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Inclusive Cross-Sections of (p, xp) and (p, xα) Reactions on ^{56}Fe Nucleus at E_p=29.9 MeV

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Abstract

In this paper, we present new experimental data measured at E_p=29.9 MeV for the inclusive reactions (p,xp) and (p,xα) on nucleus ^{56}Fe. The adequacy of the theoretical models in explaining the measured experimental data is investigated and the contributions of multi-step direct and multi-step compound processes in the formation of the cross-sections are determined. It should also be underlined that the traditional frameworks are valid for the description of the new experimental data. A comparison with the previous measurements for the (p,xp) and (p,xα) on ^{54}Fe nucleus reveals that these data are in agreement with our measurements. The only exception is within the energy region of E_p=15 and 25 MeV for both reactions, where the cross-section for the ^{56}Fe nucleus is smaller than the cross-section for the ^{54}Fe nucleus.

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I. INTRODUCTION

The pre-equilibrium decay mechanism in nuclear reactions reflects the dynamics of the formation of the excited system and its evolution to the equilibrium state. Working out this mechanism remains as an actual problem of the nuclear reaction theory. The problem is largely connected with obtaining new experimental data on double-differential cross-sections in (p,xp), (p,xd) *etc.* Thus, it is anticipated that the availability of high-quality experimental data on reactions with different proton energies [1], using charged particles for the double-differential cross-sections, could address this problem.

The reactions induced by protons within the energy range of 10-2000 MeV play a crucial role in applied research. Development of electro-nuclear installations (Accelerator Driven System) for nuclear transmutation, which arises from long-lived radioactive waste of nuclear industry and energy production [2], is one important example.

The physical scenario of such a system requires the presence of experimental data on key parameters of nucleon interaction, cross-sections of interaction, energy spectra and angle distributions of secondary particles (^{1,2,3}H, ^{3,4}He *etc.*). These particles can be agents initiating a reaction with neutrons emission. The testing and perfection of the theoretical methods and codes in describing the experimental measurements become also very important.

In this study, the subject of the research is the ^{56}Fe nucleus, which is one of the basic constructional materials of hybrid nuclear-energy installation. Early experimental studies on the targets of ^{54,56}Fe nuclei [3, 4, 5, 6, 7, 8, 9] have focused on the emission of protons, deuterons, and alpha particles. The double differential cross section measurements, angle-integrated spectra and energy-binned angular distributions obtained from these experimental studies have been compared with the predictions of the pre-equilibrium reaction theory (see a recent review by Koning and Duijvestijn [10] for a detailed discussion). Initial experimental data on reactions (p,xp), (p,xα) on nuclei of isotope ^{54}Fe at E_p=29.0 and 39.0 MeV have been measured in the work of reference [6] and the energy spectra of secondary particles have been analyzed within the intra-nuclear cascade and evaporation models. An acceptable description of the experimental data have been achieved only for a spectrum higher than 20.0 MeV.

The Japanese group [11] has investigated the cross-sections of the reaction (p,xp) on targets ^{54,56}Fe nuclei with a thickness of 500 mg/cm^2 at the energy 26.0 MeV. The experimental

data have been analyzed within the framework of FKK theory for pre-equilibrium processes, using the code FKK-GNASH and within the framework of the Hauser-Feshbach model for compound processes.

It is clear that the protons in the energy region of 30 MeV have not been studied in detail. Extending the experiment in this direction allows us to observe the mechanisms of the reaction and the level of energy-dependence in detail and to use these observations for adequate analysis within the framework of the pre-equilibrium reaction theory.

Therefore, in our experiment we consider the (p,xp)^{56}Fe and (p,xα)^{56}Fe reactions at E_p=29.9 MeV within the angle range of 30-135°. In the following section, we present our experimental method, the details of the measurement and the experimental results. Section III is devoted to the theoretical analysis of the measured experimental data by the exciton model and quantum mechanical representations. Finally, Section IV gives our summary and conclusion.

II. EXPERIMENT AND RESULTS

The experimental cross-sections measurement of reactions (p,xp) and (p,xα) have been carried out on a beam of the accelerated protons at an energy of 29.9 MeV on the isochronous cyclotron, U-150M, at the Institute of Nuclear Physics, NNC Republic of Kazakhstan, by using a self-supporting target ^{56}Fe. The properties of the target nucleus are given in table I. The measurements have been executed within the angle range of 30-135° at intervals of 15° in the laboratory system.

