# AN INTERPRETATION OF THE $^{56}Fe(n, p)^{56}Mn$ EXCITATION FUNCTION

J. RONDIO, B. MARIAŃSKI AND A. KORMAN

Soltan Institute for Nuclear Studies
Hoża 69, 00-681 Warsaw, Poland

*(Received June 17, 1993)*

The experimental excitation function of the $^{56}Fe(n, p)^{56}Mn$ reaction was compared with that calculated in the frame of statistical model. A role of the GDR excitation as a doorway state was analyzed.

PACS numbers: 25.40. Fq

## 1. Introduction

The statistical theories of nuclear reactions take into account only particle–hole configurations as the doorway states of the reaction [1–3]. According to these theories a composite nucleus formed in a neutron absorption process develops from less to more complicated configurations, the complexity of which is described by the number of excited particles above the Fermi level and holes below it. The simplest state excited in the first step of the reaction induced by a neutron energy up to about 20 MeV is a 2p–1h doorway state [4]. However, collective states, such as giant resonances, are also excited as doorway states [5, 6]. The best known giant dipole resonance (GDR) has been investigated for many years in $(\gamma, \gamma)$, $(\gamma, p)$, or $(\gamma, n)$ photoreactions. The excitation functions of these reactions described the shape of the GDR. The GDR observed in all these reactions is built on the ground state. Its building on isolated excited states was seen in proton scattering experiments [7]. In charge exchange reactions analog states of GDR can be also excited [8]. The excitation of giant resonances and their analogs in residual nuclei are described in nucleon scattering theory by a resonance amplitude. During our investigation of $^{58,60}Ni(n, p)^{58,60}Co$ reaction at neutron energies 17.3 and 18.5 MeV it was found that the GDR can be formed in the first step of the reaction and subsequently it can de-excite by proton

emission [6, 9]. This process can be analyzed, for example, in the framework of the Geramb collective core excitation model described with help of an exchange resonance amplitude [7].

We have assumed that the GDR excited in the $(n,p)$ reaction induced by neutrons of energy below 20 MeV is built on the continuum spectrum of excited states and it can be a doorway state as well as a 2p–1h state. In this paper we are looking for an effect of the GDR excitation as a doorway state in $(n,p)$ excitation function. We expect the experimental $(n,p)$ cross section to be larger than that obtained from statistical model calculations.

## 2. The $^{56}$Fe$(n,p)^{56}$Mn excitation function

It is difficult to find a proper nucleus to test our predictions because the experimental $(n,p)$ cross sections measured by activation method, even the evaluated ones, are determined with poor accuracy. We have chosen the $^{56}$Fe$(n,p)^{56}$Mn reaction because it is often used as a standard in neutron dosimetry and its cross sections have been measured and evaluated with particularly high precision [10].

In earlier investigations of excitation functions a definite choice of parameters has been commonly made to reach a satisfactory agreement between calculations and experiment. Recently the excitation functions of the $(n,p)$ reaction for nuclei of $A$ about 60 were calculated by Avrigeanu *et al.* [11] who fit the level density parameters, and by Kalka *et al.* [12] who tested their theory of nuclear excitation. In our calculations of the $^{56}$Fe$(n,p)^{56}$Mn excitation function no parameters were adjusted.

We have performed the calculation of the $^{56}$Fe$(n,p)^{56}$Mn reaction excitation function using the EMPIRE code [13] which accounts for the preequilibrium emission, according to the hybrid model [14], and for the decay of the compound nucleus as described by the multistage Hauser–Feshbach theory [15]. In these calculations the optical model parameters obtained by Becchetti and Greenlees [16] were used for both neutrons and protons, and the level density parameters were taken from Gilbert and Cameron [17]. A parameter $R$ giving a ratio of neutrons to protons excited in the first step of the reaction was taken from the fit to the experimental proton spectrum of the $^{58}$Ni$(n,p)^{58}$Co reaction.

The comparison of the measured and calculated excitation functions was done in the neutron energy range from 6 MeV to 20 MeV, see Fig. 1. The experimental cross sections are higher than the calculated ones in the whole incident neutron energy range considered. The differences between experiment and theory displays a broad maximum with a width of about 8 MeV, see Fig. 2.

