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ANALYSIS OF NEUTRON AND PROTON SPECTRA FROM NEUTRON INDUCED REACTIONS

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Final report

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I. Introduction

The exciton model of Griffin [1] developed and extended by many authors [2-4] proved to be very succesful in analyses of the nonequilibrium part of particle spectra emitted from nuclear systems at excitation energies from 20 to ~ 100 MeV. A global set of parameters was deduced [2-4, 5] which makes it possible to calculate needed and not yet measured data. The theoretical justification of the exciton model was given recently [6 - 9].

Though the exciton model is able to reproduce almost the whole non-equilibrium portion of the particle spectra, there is at least one class of data -(n,xn) spectra - for which the exciton model gives too few high energy particles [10, 11] . The same apply to the other type of preequilibrium models [12]. We have suggested that the exciton model energy distribution can be improved by assuming the depth of the hole excitation to be limited. Similar suggestion has been made in [12, 19] .

I am atempt to improve description of (n, xn) spectra we have developed the modified exciton model (MEM) in which only a limitted number of target nucleons are involved in the pre-equilibrium stage of a reaction. It turned out that MEM provides very good description of (n, xn) data at excitation energies E = 20-35 MeV where the experimental angle-integrated spectra are available.

II. Modified exciton model

Consider A ~ 60 nuclei. The shell model (see e.g. [13]) predicts a gap $d \sim 5$ MeV between the last and the next lower lying subshells for the ground states of those nuclei. Consider (nucleon, nucleon) reaction and the portion $(\mathcal{E}_{max} - d, \mathcal{E}_{max})$ of the emitted spectrum, $\mathcal{E}_{max}$ is the maximum energy of emitted nucleons. We see that this portion can originate only from the interaction of the projectile with the nucleons lying on the last subshell.

The basic modification of the exciton model is represented by the assumption that only the last subshell nucleons are involved in the preequilibrium stage of a reaction.

In the closed form formulation of the exciton model the preequilibrium nucleon energy distribution (taking into account the distinquishibility betwen protons π and neutrons ν) is given as

$$\frac{d\sigma}{d\mathcal{E}_x} = \sigma_R \sum_{\substack{n=3 \\ \Delta n = +2}} \frac{a_x(n)\, w w_x(\mathcal{E}_x, n)}{\lambda_+ n + \sum_{j=\pi,\nu} a_j(n) \int w_j d\mathcal{E}_j} D(n) \qquad (1)$$

where σ_R is the reaction cross section, n (=p+h) is the exciton number, $\mathcal{E}$ is the channel energy, λ_+ and w are the intranucleon transition rate and the emission rate resp. and D(n) is the depletion factor - the last three quantities are discussed in [2-4] . Only the nucleon channels are considered in eq. (1) as other channels are sufficiently weak for all reaction we have used to test MEM. The coeficients a_j define the fraction of nucleons of a given type in the n-exciton states.

The assumption that only last subshell nucleons are involved is incorporated in the following way:

First, the coefficients a_j are evaluated as

$$a_j(n) = \frac{1}{p} N_j \quad ; \quad p = N_\pi + N_\nu \tag{2}$$

where p is the number of excited particles and N_π (N_ν) is the number of excited protons (neutrons). For example, for neutron induced reactions and n = 3 we have

$$N_\nu = \frac{\sigma_{\pi\nu} n_\pi}{\sigma_{\pi\nu} n_\pi + \sigma_{\nu\nu} n_\nu} + 2\frac{\sigma_{\nu\nu} n_\nu}{\sigma_{\nu\nu} n_\pi + \sigma_{\nu\nu} n_\nu} = \frac{\alpha n_\pi + 2n_\nu}{\alpha n_\pi + n_\nu} \tag{3}$$

where $\alpha = \sigma_{\nu\pi} / \sigma_{\nu\nu}$ is the ratio of free NN cross sections and n_π (n_ν) is the number of protons (neutrons) lying on the last subshell of the target nucleus. Putting $n_\pi = Z$, $n_\nu = N$ eq. (3) reduces to one discussed in [12].

