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SEMIEMPIRICAL SYSTEMATICS FOR DIFFERENT HADRON-NUCLEUS INTERACTION CROSS SECTIONS

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I. INTRODUCTION

A large amount of nuclear reaction data is required for different important applications, e.g., for recent plans of transmutation of long-lived radioactive wastes with a spallation source, medical and biomedical needs, and research of cosmic-ray effects on spaceships and astronauts[1]-[3]. Experiments to measure these data are costly and a limited number of facilities are available to make these measurements. Therefore, reliable models are required to provide necessary data[4]-[6]. In some cases, it is more convenient to have fast-computing semiempirical systematics for various characteristics of nuclear reactions instead of their time-consuming calculation using nuclear model codes. Due to a long-standing work of many investigators, a host of empirical formulae is now available for estimation of inelastic [6]-[18], elastic [6, 7, 17], and total [6, 7, 14, 17] cross sections; for double differential cross sections [6, 7], [19]-[23]; energy [23] and angular [20] distributions and multiplicities of emitted particles [16, 20]; for spallation cross sections and excitation functions [6]-[12], [26]-[39], etc. The systematics [8]-[10], [13, 14], [19]-[21], and [27, 28] have recently been reviewed by Koning [6], and we will not repeat this here. Most of the old systematics available by 1970 were analyzed in the monograph [7]; the majority of systematics, proposed by 1985, for mass yields, charge dispersions, energy and angular distributions of fragments produced in pA and AA collisions at relativistic energies are presented in the review [39] by Hüfner; many useful systematics of inelastic, elastic, and total cross sections may be found in the recent book by Barashenkov [17]. Below we discuss only the most recent and some less known systematics that were not reviewed in [6, 7, 39] but are by no means worse, from our point of view.

II. INELASTIC, ELASTIC, AND TOTAL CROSS SECTIONS

Not only for different applications but also for many theoretical investigations, it is necessary to estimate cross sections for reactions induced by various projectiles. At high incident energies T, where the Coulomb forces are of no importance any longer, the inelastic cross section $\sigma_{in}(T, A)$ of a hadron-nucleus interaction is simply proportional to the geometric cross section of the target-nucleus and may be approximated as [17]:

$$\sigma_{in}(T,A) \cong \pi R^2 = \sigma_0(T)A^{\alpha_{in}}, \qquad (1)$$

where R and A are the radius and mass number of the target, $\alpha_{in} \cong 2/3$, and $\sigma_0(T)$ is a smooth function of only incident energy T. This approximation is well justified only for a "black", totally absorbing nucleus with a sharp border. For real nuclei, α_{in} and $\sigma_0(T)$ are more complicated functions and correlate with the energy dependence of the total hadron-nucleon interaction cross section $\sigma_t(hN)$.

For evaluation of σ_{in}, many authors have proposed a variety of concrete formulae based on this relation (see, e.g., [6]-[18]): from the well-known simple but crude formula $\sigma_{in} \simeq 49.9A^{2/3}$ mb, used by many authors (see, e.g., [8, 10]), to some very sophisticated systematics with many energy-dependent parameters providing a description of data with an accuracy of only few per cent [17].

A simple and useful systematics to calculate σ_{in} (in mb) for pA interactions in the incident energy T region from 100 MeV to 1 GeV for nuclei from ^{12}C to ^{238}U has recently been proposed by Fotina et al. [16]:

$$\sigma_{in} = 44. \times A_M^{0.69}\left\{1 + \frac{1}{\sqrt[3]{A_M}}(Z + Z_\pi - 2)\right\}. \qquad (2)$$

Here A_M is the mass of the target, and

$$Z = a_1 T^{-a_2} + a_3\left(\frac{e^x - 1}{e^x + 1} + 1\right); \qquad Z_\pi = A_\pi \times exp\left\{-\frac{(T - E_\pi)^2}{\omega^2}\right\};$$

$x = a_4(T - a_5)$; $a_1 = 19.301$; $a_2 = 0.461$; $a_3 = 0.860 - 1.033 \times 10^{-5}(A_M - 44.8)^2$; $a_4 = 0.01$; $a_5 = 890.0$; $A_\pi = 1.141 \times e^{0.002527A_M}$; $E_\pi = 730.43 - 0.296 \times A_M$; $\omega^2 = 31158.4 - 116.174 \times A_M$. Due to the term Z_π which allows for the π-meson production effect, this formula differs advantageously from other simple systematics by the ability of describing the measured bump of σ_{in} in the region of incident energy $T \sim 600 - 700$ MeV. Fig. 1 (taken from [16]) shows a comparison of σ_{in}, evaluated with (2) for several nuclei, with the experimental data.