The number of precompound emitted neutrons is larger than that of protons in neutron induced reactions. We assumed that the GDR excited

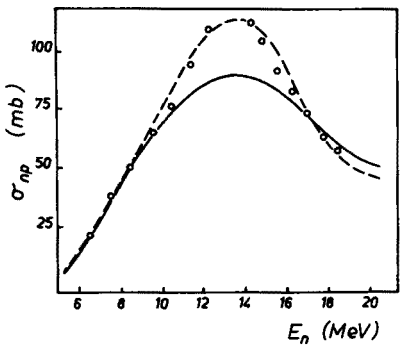


Fig. 1.

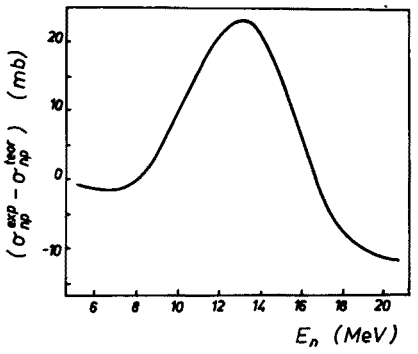


Fig. 2.

Fig. 1. The experimental $^{56}Fe(n,p)^{56}Mn$ excitation function (dashed line) and the calculated one (full line). The experimental data are evaluated ones and the calculations are performed by the use of EMPIRE code based on the statistical theory.

Fig. 2. The curve presenting the differences between the experimental and calculated cross sections of the $^{56}Fe(n,p)^{56}Mn$ reaction.

as a doorway state can change the value of the $(n,p)$ cross section which causes only a small change of the $(n,n')$ cross section. This can explain the contribution to the experimental $(n,p)$ cross section on top of the part calculated without taking into account this effect.

## 3. GDR as a doorway state

We assume that the incoming neutron gets bound on a single-particle orbital while the GDR is simultaneously built on this state. The excitation energy of the composite nucleus is shared between the GDR and the single-particle state. The excitation energy of the GDR built on various one particle states is different and the whole GDR excitation function can be built on the states lying in high level density range. Finally, assuming a model of equidistant single-particle states [18] having the width bigger than the distance between them, we obtain the GDR excitation function built on these states known from the photoreactions [19]. The excitation functions of the GDR built on one-particle states in high level density range are presented schematically in Fig. 3. In upper part of Fig. 3 is presented the GDR excitation function excited by neutrons of energy $E_n$ not high enough to cover all energies to which the GDR can be excited. These energies are limited to the excitation energy of the composite nucleus and their maximum value is equal $E_{MAX} = E_n + E_b^n$, where $E_b^n$ is a neutron binding energy. The GDR excitation function shown in lower part of Fig. 3 corresponds to higher energy of incident neutrons and the low energy part of the GDR

excitation function is built on unbound states also. This process does not contribute to the $(n,p)$ reaction cross section because the unbound incident neutron is emitted giving rise to other than $(n,p)$ reactions.

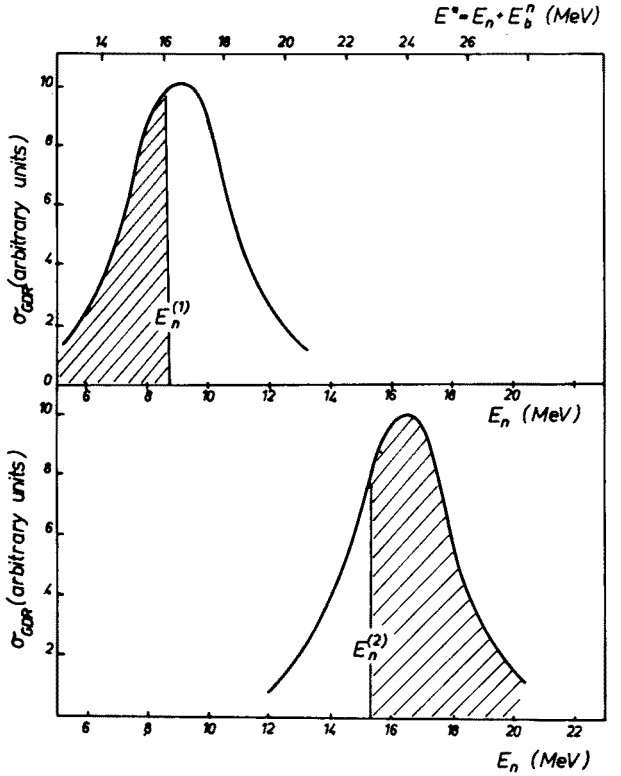


Fig. 3. The GDR built on one-particle excited states of a composite nucleus in high level density range. In upper part of the figure the incident neutron energy is too low to excite the whole GDR excitation function. In lower part of the figure the neutron energy is high enough to built the GDR on unbound states also. The shadowed areas present the parts of the GDR built on bound states at neutron energies $E_n{}^1$ and $E_n{}^2$.