The registration and identification of the reaction products have been carried out by a system of multi-programming analysis, based on the use of the ΔE-E-method, ORTEC and PC-spectrometric lines. The block-scheme of the registration system is presented in Figure 1. The detector telescope had a silicon surface-barrier detector ΔE with a thickness of 30 microns and E with a thickness of 2000 microns for the reaction ^{56}Fe(p,xα). Whereas for reaction ^{56}Fe(p,xp), the thickness of the silicon surface-barrier detector ΔE was 500 microns and the thickness of the stop detector of total absorption-crystal CsI(Tl) was 25 mm. The solid angles of telescopes equalled to 2.72 10^{-5} sr and 2.59 10^{-5} sr respectively. The energy calibration of spectrometers has been carried out by the kinematics of residual nuclei levels in reaction ^{12}C(p,x) and protons of recoil. The total energy resolution of the system basically

equalled to 400 keV, and was determined by the energy resolution of the accelerated protons beam. One should note that the real line spectra might be distorted by the impurity of the light elements in the target nucleus, accidental coincidences and background. Therefore, at each angle, we measured the spectra both with and without target as well as with the spectra of the light elements such as ^{12}C and ^{16}O.

Thus, the systematic uncertainties were conditioned by the uncertainties in determining the target thickness ($\sim$7%), the calibration of the current integrator ($\sim$1%), and the solid angle of the spectrometer ($\sim$1.3%). The energy of accelerated particles were measured accurately with 1.2%. The uncertainties of the registration angle were less than 0.5%. The whole systematic error was less than 10%. The statistical uncertainties at a long exposition time of the double-differential cross-sections were less than 10% for protons and less than 20% for α particles in the high-energy region of the spectra.

The results of the measurements are shown in Figure 2 for the ^{56}Fe(p,xα) reaction and in Figure 3 for the ^{56}Fe(p,xp) reaction together with analogical data on an isotope of the iron nucleus ^{54}Fe at 29.0 and 39.0 MeV, presented in the work of reference [6]. In accordance with the measurement of reference [6], cross-sections of reactions ^{56}Fe(p,xα) (Figure 2) and ^{56}Fe(p,xp) (Figure 3) practically coincide with the cross-sections of the appropriate reactions on ^{54}Fe. The exception is only in the energy region of E_p=15-25 MeV for both reactions, where the cross-section for the ^{56}Fe is less than the cross-section for the ^{54}Fe nucleus. We have obtained the experimental partial cross section by integrating the integral spectra (dσ/dE) on energy. The experimental partial cross-sections of reactions ^{56}Fe(p,xα), (p,xp) are given in table II.

III. ANALYSIS OF THE RESULTS

Many different theoretical approaches have been used to describe the equilibrium reactions data over a wide range of incident energies (see references [10, 11, 12, 13, 14, 15] for a detailed discussion). In this paper, the analysis of the experimental results has been conducted in the Griffin exciton model [16] of the pre-equilibrium decay of nuclei. The program PRECO-D2 [17], which describes the emission of particles with mass numbers from 1 up to 4, has been used in our theoretical calculations. The Griffin exciton model is a statistical model where the excited levels of the intermediate system are described in terms of the

single-particle shell model, *i.e.* characterized by the number of the excited particles (above the Fermi level) and holes (below the Fermi level). It is assumed that the evolution of the system occurs through a sequence turning into complicated configurations and the emission of particles is possible on each phase of this evolution. The conditions of the intermediate system are divided into two classes; bound and unbound. This allows the calculation of the integrated cross-sections on angle for the statistical multi-step direct (MSD) and multi-step compound (MSC) processes [18] in the exciton model. The calculated contributions of the MSD and MSC processes in the formation of the total cross-section of reactions ^{56}Fe(p,xp), (p,xα) are shown in figures 4 and 5. The contribution of additional MSD components that are not taken into account by the Griffin model have been determined semi-empirically by taking into account the direct nucleon transfer reaction and knock-out direct processes, including cluster freedom degrees. The evaporation from the equilibrium state of the nucleus has been included in the total cross-section. The configuration (1p0h) has been accepted as the initial particle-hole configuration in all calculations.

