acta physica slovaca vol. 45 No. 6, 705 – 710 December 1995

PRE-EQUILIBRIUM EMISSION OF CLUSTERS[1]

A.Yu. Konobeyev
Institute of Nuclear Power Engineering, 249020 Obninsk, Russia

V.P. Lunev, Yu.N. Shubin[2]
Institute of Physics and Power Engineering, 249020 Obninsk, Russia

Received 23 October 1995, accepted 27 October 1995

A new approach to the description of the emission of α-particle spectra unifying knock-out and pick-up models is proposed. The approach considered strives to remove discrepancies between experimental data and earlier calculations. It is shown that a good description of the experimental α-spectra in a wide energy range can be obtained only when multiple preequilibrium emission and a pick-up as well as a knock-out mechanism are taken into account.

1. Introduction

The methods of direct reaction theory (DWBA, CC) enable to reproduce relatively small part of a experimental spectra of α-particles connected with discrete states of the residual nuclei. The description of the shape of α-spectra is obtained only, but not the absolute values [1].

The α-particle knock-out model [2], despite of wide and successful application for practical calculations at the energies up to 20 MeV [3], does not give a good description of α-spectra at higher energies [4]. The coalescence model proposed by Ribansky and Oblozinsky [5] was widely used for the analysis of experimental spectra of α-particles [6]. The model assumes that α-particle emission in the reactions with nucleons occurs from the complex states with the number of excitons $n \geq 7$ only and neglects pick-up and knock-out processes. The pick-up model by Iwamoto-Harada [7] reproduces experimental spectra of α-particles at incident nucleon energies 14–62 MeV [8] but strongly underestimated the high energy part of α-spectra in the reactions at 90 MeV.

The deficiency of the approaches offered earlier is that their authors proceed from the existence of one only mechanism of α-particle emission (knock-out, pick-up) and attribute to it the total nonequilibrium α-spectrum. In the present paper, an attempt is made to unify knock-out and pick-up models for the description of α-emission at energies up to 90 MeV.

[1] Presented at the International Symposium on Pre-Equilibrium Reactions, Smolenice Castle, 23 – 27 October, 1995

[2] E-mail address: SHUBIN@CJD.OBNINSK.SU

2. Description of the model

In the present work the spectrum of α-particles is represented as a sum of three components corresponding to pick-up, knock-out and evaporation processes:

$$\frac{d\sigma}{d\epsilon_\alpha} = \frac{d\sigma^{pick-up}}{d\epsilon_\alpha} + \frac{d\sigma^{knock-out}}{d\epsilon_\alpha} + \frac{d\sigma^{evap}}{d\epsilon_\alpha} \qquad (1)$$

To describe pick-up reaction Iwamoto-Harada model is used [7,9].

The modified approach [2] for α-particle knock-out process description is used in the present work. The approach developed here does not have a number of deficiencies of "preformed cluster" model [2] that have been noted in papers [4,10], gives the description of high energy part of nonequilibrium α-spectrum close to one of knock-out model [4] and is realized more simply in numerical calculations as compared with [4].

The emission of nonequilibrium α-particles after nonequilibrium emission of neutron or proton have to be taken into account at energies higher than 100 MeV. In this case the formula for the preequilibrium emission spectra of α-particle formed due to pick-up process and emitted after preequilibrium nucleon can be written as follows:

$$\frac{d\sigma_2^{pick-up}}{d\epsilon_\alpha} = \sigma_{non} \sum_{x=\pi,\nu}^{2} \sum_{n=n_0} R_x(n) \frac{\omega(p-1,h,E-Q_x-\epsilon_x)}{\omega(p,h,E)} \frac{\lambda_c^x(\epsilon_x)}{\lambda_c^x(\epsilon_x)+\lambda_+^x(\epsilon_x)} g_x D(n)$$

$$\times \sum_{n'=p+h-1} \sum_{l+m=4} F_{l,m}(\epsilon_\alpha) \frac{\omega(p'-l-1,h',E-Q_x-\epsilon_x-Q_\alpha-\epsilon_\alpha)}{\omega(p-1,h,E-Q_x-\epsilon_x)}$$