Next the quantities λ_+ and w are evaluated using the exciton state density for finite potential well E_H [14]

$$\omega_{ph}(E) = \frac{g^n}{p!h!(n-1)!} \sum_{l=0}^{h} \binom{h}{l} (-)^l \left[E - lE_H\right]^{n-1} \Theta(E - lE_H) \tag{4}$$

where g is the single particle state density and Θ is the Heaviside function. The E_H was approximated by the energy spread of the last subshell (due to residual interaction)[15]. In all our calculations we have assumed E_H = 1 MeV and α = 2.5.

The quantity λ_+ has been parametrized in a usual way [5]

$$\lambda_+ = \frac{2\pi}{\hbar} CE^{-1}A^{-3} \omega_f^+ \tag{5}$$

where ω_f^+ is the accessible final state density for $\Delta n = +2$ process and was evaluated using eq. (4). The factor C was treated as a fit parameter of MEM.

The equilibrium portion of nucleon spectra was approximated by the evaporation process assuming state density of the form

$$\rho(U) \propto U^{-2} \exp(2\sqrt{aU})$$

$$U = E - \delta \tag{6}$$

where a is the level density parameter and δ is the pairing correction.

III. Results

A number of experimental neutron [16] and proton [17] spectra measured at ~ 14 MeV incident neutron nenergy have been used to test MEM. As a results of this analysis the parameters C, a and δ were extracted. They are collected in tab. 1.

Table 1.

Parameters resulting from the analysis of 14 MeV data

Target nucleus	n_π	n_ν	C [MeV^3]	$\lambda_+(3)$ 10^{22} s^{-1}	a [MeV^{-1}]	δ_π [MeV]	δ_ν [MeV]
^{51}V	1	8	6400	1.9	6.8	2.1	2.2
^{54}Fe	6	8	5000	1.5	6.7	0	3.0
^{56}Fe	6	2	4500	1.3	7.2	0	3.0
^{58}Ni	8	2	5540	1.7	7.2	0	3.5
^{60}Ni	8	4	6000	1.7	7.5	0	3.5
^{63}Cu	1	2	7000	2.0	7.9	2.0	1.7
^{65}Cu	1	4	7400	2.0	8.1	2.0	1.7
^{93}Nb	1	2	6000	2.2	9.0	1.2	0.9

The numbers n_π and n_ν were taken from [13] . However, for ^{51}V+n reaction the simultaneous fit of both neutron and proton channels n_π =1 gave much better fit than n_π =3. This is probable the demonstration that the unpaired nucleon is preferentially excited.

An example of the analysis of 14 MeV spectra is shown in figs. 1-3 for Fe+n reaction. In fig. 1 the experimental neutron spectrum is compared with our calculations. The solid curve represents the weighted of neutron spectra for ^{54}Fe and ^{56}Fe targets. The dotted curve represents the MEM contributions. The dashed curve is the sum of preequilibrium and equilibrium contributions calculated under the assumption E_H=20 MeV, n_π = Z, n_ν = N, α = 1 and exciton model parameters from ref. [4] . We