The density of the particle-hole states is given by

$$\omega(p,h,E) = \frac{g(gE - A_{ph})^{n-1}}{p!h!(n-1)!}, \tag{1}$$

where

$$A_{ph} = \frac{(p^2 + h^2) + (p - h) - 2h}{4} \tag{2}$$

The single-particle density of levels has been accepted as g=A/13.

The optical potential parameters of Huizenga [19] for α-particles and of F. D.Becchetti and G. W.Greenlees [20] for protons have been used.

The comparison of the experimental results and theoretically calculated spectra is shown in Figures 4 and 5. It can be seen from these figures that the basic contribution to the hard part of the total cross-section is caused by the MSD mechanism. It is also observed that the evaporated part of the cross-section is underestimated within the framework of the exciton model used. This may be due to the fact that the preferred approach gives only the pre-equilibrium part of the MSC process without taking into account the emission from complex equilibrium configuration of the compound system. Therefore, the analysis of the experimental cross-sections of the ^{56}Fe(p,xp) reaction is carried out within the Hauser-

Feshbach theory by considering the multi-particle emission of both single-charged (protons, deuterons) and two-charged fragments (α-particles) by using the program EMPIRE-II [21]. In this code, the contributions of statistical direct and compound processes are described by the optical model (SCAT 2 [22]), multi-step direct (ORION+TRISTAN [23, 24] and multi-step compound (NVWY [25]) models. The parameter of the level density has been defined by the Gilbert-Cameron parameterizations [26].

The results of the calculations using the Hauser-Feshbach theory are given in table III and are shown in Figures 4 and 5. These results display that the contribution of the multi-particle compound mechanism determines the emission of protons from 2.5 MeV up to 10 MeV and that the contribution of multi-step direct process ranges from 5 MeV up to the kinematical limit. The form of integral spectra of reaction (p,xp) is determined by the multi-step direct processes.

IV. SUMMARY AND CONCLUSIONS

We have measured the experimental data at E_p=29.9 MeV within the angle range of 30-135° for the inclusive reactions (p,xp) and (p,xα) on nucleus ^{56}Fe, which has not been investigated in detail so far. We have shown the extension of the pre-equilibrium reactions to this energy region and have interpreted the results of the experiments. The adequacy of the theoretical models in explaining the measured experimental data is also discussed. In our theoretical analysis, the contributions of multi-step direct and compound processes in the formation of cross-sections are determined and we assert that the traditional frameworks are valid for the description of the experimental data.

[1] A. Duisebayev, K.M. Ismailov and I. Boztosun, Phys. Rev. **C67** (2003) 044608.

[2] A.S. Gerasimov and G.V. Kiselev, EPAN **32** (2001) 143.

[3] S.M. Grimes, R.C. Haight, K.R. Alvar, H.H. Barschall and R.R. Borchers, Phys. Rev. **C19** (1979) 2127.

[4] A. Marcinkowski, R.W. Finlay, G. Randers-Pehrson, C.E. Brient, R. Kurup, S. Mellema, A. Meigooni and R. Tailor, Nucl. Phys. **A402** (1983) 220.

[5] N.S. Birjukov, B.V. Zhuravlev, A.P. Rudenko, O.A. Salnikov and V.I. Trykova, Yad. Fiz. **31** (1980) 561.

[6] F.E. Bertrand and R.W. Peelle, Phys. Rev. **C8** (1973) 1045.

[7] W. Scobel, M. Blann, T.T. Komoto, M. Trabandt, S.M. Grimes, L.F. Hansen, C. Wong and B.A. Pohl, Phys. Rev. **C30** (1984) 1480.

[8] A. Sprinzak, A.J. Kennedy, J.C. Pacer, J. Wiley and N.T. Porile, Nucl. Phys. **A203** (1973) 280.

[9] Y. Watanabe, S. Yoshioka, M. Harada, K. Sato, Y. Nakao, H. Ijiri, S. Chiba, T. Fukahori, S. Meigo, O. Iwamoto and N. Koori, Proceedings of the International Conference on Nuclear Data for Science and Technology, Edited by G. Reffo (1997) 580.

[10] A.J. Koning and M.C. Duijvestijn, Nucl. Phys. **A744** (2004) 15.

[11] Y. Watanabe, S. Yoshioka, M. Harada *et al.*, JAERI-Rev. 1997, 97-010, p.55-56.

[12] H. Feshbach, A. Kerman and S. Koonin, Ann. Phys. (N.Y.) **125** (1980) 429.