The excitation probability of the GDR being built on bound states of the composite nucleus is proportional to the shadowed areas in Fig. 3. At the beginning, as it is seen from the upper part of Fig. 3, this probability increases with the increase of the incident neutron energy until the neutron energy is sufficient to excite the whole GDR excitation function. Then the probability of the GDR excitation decreases because the part of the GDR built on unbound states increases, as it is shown in lower part of Fig. 3.

To calculate the contribution to the $(n,p)$ cross section due to the GDR excitation in the entrance channel the following relation can be used:

$$\sigma_{np}^{\mathrm{GDR}}(E_{\mathrm{n}}) = \left[\int_0^{E_{\mathrm{n}}} L(E_{\mathrm{n}} - E_{\mathrm{b}}^{\mathrm{n}})dE_{\mathrm{n}} - \int_0^{E_{\mathrm{n}}} L(E_{\mathrm{n}})dE_{\mathrm{n}}\right] \frac{\sigma_{np}(E_{\mathrm{n}})}{\sigma_{\mathrm{abs}}(E_{\mathrm{n}})}, \quad (1)$$

where $\sigma_{np}^{\mathrm{GDR}}(E_{\mathrm{n}})$ is the calculated $(n,p)$ cross section due to the GDR formation as the doorway state for neutron energy $E_{\mathrm{n}}$, $L(E_{\mathrm{n}})$ is a function describing the shape of the GDR excitation function and the ratio $\sigma_{np}(E_{\mathrm{n}})/\sigma_{\mathrm{abs}}(E_{\mathrm{n}})$ gives the part of the composite nuclei de-excited by the proton emission; this ratio was calculated using code EMPIRE.

## 4. Results

The $(n,p)$ cross section was considered as a sum of the two contributions: one when the 2p–1h state is excited as a doorway state and the second when the GDR is. Shape of the contribution to the $(n,p)$ cross section due to the GDR excitation is described by relation (1). The calculated on the base of this relation excitation function was compared with the differences between experimental and calculated cross sections presented in Fig. 2 using derivatives of both functions. For the low values of the incident neutron energy, the differential curve of that calculated on the basis of relation (1) reproduces approximately the shape of the GDR: Its value increases with the energy of the incident neutron energy to get maximum at neutron energy about $E_{\mathrm{n}} = E_{\mathrm{GDR}} - E_{\mathrm{b}}^{\mathrm{n}}$, where $E_{\mathrm{b}}^{\mathrm{n}}$ is the binding energy of neutron in $^{57}$Fe. Then it drops for higher neutron energies to get negative values reproducing the GDR spectrum with opposite sign with minimum close to $E_{\mathrm{n}} = E_{\mathrm{GDR}}$. The shape of the GDR was approximated in the calculation by the Lorentz function [20]. The centroid of the Lorentz function was fixed at $E_{\mathrm{n}} = 16.6$ MeV in agreement with the GDR parameters obtained in the isospin splitting investigation of the GDR excitation in the $^{56}\mathrm{Mn}(p,\gamma)$ and $^{52}\mathrm{Cr}(\alpha,\gamma)$ reactions [21]. The width of the GDR excitation function was taken to be $\Gamma_{\mathrm{GDR}} = 4$ MeV. The agreement of the differential curve in Fig. 2 presenting differences between the experimental and calculated $^{56}\mathrm{Fe}(n,p)^{56}\mathrm{Mn}$ cross sections (see Fig. 4) indicates that the $(n,p)$ cross section can be really taken as a sum of two kinds of the cross sections which characterize various doorway states in 6–20 MeV neutron energy range. This result suggests that the future investigation of the GDR excitation as the doorway state at neutron energies below about 20 MeV is necessary to learn some more about the mechanism of the $(n,p)$ reaction and the role of the GDR excitation.