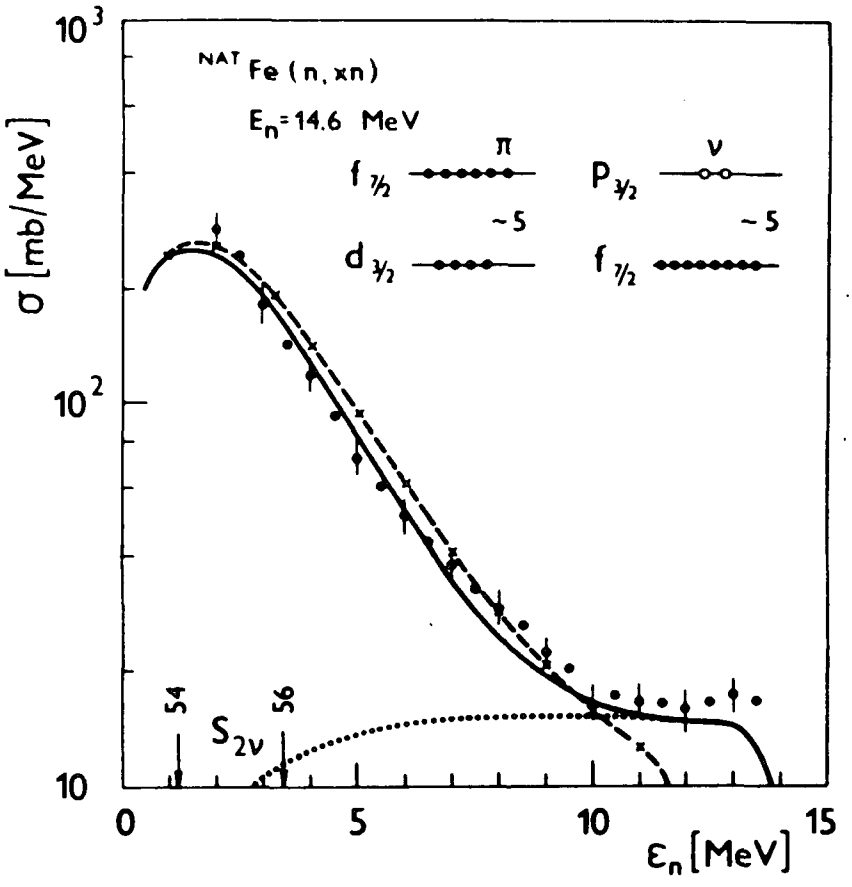

Fig. 1 Comparison of our calculations with the experimental ^{NAT}Fe (n,xn) spectra , [16] . The full line represents the sum of the modified exciton model /dotted line/ and the evaporation contributions. The dashed line is the same sum but calculated using the exciton model 3,4 .

see that our MEM describes the high energy neutron tail better than the exciton model. For proton spectra this difference is not so visible. Here the preequilibrium effects are less pronounced as - due to Coulom barrier - the evaporation peak is shifted to higher energies. In either case MEM describes the proton spectra slightly better than the exciton model [3, 4] . Similar results were obtained for other reactions.

In fig. 4 and 5 the comparison of the experimental neutron spectra measured at ~ 26 MeV with our calculations are shown. The solid curves represent only the MEM contributions as the