[13] E. Gadioli and P.E. Hodgson, *Pre-Equilibrium Nuclear Reactions* (Oxford University Press, Oxford, 1992).

[14] R. Bonetti, M.B. Chadwick, P.E. Hodgson, B.V. Carlson and M.S. Hussein, Phys. Rep. **202** (1991) 171.

[15] R. Bonetti, A.J. Koning, J.M. Akkermans and P.E. Hodgson, Phys. Rep. **247** (1994) 1.

[16] J.J. Griffin, Phys. Rev. Lett. **17**(1966) 478.

[17] C. Kalbach, PRECO-D2: Program for Calculating Pre-equilibrium and Direct Reaction Double Differential Cross-Sections, LA-10248-MS (February 1985).

[18] C. Kalbach, Phys. Rev. C**23** (1981) 124;
C. Kalbach, Phys. Rev. **C24** (1981) 819.

[19] J.R. Huizenga and G. Igo, Nucl. Phys. **29** (1962) 462.

[20] F.D. Becchetti and G.W. Greenlees, Phys. Rev. **C182** (1964) 1190.

[21] M. Herman, G. Reffo and H.A. Weidenmüller, Nucl. Phys. **A536** (1992) 124. EMPIRE v2.13. Private communication.

[22] O. Bersillon, SCAT2: Un programme de modèle optique sphérique, Report CEA-N-2227, NEANDC(FR), INDC(E) 49/L, Oct. 1981.

[23] T. Tamura, T. Udagawa and H. Lenske, Phys. Rev. **C26** (1982) 379.

[24] H. Lenske and H.H. Wolter, Private communication to M. Herman

[25] H. Nishioka, JJ. Verbaarschot, H.A. Weidenmüller and S. Yoshida, Ann. Phys. **172** (1986) 67.

[26] A. Gilbert and A.G.W. Cameron, Can. J. Phys. **43** (1965) 1446.

	Thickness, mg/cm^2	Enrichment, %
^{56}Fe	2.7	95

TABLE I: Characteristics of the target nucleus.

^{56}Fe	Energy range (MeV)	σ(mb)
(p,xα)	5-25	132.2±1.2
(p,xp)	11-27	219.41±1.4

TABLE II: The experimental partial cross-section of the reactions (p,xα) and (p,xp).

	Energy range (MeV)	Total cross-section (mb)	MSD cross-section (mb)	MSC cross-section (mb)	Equilibrium cross-section (mb)	Hauser-Feshbach emission (mb)
PRECO-D2 ^{56}Fe (p,xα)	6-28	46.8	11.3	3.2	32.24	-
EMPIRE-II ^{56}Fe (p,xp)	1-30	1083.6	559.2	64.9	-	459.5

TABLE III: The theoretical contributions of various mechanisms forming the total cross-sections of reactions (p,xα) and (p,xp).