Expressions of a power form like (1) may be used also for evaluation of total $\sigma_t(T,A)$ and elastic $\sigma_{el}(T,A)$ cross sections, but their accuracy,

especially for $T \leq 100$ MeV and light nuclei, is significantly worse than for $\sigma_{in}(T,A)$ (see [17]).

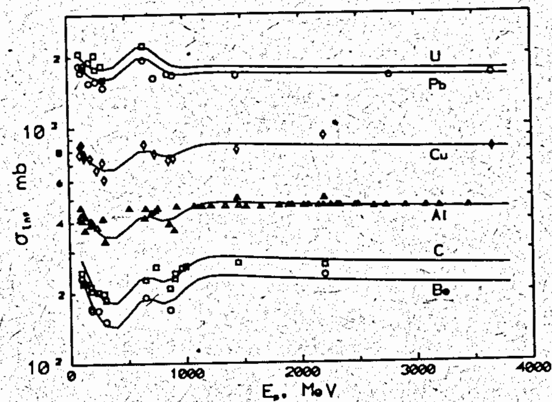

Fig. 1. The proton-nucleus inelastic cross section for U, Pb, Cu, Al, C, and Be according to the systematics (2) together with the experimental data (received from Dr. O.V. Fotina [16]).

Along with expressions like (1), it is possible to use relations of the following type:

$$\sigma(T,A) = \pi[r_0 A^{1/3} + b(A) + C(T) + \cdots]^2(1 - V/T_c), \qquad (3)$$

derived from a series expansion of the optical model formulae when the whole energy-dependence is contained in only one additive term $C(T)$ [17]. An interesting universal systematics like this was suggested by Barashenkov [17]

$$\sigma(T,A) = \pi r_0^2\{A_P^{1/3} + A_T^{1/3} + bA_P^{1/3}A_T^{1/3}/(A_P^{1/3} + A_T^{1/3}) + d(1 - 2Z/A) - C(T)\}^2(1 - V/T_c). \qquad (4)$$

Here V is the Coulomb barrier, T_c is the kinetic energy of the projectile in the CM frame, A_P and A_T are mass numbers of projectile and target, respectively. This expression was successfully used [17] to describe σ_{in}, σ_{el} (and σ_t, as $\sigma_t = \sigma_{in} + \sigma_{el}$) for nucleon-, pion-, kaon-, antinucleon-, and nucleus-nucleus interactions. For example, in the case of nucleon-nucleus interactions we have to use $A_P = 1$; $r_0 = 1.1$ fm; $b = 1.85$; $d_{in} = 2.5$, for σ_{in}, and $d_{el} \cong 0.3$ for σ_{el}. The energy dependences of

$$\sigma_{in}^{\pi^-}(T,A) = \sigma_1^{\pi^-}(T,A) + \sigma_2^{\pi}(T,A); \qquad (6)$$

where

$$\sigma_1^{\pi^-}(T,A) = \sigma_1^{\pi^+}(T,A) + \sigma_3^{\pi}(T,A);$$
$$\sigma_1^{\pi^+}(T,A) = \sigma_4(A)(T/160)^{\gamma} exp((160-T)/E);$$
$$\sigma_4(A) = 220(A/12)^{0.6};$$
$$\gamma = 2 + 36/A; \quad E = 160/\gamma, \quad \text{if } 160 \le T \le 400 \text{ MeV};$$
$$\gamma = (2 + 36/A)/3; \quad E = 160/\gamma, \quad \text{if } T < 160 \text{ MeV};$$
$$\sigma_2^{\pi}(T,A) = \sigma_5(A)(0.7 + 3.3(1 - exp(-(AT/1000)^2)))/4;$$
$$\sigma_3^{\pi}(T,A) = A^{3/2} exp(-T/60);$$
$$\sigma_5(A) = 220(A/12)^{0.6} + 0.5A.$$

Here, cross sections are in mb; and pion incident energy T, in MeV.

In Ref. [15], one can also find similar formulae providing reliable description of σ_{in} for incident pions at higher energies (up to 300 GeV); and for nucleon-induced reactions in the energy region from $\sim$ 20 MeV to 1 TeV.