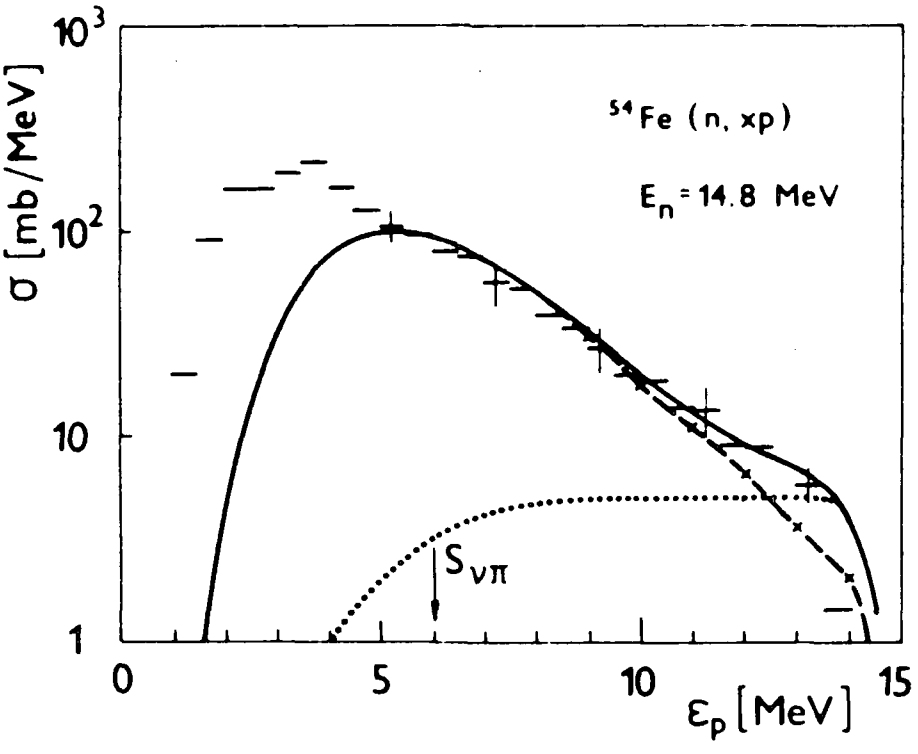

Fig. 2 The same as in fig. 1 but for ^{54}Fe(n,xp) reaction

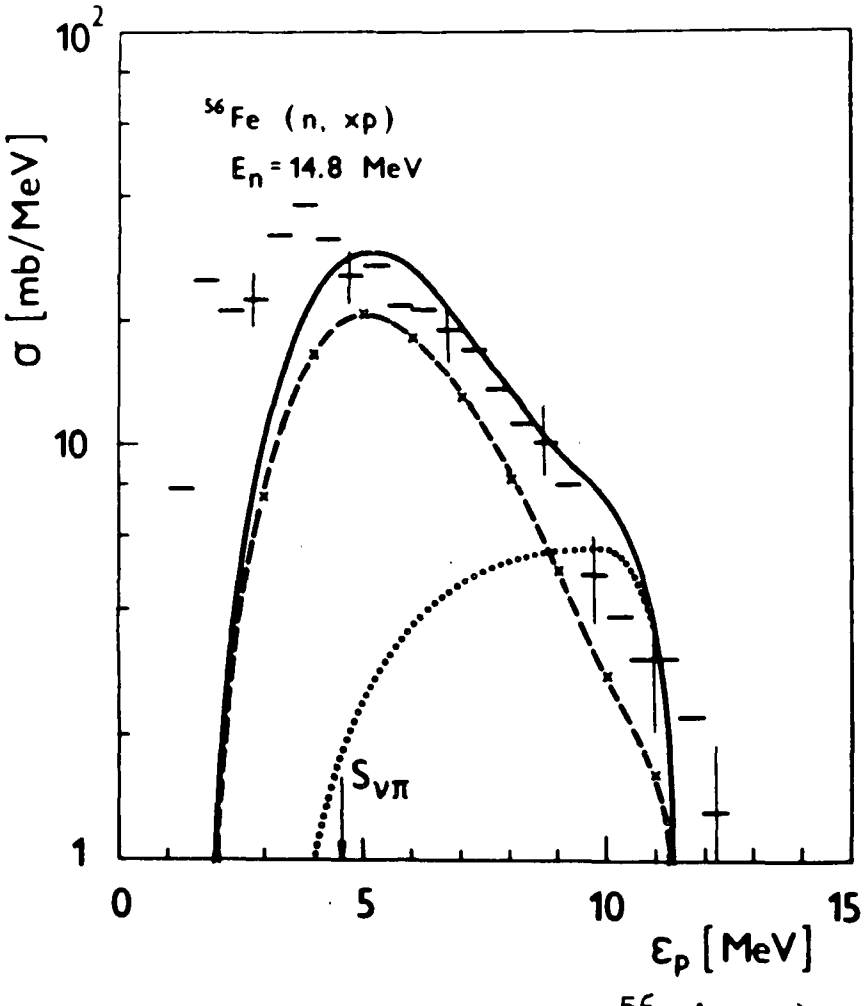

Fig. 3 The same as in fig. 2 but for ^{56}Fe(n,xp) reaction