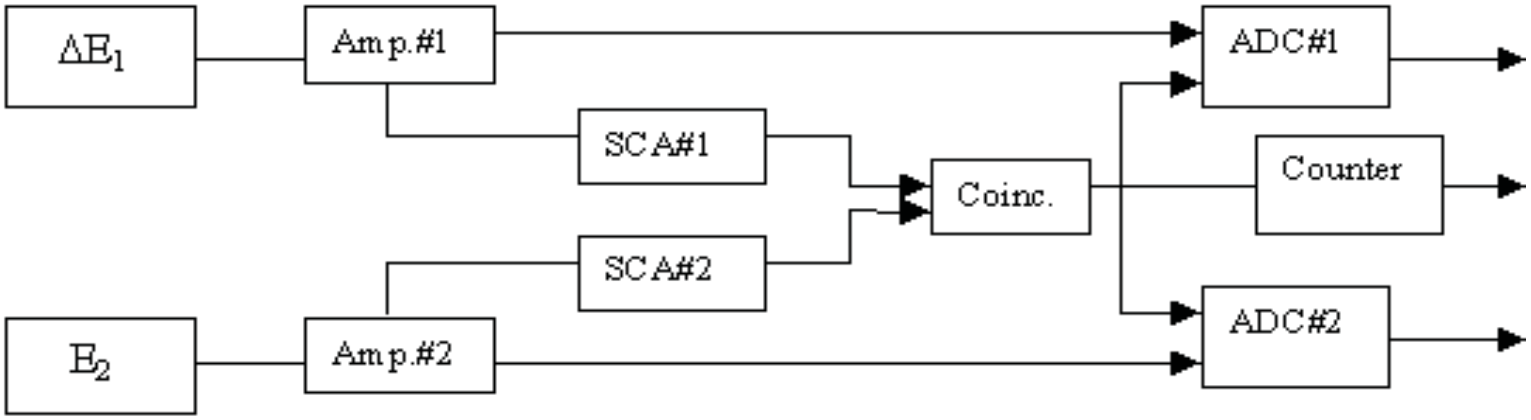


FIG. 1: The block-scheme of the registration system: Amp.#1,2- Spectroscopic Amplifiers; SCA#1,2- Single Channel Analyzers; Coinc. - Scheme of Coincidences; Counter-Counter Scheme; ADC#1,2- Analog - Digital Converters.

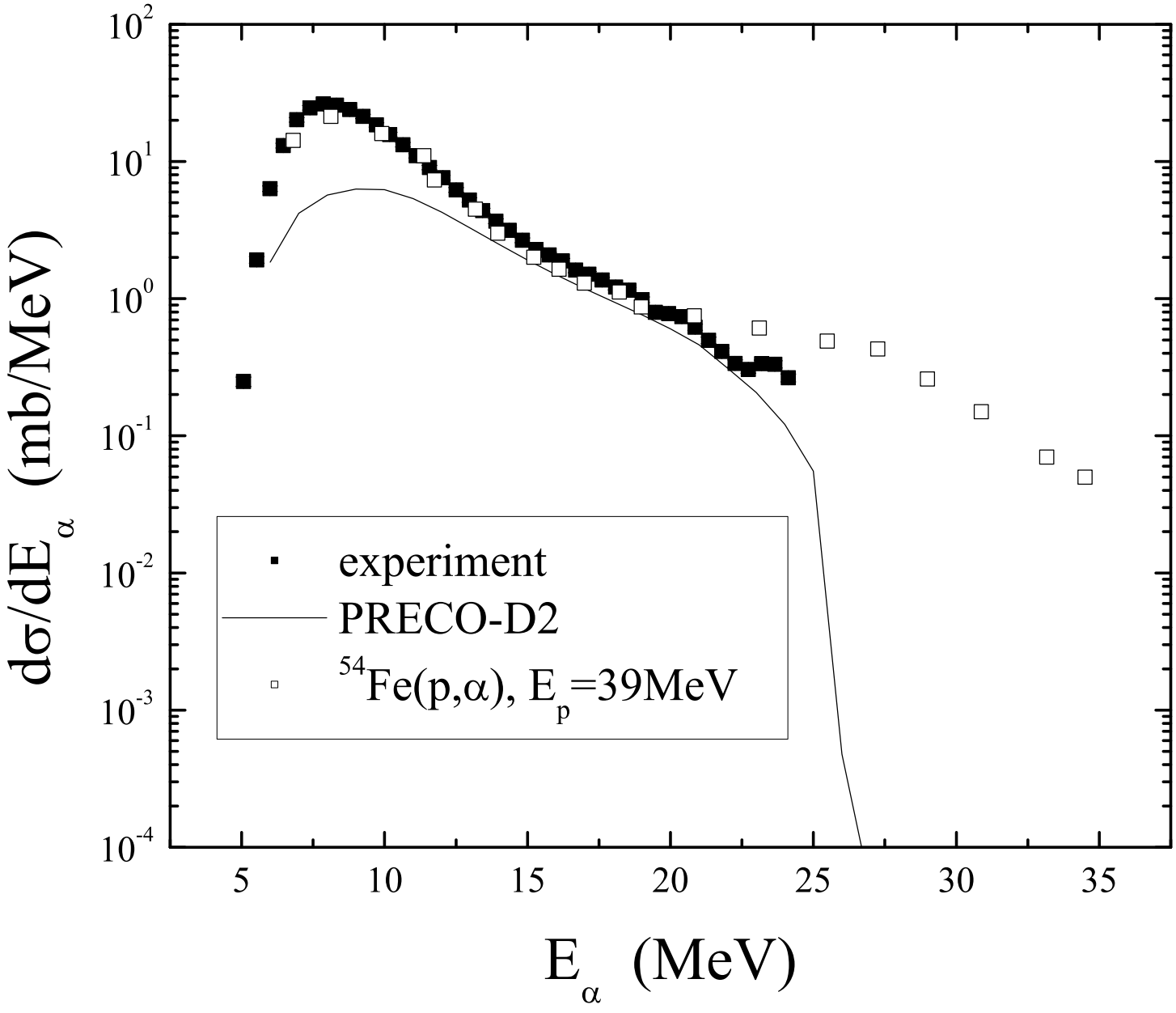


FIG. 2: The integral cross-section of the ^{56}Fe(p,xα) reaction at E_p=29.9 MeV (filled squares). ^{54}Fe(p,α) reaction at E_p=39.0 MeV [6] is also shown in comparison for the isotope dependence of the reactions (empty squares).

