated cross sections for hydrogen and helium particles produced by 61 MeV protons on 56-Fe, Oak Ridge National Lab. Reports, No.4456 (1969).
[27] F.E.Bertrand, R.W.Peelle, Tabulated cross sections for hydrogen and helium particles produced by 62 and 29 MeV protons on 197-Au, Oak Ridge National Lab. Reports, No.4460 (1969).

[28] V.Blideanu, F.R.Lecolley, J.F.Lecolley, T.Lefort, N.Marie, A.Atac, G.Ban, B.Bergenwall, J.Blomgren, S.Dangtip, K.Elmgren, Ph.Eudes, Y.Foucher, A.Guertin, F.Haddad, A.Hildebrand, C.Johansson, O.Jonsson, M.Kerveno, T.Kirchner, J.Klug, Ch.Le Brun, C.Lebrun, M.Louvel, P.Nadel-Turonski, L.Nilsson, N.Olsson, S.Pomp, A.V.Prokofiev, P.-U.Renberg, G.Riviere, I.Slypen, L.Stuttge, U.Tippawan, M.Osterlund, Nucleon-induced reactions at intermediate energies: New data at 96 MeV and theoretical status, Phys. Rev. C, Vol.70, Issue.1, p.014607 (2004).

[29] J.Csikai, S.Nagy, Disintegration of N-14 by fast neutrons, Acta Physica Hungarica, Vol.21, p.303 (1966).

[30] P.Demetriou, Ch.Dufauquez, Y.El Masri, A.J.Koning, Light charged-particle production from proton- and α-induced reactions on natsi at energies from 25 to 65 MeV: a theoretical analysis, Phys. Rev. C, Vol.72, p.034607 (2005).

[31] C.Derndorfer, R.Fischer, P.Hille, H.Vonach, P.Maier-Komor, Investigation of the ^{50}Cr(n,α)^{47}Ti reaction at E(n) = 14.1 MeV, Zeitschrift fuer Physik A, Hadrons and Nuclei, Vol.301, p.327 (1981).

[32] A.Duisebayev, K.M.Ismailov, I.Boztosun, Inclusive cross-sections of (p,xp) and (p,xα) reactions on ^{56}Fe at Ep = 29.9 MeV, Phys. Rev. C, Vol.72, p.054604 (2005).

[33] A.Ferrero, E.Gadioli, E.Gadioli Erba, I.Iori, N.Molho, L.Zetta, α emission in proton induced reactions, Zeitschrift fuer Physik A, Hadrons and Nuclei, Vol.293, p.123 (1979).

[34] R.Fischer, C.Derndorfer, B.Strohmaier, H.Vonach, Investigation of the α-Particle emission from the reaction ^{93}Nb +n at E(n) = 14.1 MeV, Annals of Nuclear Energy, Vol.9, p.409 (1982).

[35] R.Fischer, G.Traxler, M.Uhl, H.Vonach, ^{56}Fe(n,α)^{53}Cr and ^{60}Ni(n,α)^{57}Fe reactions at E(n) = 14.1 MeV, Phys. Rev. C, Vol.30, Issue.1, p.72 (1984).

[36] R.Fischer, G.Traxler, M.Uhl, H.Vonach, P.Maier-Komor, ^{55}Mn(n,α)^{53}Cr and ^{59}Co(n,α) reactions at E(n)=14.1 MeV, Phys. Rev. C, Vol.34, Issue.2, p.460 (1986).

[37] E.Gadioli, I.Lori, N.Molho, L.Zetta, (p,alpha) reactions on heavy nuclei, INFN Reports / Low Energy Physics Series, No.73/5 (1973).

[38] S.M.Grimes, R.C.Haight, K.R.Alvar, H.H.Barschall, R.R.Borchers, Charged-particle emission in reactions of 15-MeV neutrons with isotopes of chromium, iron, nickel, and copper, Phys. Rev. C, Vol.19, p.2127 (1979).

[39] P.Guazzoni, L.Zetta, P.Demetriou, P.E.Hodgson, Multistep direct analysis of (p,α) reactions to the continuum, Zeitschrift fuer Physik A, Hadrons and Nuclei, Vol.354, p.53 (1996).

[40] A.Guertin, N.Marie, S.Auduc, V.Blideanu, Th.Delbar, P.Eudes, Y.Foucher, F.Haddad, T.Kirchner, Ch.Le Brun, C.Lebrun, F.R.Lecolley, J.F.Lecolley, X.Ledoux, F.Lefebvres, T.Lefort, M.Louvel, A.Ninane, Y.Patin, Ph.Pras, G.Riviere, C.Varignon, Neutron and light-charged-particle productions in proton-induced reactions on ^{208}Pb at 62.9 MeV, Europ. Phys. J. A, Vol.23, p.49 (2005).