$$\times \frac{\lambda_c^\alpha(\epsilon_\alpha)}{\lambda_c^\alpha(\epsilon_\alpha)+\lambda_+^\alpha(\epsilon_\alpha)} g_\alpha D(n') d\epsilon_x, \qquad (2)$$

where x is a neutron/proton index, Q_x is the binding energy of particle x in the composite system, $R_x(n)$ is a factor describing the number of protons and neutrons in n-exciton state, Q_α is the separation energy of the α-particle after emission of particle x, $D(n)$ is a depletion factor, and $F_{l,m}$ is the coalescence factor as defined in Ref. [7]. The analogous expression can be written for the component corresponding to α-particle knock-out that occurs after preequilibrium nucleon emission. It involves a preformation factor φ_α.

Parameters of the model are the sum of the probability of α-particle formation $\sum F_{l,m}$ and the interaction probability of incident nucleons with the "preformed" α-particle φ_α.

The values of $\sum F_{l,m}$ and φ_α can be determined independently. At 90 MeV incident energy the knock-out model describes the hard part of experimental α-spectra [6] where the component $d\sigma^{pick-up}/d\epsilon_\alpha$ makes a small contribution. At the same time the soft part of nonequilibrium spectrum is determined by pick-up mechanism (see Ref. [8]). For this reason, $\sum F_{l,m}$ and φ_α can be obtained from comparison between calculated and experimental spectra if values of g_α and the imaginary optical potential W^α are known.

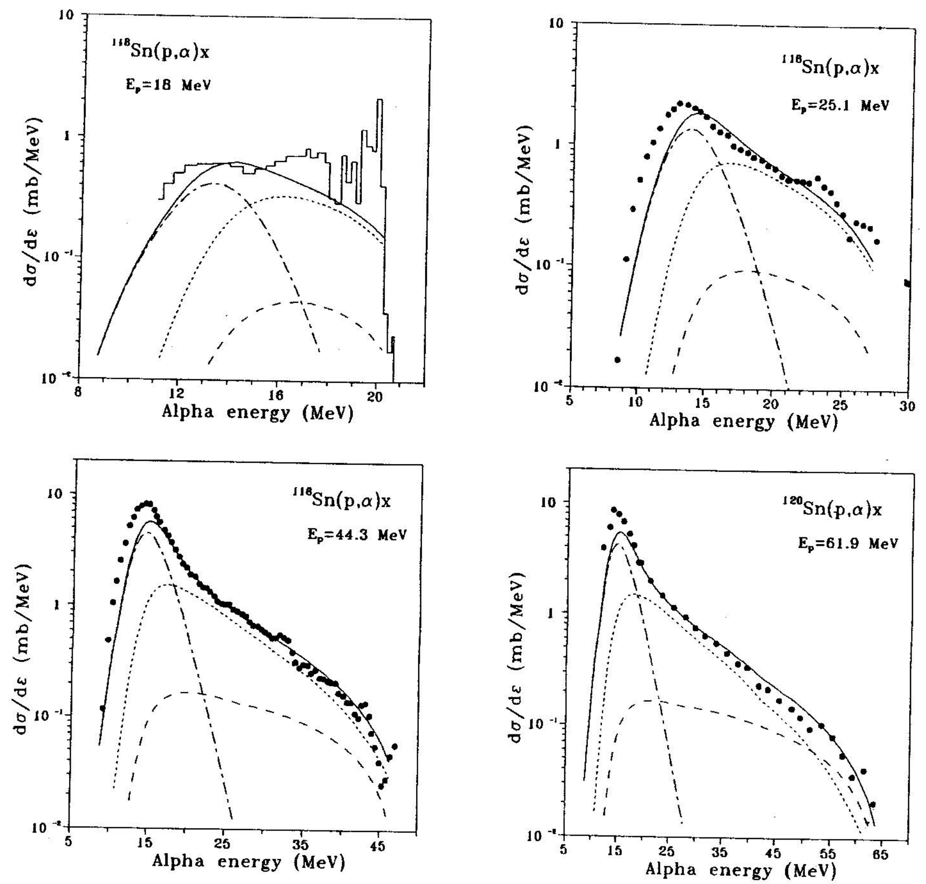

Fig. 1. Experimental [12–14] (points) α-spectra from the reactions on tin isotopes irradiated by 18–62 MeV protons and calculated in this work. Total spectrum (solid line), pick-up contribution (short dash line), knock-out (long dash line), evaporation emission (dot-dash) line.