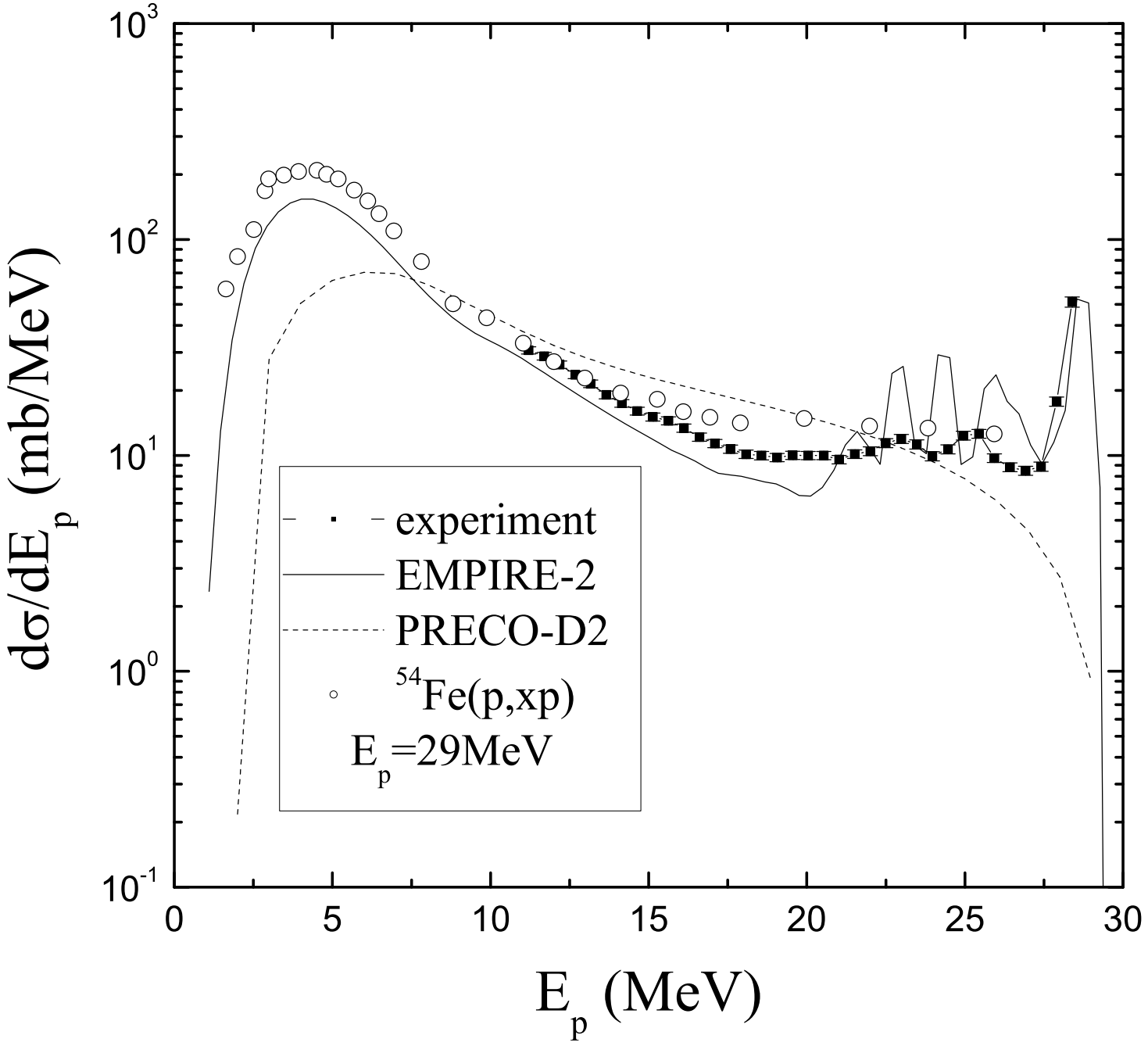


FIG. 3: The integral cross-section of the ^{56}Fe(p,xp) reaction at E_p=29.9 MeV (filled circles). ^{54}Fe(p,xp) reaction at E_p=29.0 MeV [6] is also shown in comparison for the isotope dependence of the reactions (empty circles).