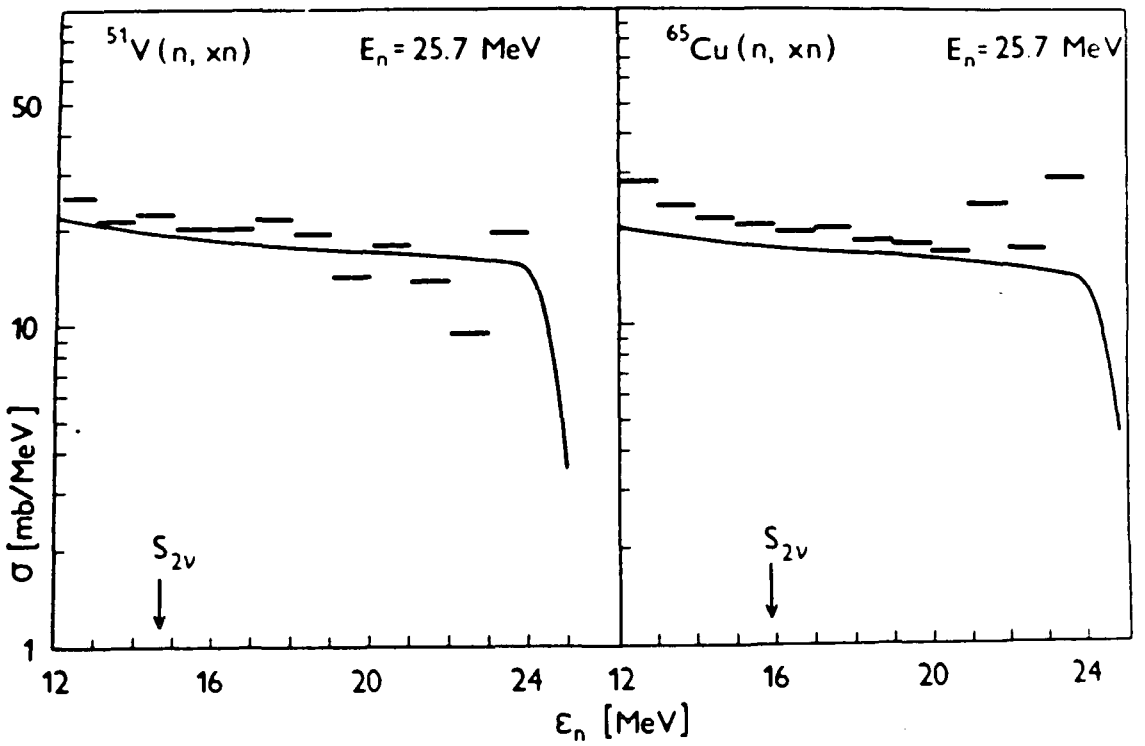

Fig. 4 Comparison of our calculations with the experimental ^{51}U and ^{93}Nb (n,xn) neutron spectra (bars). The full lines represent the MEM contributions