The energy dependence of W^α was determined from comparison of theoretical and experimental α-particle spectra for proton induced reactions at energies of 18 – 90 MeV [6,11–15]. The cross sections of (n,α) reactions obtained from the analysis of various experiments at 14.5 MeV [16] for 42 nuclei with nuclear number $Z \geq 60$ were used also.

The following values of parameters were used in the calculations of this work: $\sum F_{l,m} = 0.3$, and $\varphi_\alpha = 0.012$. The single particle state density for α-particles was $g_\alpha = A/13$. The imaginary part of optical potential was calculated as $W^\alpha = (\epsilon_\alpha/\epsilon_0)W'$ at $\epsilon_\alpha \leq \epsilon_0$ and $W^\alpha = W'$ at $\epsilon_\alpha > \epsilon_0$, where ϵ_α is the α-particle energy, $W' = \beta W_0$, and W_0 is the value of the imaginary part of optical potential in a center of a nucleus; $\epsilon_0 = 0.228A$ and $\beta = 0.25$. The value of W_0 was taken from Refs. [17,18] as

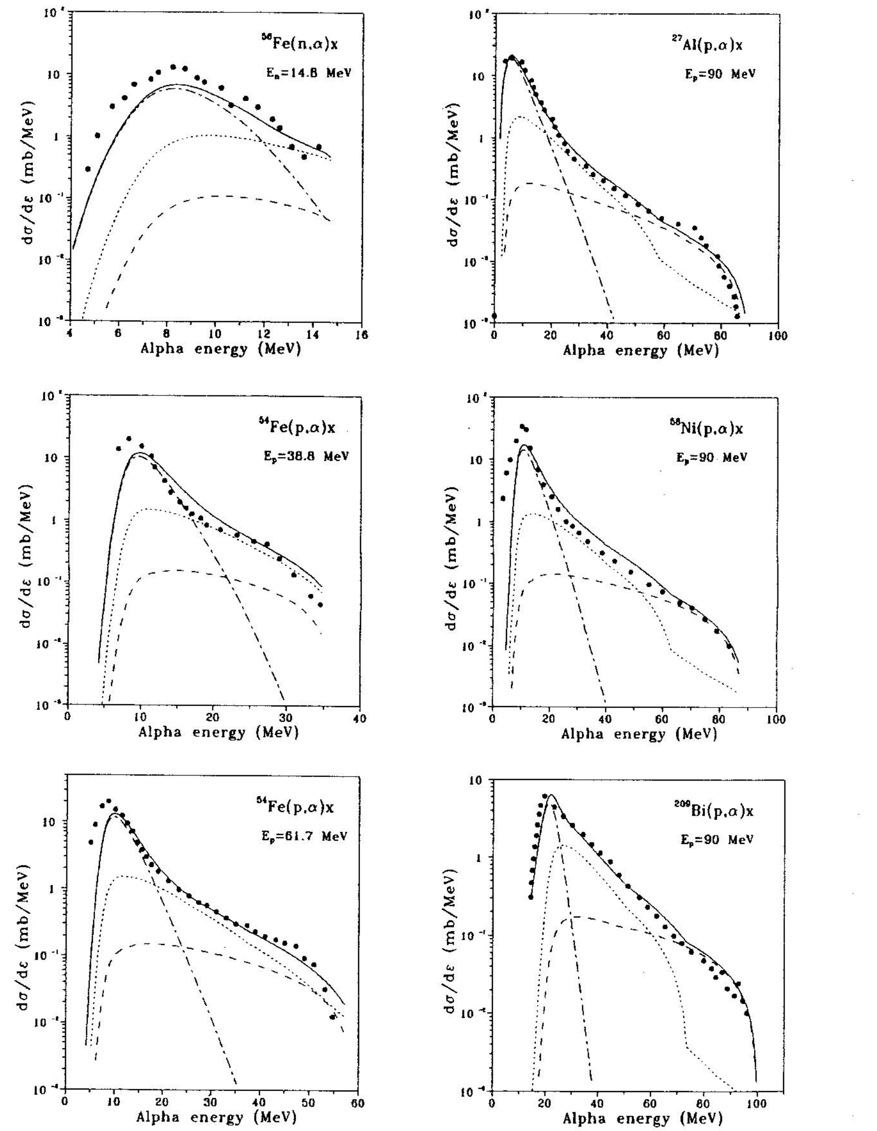

Fig. 2. The same as in Fig. 1 for the reactions on iron isotopes (left) and on ^{27}Al, ^{58}Ni and ^{209}Bi (right) irradiated by protons. Experimental data are taken from [6,14,19].

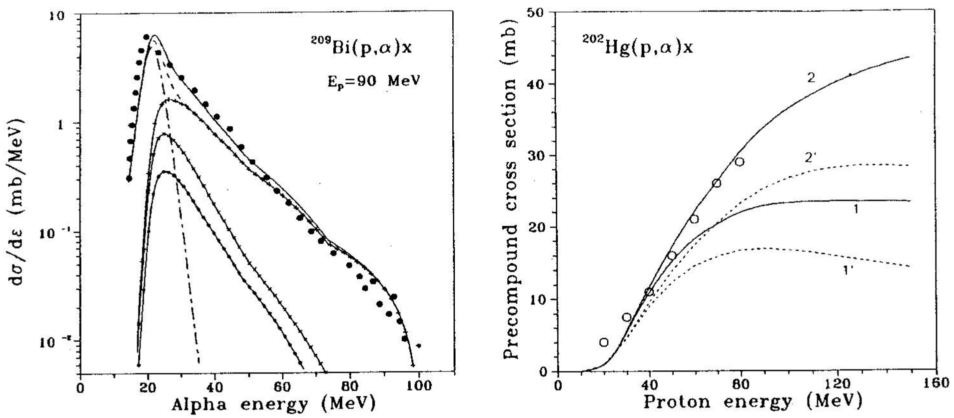

Fig. 3. *Left:* Calculated contributions of various α-emission mechanisms to the total α-spectrum for reactions on ^{209}Bi at 90 MeV proton energy. First preequilibrium (α-particle (+), preequilibrium (α-particle emitted after neutron (×) and proton (*), equilibrium emission (dot-dash line), sum of the first preequilibrium particle and evaporation spectra (dashed line), and total spectrum (solid line). *Right:* Preequilibrium α-particle emission cross section in reactions on ^{202}Hg irradiated by protons, calculated with (2) and without (1) taking into account multiple preequilibrium emission. Pick-up process contributions (dashed lines 1' and 2'). Experimental data are taken from [22].