To our knowledge, the most complete compilation of experimental data on elastic, inelastic, and total cross sections for nucleon- and pion-induced reactions at energies higher than several MeV is published in a tabulated form in the recent book by Barashenkov [17]. Files with data for nucleon-induced reactions, prepared according to this compilation, are available at present from NEA OECD. The book [17] contains a compilation (but not so rich) of measured cross sections for reactions induced by kaons, antinucleons, antideutrons, and nuclei, as well as many systematics for these cross sections. It also contains a huge number of figures with experimental and evaluated σ_{in}, σ_{el}, and σ_t for the majority of nuclei, which may be convenient for investigators for a prompt reveal of cross sections of interest. Moreover, Barashenkov and Polanski have prepared the code CROSEC [18] which provides σ_{in}, σ_{el}, and σ_t for pion-, nucleon-, and nucleus-nucleus interactions for targets with the charge number $Z > 3$ at incident energies from 14 MeV up to 1 TeV. The hadron-nucleus cross sections are obtained by means of interpolation between estimated experimental data compiled in Ref. [17], while the nucleus-nucleus cross sections are calculated

using a phenomenological formula with coefficients fitted at energies above several MeV/nucleons. Fractions of the CROSEC code can be used as subroutines employed by other codes. Investigators interested in using the code CROSEC have to contact Prof. V.S. Barashenkov: **barashenkov@lcta30.jinr.dubna.su**, or Dr. A. Polanski: **polanski@cv.jinr.dubna.su** .

III. DOUBLE DIFFERENTIAL CROSS SECTIONS, ENERGY AND ANGULAR SPECTRA, AND MEAN MULTIPLICITIES OF EMITTED PARTICLES

Systematics for double differential cross sections $d^2\sigma/dTd\Omega$ for secondary particles emitted from different nuclear reactions are of interest as input for some preequilibrium nuclear models and, which is more important, as generators for transport codes widely used in essential applications.

The Kalbach, and earlier, Kalbach-Mann systematics [19] for continuum angular distribution of secondary n, p, d, t, ^{3}He, and ^{4}He emitted in nucleon-, deuteron-, and alpha-particle-induced reactions at incident energies up to several hundred MeV have been obtained from the analysis of many sets of experimental data. These systematics are well-known and used in such preequilibrium model codes as ALICE-F [40] and GNASH[41]; they have recently been reviewed by Koning [6]; therefore, we will not discuss them here.

Pearlstein [20] has analyzed experimental data on neutron emission from a target bombarded by 318-, 590-, and 800-MeV protons and obtained a set of phenomenological systematics with 24 parameters for double differential cross sections $d^2\sigma(p,xn)/dTd\Omega$, angular distribution $d\sigma(p,xn)/d\Omega$, and angle-energy integrated $\sigma(p,xn)$ cross sections. These systematics are used in the preequilibrium model code ALICE-F [40] and have also been reviewed by Koning [6]. A comprehensive comparison of the results of Pearlstein's calculations with experimental data and predictions of many nuclear models may be found in the recent review [4].

More recent systematics for $d^2\sigma(p,xn)/dTd\Omega$ with fewer parameters has been suggested by Ishibashi et al. [21] for incident protons of 25 MeV to 800 MeV and nuclei-targets in a wide range of mass-number.

The authors of Ref. [21] used a moving source model with three components corresponding to the intranuclear-cascade, preequilibrium, and evaporation processes in the incident proton energy region from 600 to 800 MeV, and a new double moving source, that is called "Watt moving source" model, at energies below 400 MeV for the cascade component to fit the experimental data. Ishibashi et al. [21] found a set of parameters for each analyzed incident energy and target allowing to describe well double differential (and integrated) cross sections of secondary neutrons. These systematics were reviewed by Koning [6] and further developed by Fotina et al. [16] for description of secondary protons as well.

In addition, Fotina et al. [16] obtained smooth dependences of all parameters on incident energy and target mass number, which permits one to use these systematics for any nuclei from C to U and incident energies from ~ 100 MeV to 1 Gev without additional fitting. Moreover, Fotina et al. [16] prepared two fortran codes MSM and MSPN according to these systematics for calculation of double differential cross sections, energy and angular spectra, angle-energy integrated yields, and mean multiplicities for secondary neutrons and protons. The code MSM provides also calculation of total pA inelastic cross section σ_{in} from the formula (2) and some more useful output. An example of comparison of proton spectra from p + ^{27}Al and p + ^{208}Pb reactions at energies 90 MeV and 740 MeV calculated with Fotina et al. systematics [16] with the experimental data is given in Fig. 2. One can see a good agreement.

Fotina et al. systematics [16] were successfully used by the authors as generators for the well-known Monte Carlo transport code MCNP (together with the code SOURCE which generates the input for MCNP) which allows one to calculate neutron and proton transition in samples of arbitrary shapes with constituent substance (for details, see [16]). The MSM and MSPN codes are available upon request from Dr. O.V. Fotina: **fotina@p5-lnr.npi.msu.su** or **fotina@p6-lnr.npi.msu.su** .