[41] R.C.Haight, S.M.Grimes, R.G.Johnson, H.H.Barschall, Charged-particle emission in reactions of 15-MeV neutrons with ^{89}Y, ^{90}Zr,and ^{92,94,95,96}Mo, Phys. Rev. C, Vol.23, p.700 (1981).
[42] R.C.Haight, S.M.Grimes, J.D.Anderson, Hydrogen and helium production cross sections for 15-MeV neutrons on types 316 and 304 stainless steel, Nucl. Sci. Eng., Vol.63, p.200 (1977).
[43] O.N.Kaul, Alpha particles from the interaction of 14 MeV neutrons with arsenic, Nucl. Phys., Vol.29, p.522 (1962).
[44] Kokooo, I.Murata, A.Takahashi, Measurements of double-differential cross sections of charged particles emission reactions for several structural elements of fusion power reactors by 14.1 MeV incident neutrons, Nucl. Sci. Eng., Vol.132, Issue.1, p.16 (1999).
[45] O.N.Koul, Alpha particles from the interaction of 14 MeV neutrons with arsenic, Nucl. Phys., Vol.29, p.522 (1962).
[46] I.Kumabe, Y.Mito, M.Hyakutake, N.Koori, H.Sakai, Y.Watanabe, Shell and odd-even effects on alpha-particle energy spectra from the (p,α) reaction on nuclei around neutron number 50, Phys. Rev. C, Vol.35, Issue.2, p.467 (1987).
[47] I.Kumabe, Y.Inenaga, M.Hyakutake, N.Koori, Y.Watanabe, K.Ogawa, K.Orito, Alpha-particle energy spectra from the (p,α) reaction on nuclei around atomic number 50, Phys. Rev. C, Vol.38, Issue.6, p.2531 (1988).
[48] J.Kvitek, Z.Kosina, Yu.P.Popov, Investigation of the Nd-143(n,alpha)Ce-140 reaction induced by thermal neutrons, Ustav Jad. Fyziky (Inst.Nucl.Phys.) Reports, No.3303.F (1974).
[49] Z.Lewandowski, E.Loeffler, R.Wagner, H.H.Mueller, W.Reichart, P.Schober, E.Gadioli, E.Gadioli Erba, Proton-induced α- and τ-Emission at 72 MeV, Lettere al Nuovo Cimento, Vol.28, p.15 (1980).
[50] M.G.Marcazzan, F.Merzari, F.Tonoloni, Application of silicon detectors to measurements of monoenergetic neutron beams, Physics Letters, Vol.1, Issue.1, p.21 (1962).
[51] I.Matsuyama, M.Baba, S.Matsuyama, T.Kiyosumi, T.Sanami, N.Hirakawa, N.Ito, S.Chiba, T.Fukahori, M.Mizumoto, K.Hasegawa, Sh.Meigo, Measurements of double-differential alpha-particle production cross-sections using a gridded ionization chamber -- application of 14-N(D,N)15-O and 15-N(d,N)16-O neutron sources, JAERI-M Reports, No.94-019, p.191 (1993).
[52] Y.Mukhamejanov, G.Alieva, D.Alimov, G.D.Kabdrakhimova, M.Nassurlla, N.Saduyev, B.M.Sadykov, T.K.Zholdybayev, K.M.Ismailov, Y.Kucuk, Investigation of (p,xp) and (p,xα) reactions of 30-MeV protons with the 103Rh nucleus, Acta Physica Polonica, Part B, Vol.51, p.783 (2020).
[53] N.Nica, S.Benck, E.Raeymackers, I.Slypen, J.P.Meulders, V.Corcalciuc, Light charged particle emission induced by fast neutrons (25 to 65 MeV) on 59Co, J. Phys. G, Vol.28, p.2823 (2002).
[54] W.Patzak, H.Vonach, Die reaktionen Al27(n,α)Na24 und Co59(n,α)Mn56 mit 14 MeV neutrons, Nucl. Phys., Vol.39, p.263 (1962).

[55] P.Plischke, W.Scobel, M.Bormann, Preequilibrium proton and α emission from neutron induced reactions in CsI, Zeitschrift fuer Physik A, Hadrons and Nuclei, Vol.281, Issue.3, p.245 (1977).

[56] E.Raeymackers, S.Benck, I.Slypen, J.P.Meulders, N.Nica, V.Corcalciuc, A.Koning, Light charged particle production in the interaction of fast neutrons (25-65 MeV) with uranium nuclei, Phys. Rev. C, Vol.68, p.024604 (2003).

[57] E.Raeymackers, S.Benck, N.Nica, I.Slypen, J.P.Meulders, V.Corcalciuc, A.J.Koning, Light charged particle emission in fast neutron (25-65 MeV) induced reactions on ^{209}Bi, Nucl. Phys. A, Vol.726, p.210 (2003).

[58] T.Sanami, M.Baba, T.Kawano, S.Matsuyama, T.Kiyosumi, Y.Nauchi, K.Saito, N.Hirakawa, High resolution measurements of double differential (n,α) cross sections of ^{58}Ni and ^{nat}Ni between 4.2 and 6.5 MeV neutrons, J. Nucl. Sci. Technol., Vol.35, p.851 (1998).