$$W_0 = 10 + 0.345(A - 2Z) \text{ MeV}.$$

3. Results

On the basis of the approach developed, calculations of spectra and excitation functions for nucleon induced α-particle emission were performed in a wide range of nuclei. Some results are shown in Figs. 1 to 3. The calculated and experimental [12–14] α-particle spectra for tin isotopes irradiated by protons with the energy 18 – 62 MeV are shown in Fig. 1. The measured [6,14,19] and calculated α-spectra for different nuclei irradiated by 14.8 MeV neutrons and 39, 62 and 90 MeV protons are shown in Fig.2. The calculations were performed taking into account preequilibrium α-emission after the emission of preequilibrium a neutron and/or a proton. It is seen that at relatively low incident energies the nonequilibrium α-particle emission is due to the pick-up mechanism. The contribution of knock-out processes increases as the incident energy increses. The knock-out mechanism determines the hardest part of the α-spectrum. This conclusion about a role of various mechanisms of α-particle emission is in accordance with the results of Refs. [1,20,21]. In [1,20] on the base of DWBA method experimental spectra of α-particles for the reactions induced by 12 – 20 MeV energy neutrons were analysed. It was shown that at these energies the pick-up process dominates in nonequilibrium α-particle emission. In the work of Kalbach [21], a parameterization of the pick-up and knock-out contributions has been performed using phenomenological relations and experimental data for reactions at energies up to 62 MeV. According to Kalbach, the