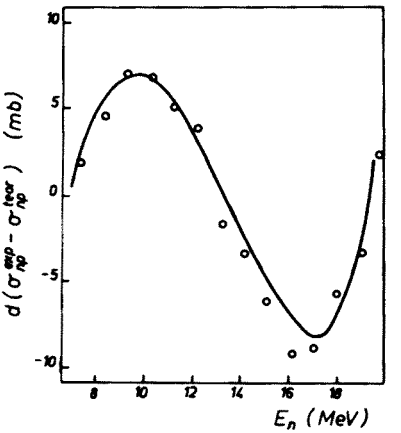


Fig. 4. The derivative of the curve in Fig. 2 which presents arising and disappearing of differences between the experimental and calculated $^{56}$Fe$(n,p)^{56}$Mn cross sections. The circles present the differential cross sections due to the GDR excitation as the doorway state calculated on the base of relation (1). The calculated values are normalyzed to the curve at neutron energy $E_n = 10$ MeV.

## 5. Summary

The $^{56}$Fe$(n,p)^{56}$Mn excitation function was calculated assuming that only 2p–1h state is excited in the first step of the reaction. Standard parameters were used in the calculation. The difference between the calculated excitation function and the experimental one was explained as coming from the contribution to the $(n,p)$ cross section due to the GDR excitation as a doorway state. This interpretation was based on the agreement of the difference between the experimental $^{56}$Fe$(n,p)^{56}$Mn excitation function and the calculated one with the shape of the estimated contribution due to the GDR excitation as a doorway state. The differential curves were used to compare the shapes of the compared functions.

We would like to thank prof. A. Marcinkowski for useful discussions and for making the code EMPIRE available to us.

## REFERENCES

[1] H. Feshbach, A. Kerman, S. Koonin, *Ann. Phys.* (N.Y.) **125**, 429 (1980).
[2] T. Tamura, T. Ugadawa, H. Lenske, *Phys. Rev.* **C26**, 379 (1982).
[3] H. Nishioka, H.A. Weidenmüller, S. Yoshida, *Ann. Phys.* (N.Y.) **183**, 166 (1988).
[4] J.J. Griffin, *Phys. Rev. Lett.* **17**, 478 (1966); *Phys. Lett.* **B24**, 5 (1967).
[5] M.B. Levis, F.E. Bertrand, *Nucl. Phys.* **A196**, 337 (1972).

[6] J. Rondio, B. Mariański, A. Korman, K. Czerski, *Nucl. Phys.* **A487**, 62 (1988).
[7] H.V. Geramb, K. Amos, R. Sprinckmann, K.T. Knöpfle, M. Rogger, D. Ingham, C. Mayer-Böricke, *Phys. Rev.* **C12**, 1697 (1975).
[8] G.A. Needham, F.P. Brady, D.H. Fitzgerald, J.L. Romero, J.L. Ullman, J.W. Watson, C. Zenelli, N.S.P. King, G.R. Satchler, *Nucl. Phys.* **A385**, 349 (1982).
[9] J. Rondio, B. Mariański, A. Korman, K. Czerski, *Acta Phys. Pol.* **B18**, 1065 (1987).
[10] *Handbook on Nuclear Activation Data*, Vienna 1987, p.344.
[11] M. Avrigeanu, M. Ivascu, V. Avrigeanu, *Z. Phys.* **A335**, 299 (1990).
[12] H. Kalka, M. Torjman, H.N. Lien, R. Lopez, D. Seeliger, *Z. Phys.* **A335**, 163 (1990).
[13] M. Herman, A. Marcinkowski, K. Stankiewicz, *Comput. Phys. Commun.* **33**, 373 (1984).
[14] M. Blann, *Ann. Rev. Nucl. Sci.* **25**, 123 (1975).
[15] W. Hauser, H. Feshbach, *Phys. Rev.* **87**, 336 (1952).
[16] F.D. Beccheti Jr., G.W. Greenlees, *Phys. Rev.* **43**, 1146 (1972).
[17] A. Gilbert, A.G.W. Cameron, *Can. J. Phys.* **43**, 1146 (1972).
[18] H.A. Bethe, *Rev. Mod. Phys.* **9**, 69 (1937).
[19] J.W. Norbury, M.N. Thompson, K. Shoda, H. Tsubota, *Austr. J Phys.* **31**, 471 (1978).
[20] B.L. Berman, S.C. Fultz, *Rev. Mod. Phys.* **47**, 729 (1975).
[21] D.G. Rickel, C.P. Cameron, R.D. Ledford, N.R. Roberson, H.R. Weller, D.R. Tilley, *Phys. Rev.* **C14**, 338 (1976).