[59] S.K.Saraf, C.E.Brient, P.M.Egun, S.M.Grimes, V.Mishra, R.S.Pedroni, Cross sections and spectra for the ^{54}Fe and ^{56}Fe(n,xp) and (n,xα) reactions between 8 and 15 MeV, Nucl. Sci. Eng., Vol.107, p.365 (1991).

[60] I.Slypen, S.Benck, J.P.Meulders, V.Corcalciuc, Experimental cross sections for light charged particle production induced by neutrons with energies between 25 and 75 MeV incident on carbon, Atomic Data and Nuclear Data Tables, Vol.76, p.26 (2000).

[61] I.Slypen, N.Nica, A.Koning, E.Raeymackers, S.Benck, J.P.Meulders, V.Corcalciuc, Light charged particle emission induced by fast neutrons with energies between 25 and 65 MeV on iron, J. Phys. G, Vol.30, p.45 (2004).

[62] A.Sprinzak, A.J.Kennedy, J.C.Pacer, J.Wiley, N.T.Porile, Systematics of (p,p') and (p,α) spectra from 14 MeV proton bombardment of medium-a targets, Nucl. Phys. A, Vol.203, p.280 (1973).

[63] S.M.Sterbenz, F.B.Bateman, T.M.Lee, R.C.Haight, P.G.Young, M.B.Chadwick, F.C.Goeckner, C.E.Brient, S.M.Grimes, The ^{56}Fe (n,xα) reaction from threshold to 30 MeV, Conf. on Nucl. Data for Sci. and Techn.,Gatlinburg 1994, Vol.1, p.314 (1994).

[64] H.Takagi, Kokooo, I.Murata, A.Takahashi, Measurement of double-differential cross sections of charged particle emission reactions for nat-Zr, ^{27}Al, and nat-Ti by incident DT neutrons, JAERI Conference proceedings, No.99-002, p.204 (1998).

[65] Y.Terada, H.Takagi, Kokooo, I.Murata, A.Takahashi, Measurements of double differential cross sections for charged particle emission reactions by 14.1 MeV incident neutrons, J. Nucl. Sci. Technol. Suppl., Vol.2, p.413 (2002).

[66] U.Tippawan, S.Pomp, J.Blomgren, S.Dangtip, C.Gustavsson, J.Klug, P.Nadel-Turonski, L.Nilsson, M.Osterlund, N.Olsson, O.Jonsson, A.V.Prokofiev, P.-U.Renberg, V.Corcalciuc, Y.Watanabe, A.J.Koning, Light-ion production in the interaction of 96 MeV neutrons with carbon, Phys. Rev. C, Vol.79, p.064611 (2009).

[67] U.Tippawan, S.Pomp, A.Atac, B.Bergenwall, J.Blomgren, S.Dangtip, A.Hildebrand, C.Johansson, J.Klug, P.Mermod, L.Nilsson, M.Osterlund, N.Olsson, K.Elmgren, O.Jonsson, A.V.Prokofiev, P.-U.Renberg, P.Nadel-

Turonski, V.Corcalciuc, Y.Watanabe, A.J.Koning, Light-ion production in the interaction of 96 MeV neutrons with silicon, Phys. Rev. C, Vol.69, p.064609 (2004).

[68] U.Tippawan, S.Pomp, A.Atac, B.Bergenwall, J.Blomgren, S.Dangtip, A.Hildebrand, C.Johansson, J.Klug, P.Mermod, L.Nilsson, M.Osterlund, N.Olsson, A.V.Prokofiev, P.Nadel-Turonski, V.Corcalciuc, A.J.Koning, Light-ion production in the interaction of 96 MeV neutrons with oxygen, Phys. Rev. C, Vol.73, p.034611 (2006).

[69] C.Tsabaris, E.Wattecamps, G.Rollin, C.Papadopoulos, Measured and calculated differential and total yield cross section data of Ni-58(n,xα) and Cu(n,xp) in the neutron energy range from 2.0 to 15.6 MeV, Nucl. Sci. Eng., Vol.128, p.47 (1998).

[70] J.R.Wu, C.C.Chang, H.D.Holmgren, Charged-particle spectra: 90 MeV protons on 27Al, 58Ni, 90Zr, and 209Bi, Phys. Rev. C, Vol.19, p.698 (1979).

[71] B.Ye, R.Han, Z.Wang, Y.Fan, X.Yu, H.Du, Z.Xiao, Measurement of alpha-particles emitted from interaction of 14.6 MeV neutrons with elemental nickel, J. Nucl. Sci. Technol., Vol.35, Issue.1, p.1 (1998).

[72] T.Zholdybayev, Zh.Mukan, B.M.Sadykov, B.A.Duisebayev, Maulen Nassurlla, K.M.Ismailov, Y.Kucuk, Continuous spectra of light charged particles from interaction of 30 MeV energy protons with cooper, EPJ Web of Conferences, Vol.239, p.01033 (2020).

KIT Scientific Working Papers
ISSN 2194-1629
www.kit.edu