α-particle emission occurs predominantly as pick-up process, the knock-out process contribution is observable in the high energy part of the α-spectrum only.

The significance of multiple preequilibrium emission is shown in the left part of Fig. 3. The calculated contributions of the first preequilibrium α-particle and α-particles emitted after preequilibrium neutron and proton to the total spectrum are shown for the $^{209}Bi(p,\alpha)x$ reaction. One can see that the sum of the first preequilibrium α-particle only and the evaporation emission gives a poor description of the experimental data. Similar conclusion arise from the comparison of calculations and measurements of other characteristics of the nuclear reactions. The cross sections for nonequilibrium α-particle emission for reactions on ^{202}Hg, obtained from the analysis of experimental data [22] and calculated in the present work, are shown in the right side of Fig. 3. The calculated results for the first preequilibrium α-particle, the total cross section for α-particle emission, and the pick-up contribution to this cross section are given in the Figure. It is seen that a satisfactory description of experimental data is obtained only after taking into account multiple α-particle emission and bouth pick-up and knock-out.

References

[1] E.Gadioli *et al.*: *Phys. Rev. C* **34** (1986) 2065
[2] L.Milazzo-Colli, G.M.Braga-Marcazzan: *Nucl. Phys. A* **210** (1973) 297
[3] I.Kumabe *et al.*: *Phys. Rev. C* **35** (1987) 467
[4] A.Ferrero *et al.*: *Z. Phys. A* **293** (1979) 123
[5] I.Ribansky, P.Oblozinsky: *Phys. Lett. B*, **45** (1973) 318
[6] J.R.Wu, C.C.Chang, H.D.Holmgren: *Phys. Rev. C* **19** (1979) 698
[7] A.Iwamoto, K.Harada: *Phys. Rev. C* **26** (1982) 1821
[8] A.Yu.Konobeyev, Yu.A.Korovin: *Kerntechnik* **59** (1994) 72
[9] Yu.N.Shubin *et al.*: Report INDC(CCP)-385, IAEA Vienna 1995
[10] P.Oblozinsky, I.Ribansky: *Phys. Lett. B* **74** (1978) 6
[11] Z.Lewandowski *et al.*: *Lett. Nuovo Cim.* **28** (1980) 15
[12] I.Kumabe *et al.*: *Phys. Rev. C* **38** (1988) 2531
[13] A.Ferrero *et al.*: Report INFN/BE-78/6, Milano 1978
[14] F.E.Bertrand, R.W.Peelle: *Phys. Rev. C* **8** (1973) 1045
[15] A.Chevarier *et al.*: *Phys. Rev. C* **11** (1975) 886
[16] A.Yu.Konobeyev *et al.*: *Nucl. Instr. Meth. B*, *(to be published)*
[17] O.T.Grudzevich *et al.*: Report N1802 IPPE Obninsk (USSR) 1986
[18] J.R.Huizenga, G.Igo: *Nucl. Phys.* **29** (1962) 462
[19] S.M.Grimes *et al.*: *Phys. Rev. C* **19** (1979) 2127
[20] E.Gadioli *et al.*: *Phys. Rev. C* **38** (1988) 1649; *ibid.* **43** (1991) 1932
[21] C.Kalbach: *Z. Phys. A* **283** (1977) 401
[22] M.V.Kantelo, J.J.Hogan: *Phys. Rev. C* **13** (1976) 1095