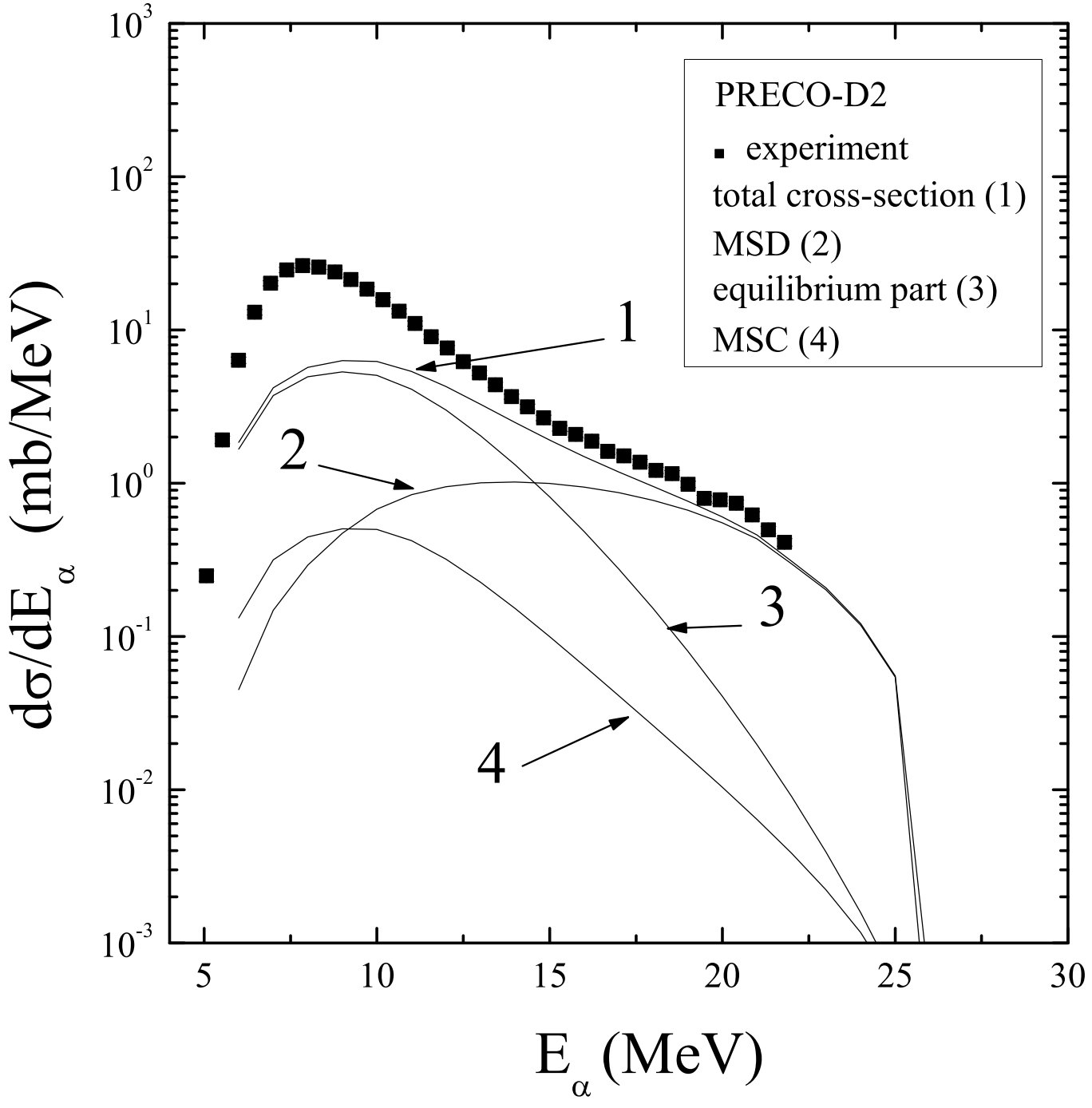


FIG. 4: The contribution MSD and MSC mechanisms to the formation of the integral spectra of reactions ^{56}Fe(p,xα) at E$_p$=29.9 MeV obtained by using the code PRECO-D2.