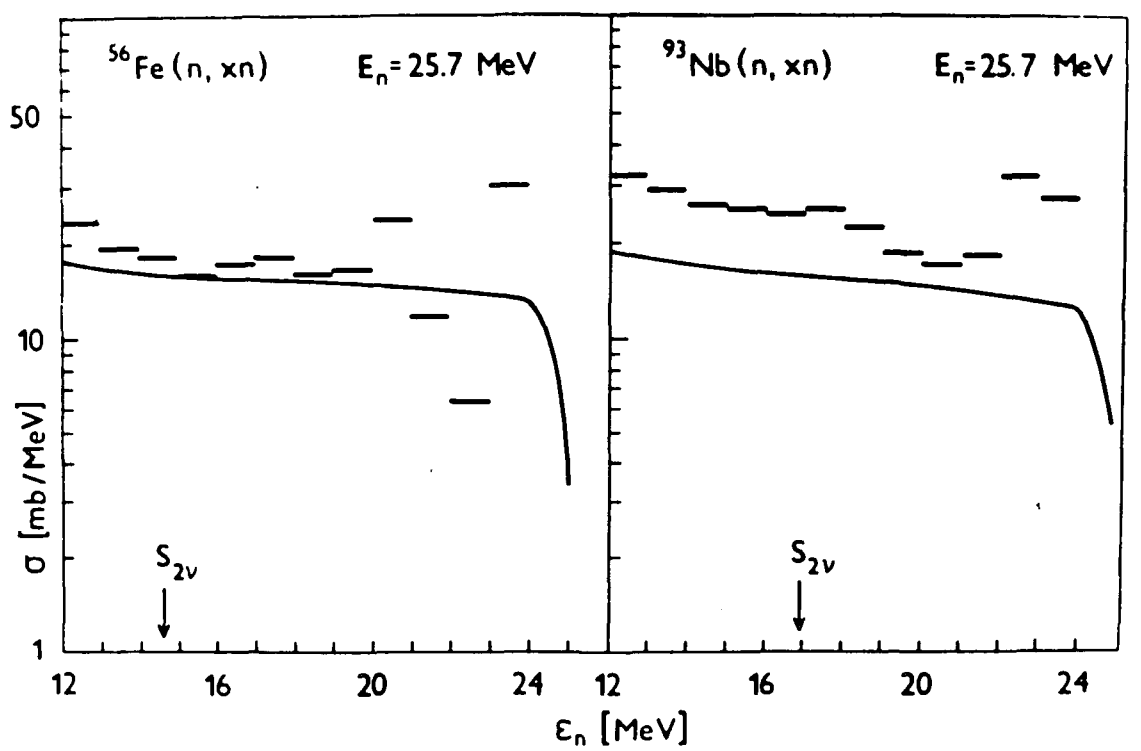

Fig. 5 Comparison of our calculations with the experimental ^{56}Fe and ^{63}Cu (n, xn) neutron spectra (bars). The full lines represent the MEM contributions

displayed energy region is free from the evaporation contributions. They were calculated using parameters of tab. 1. We see that the paculiar flat shape of the experimental spectra are nicely reproduced by MEM as well as its magnitude. As for as we know no other preequilibrium model can describe these data as closely as our MEM.

More details are given in ref. [18].

Literature

[1] J.J. Griffin, Phys. Rev. Lett. 17 (1966) 478
J.J. Griffin, Phys. Lett. 24B (1967) 5

[2] M. Blann, Ann. Rev. Nucl. Sci. 25 (1975) 123

[3] E. Gadioli, Nukleonika 21 (1976) 335

[4] E. Gadioli and E. Gadioli Erba, Nuclear Theory for Application - 1930, IAEA-SMR-63/I, Vienna 1931

[5] C. Kalbach - Cline, Nucl. Phys. A210 (1973) 590

[6] M. Feschbach et al., Ann. Phys. 125 (1930) 429

[7] D. Agassi et all., Phys. Rep. 226 (1975) 145

[8] W.A.Friedman et all, Phys. Rep. 77 (1931) 47

[9] K.W. McVoy and X.T. Tang, Phys. Rep. 94 (1933) 141

[10] Š. Gmuca and I. Ribanský, Neutron Induced Reactions, Ed. I. Ribanský and E. Bětík, VEDA, Bratislava 1930

[11] M. Marcinkowski et al., Nucl. Phys. A402 (1933) 220

[12] M. Blann and H.K. Vonach, Phys. Rev. C23 (1933) 1475

[13] K. Bleuer and M. Beiner, Nuovo Cim. B52 (1967) 149

[14] E. Bětík and J. Dobeš, Z. Phys. A279 (1976) 319

[15] D. Wilkinson, Nucl. Instr. Meth. 146 (1977) 143

[16] D. Hermsdorf et al., Rep. ZfK-277Ö, Zentralinstitut für Kernforschung Rosendorf bei Dresden 1975

[17] S.M. Grimes et al., Phys. Rev. C17 (1973) 508
S.M. Grimes et al., Phys. Rev. C19 (1979) 2127

[18] I. Ribanský, Acta Phys. Slov. 35 (1935) 9

[19] C. Kalbach, Phys. Rev. C (1935)