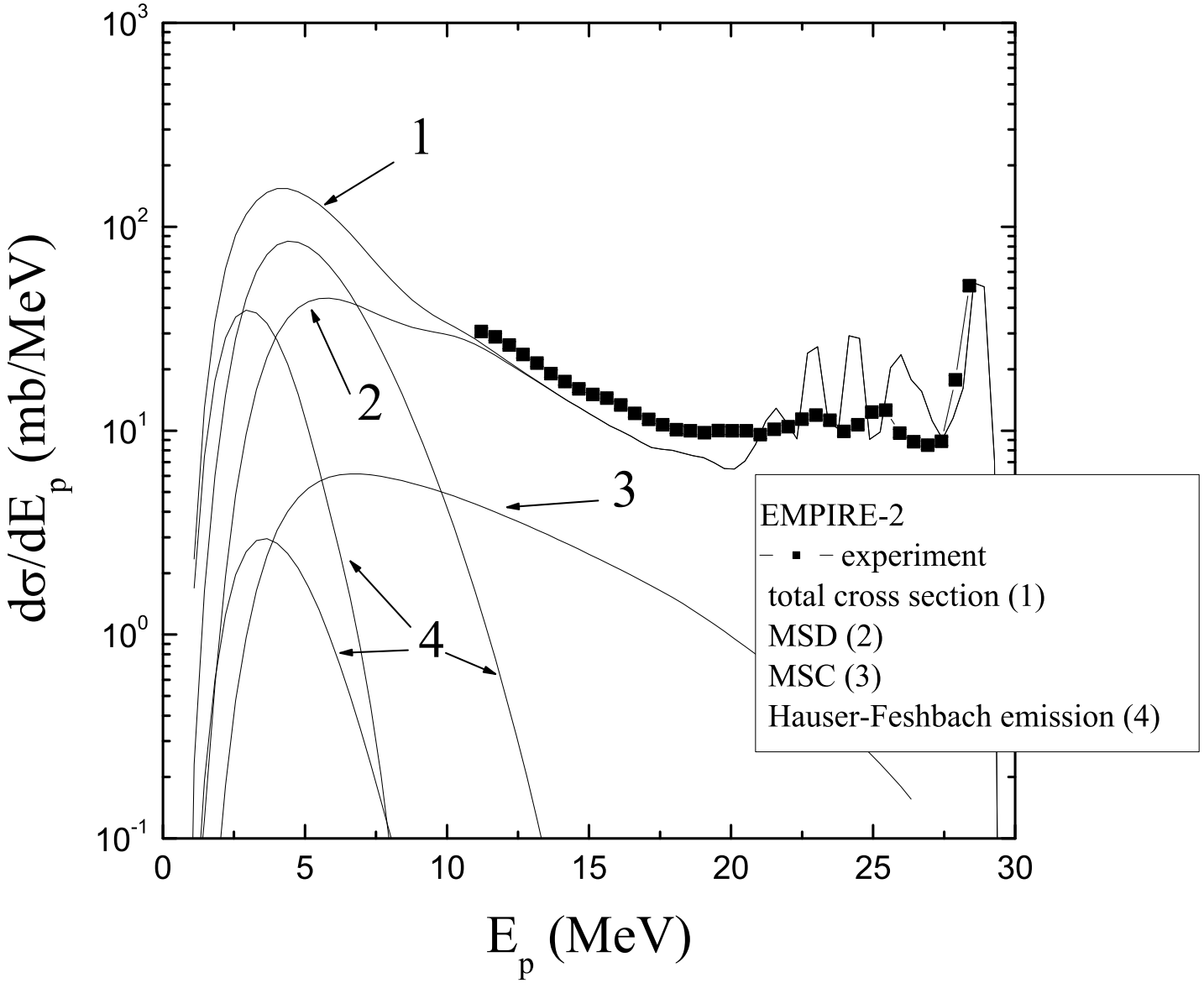


FIG. 5: The contribution MSD and MSC mechanisms to the formation of the integral spectra of reactions ^{56}Fe(p,xp) at E_p=29.9 MeV obtained by using the code EMPIRE-II.