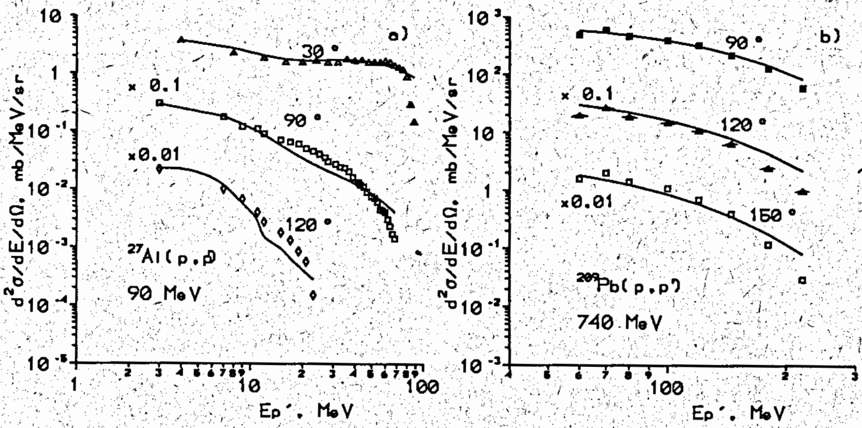

Fig. 2. Comparison of Fotina et al. systematics [16] with experimental data for double-differential proton spectra from p + ^{27}Al (fig. a), T_0 = 90 MeV) and p + ^{208}Pb (fig. b), T_0 = 740 MeV) interactions (received from Dr. O.V. Fotina [16]).

Gorbatkov, Kryuchkov, and Striganov [22], recognized experts in systematics and transport calculations, consider Sychev's et al. [23] approximations to be the best by 1992 universal systematics for double differential cross sections of secondary hadrons emitted from hadron-nucleus interactions at incident energies from ~ 20 MeV up to hundreds of GeV. These systematics were used in transport calculations and are realized as several fortran codes: D2N2 for calculation of $d^2\sigma(p,xn)/dTd\Omega$ of fast hadrons; D2N1 for integrated $d\sigma(p,xn)/dT$; EVAP for calculation of evaporation of slow particles; NECS for calculation of nucleon-nucleus quasielastic and nucleon-nucleon elastic cross sections. Unfortunately, formulae of these systematics are too cumbersome to be shown here, and the full set of all parameters is not at our disposal; therefore, interested users have to contact directly the authors of Ref. [23].

To perform reliable calculation of n, p, π, K, and γ transport through the matter [24], Gorbatkov et al. [22] have recently derived a new, more precise than those of Sychev et al. [23] systematics for double differential cross sections of hadrons produced in inelastic hA interactions at energies from ~ 10 MeV to ~ 10 TeV.

An example of comparison of Gorbatkov et al. systematics [22] of $d^2\sigma/dTd\Omega$ for proton-induced neutron production on Al and Pb at 585 MeV with the Sychev et al. [23] one and with experimental data is shown in Fig. 3 (adapted from Ref. [22]).

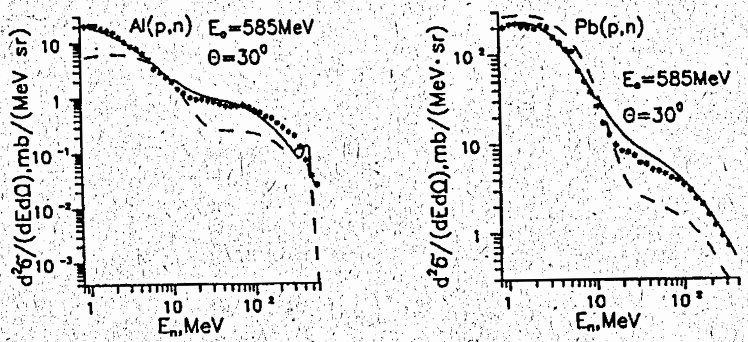

Fig. 3. Double differential cross sections of neutron production from interactions of 585 MeV protons with Al and Pb. Solid lines show Gorbatkov et al. systematics [22]; dashed lines are calculated with Sychev et al. systematics [23]; points indicate experimental data. This figure is adapted from Gorbatkov et al. [22].

One can see that for these reactions, Gorbatkov et al. systematics [22] describe experimental data better than those of Sychev et al. [23]. The systematics of Gorbatkov et al. were incorporated in the code system SADCO-2 [22], used to provide high-energy particle transport calculations by a group method with the new Monte Carlo fast code MOSKIT1 [24]. Unfortunately, the whole set of formulae and parameters of Gorbatkov et al. systematics is not given in Ref. [22], and we again suggest interested users to contact the authors.

IV. SPALLATION CROSS SECTIONS AND EXCITATION FUNCTIONS

Reliable systematics for integral cross sections of production of different isotopes or for excitation functions are of special importance [25] for such applications as: optimization of isotope production; design and operation of high-energy accelerators; accelerator-based waste transmutation; accelerator-based energy amplification; astrophysics; cosmic

ray physics; and, last but not least, for understanding theories of strong nuclear interactions and for tests of nuclear reaction models (for more details see, e.g., [1, 2]).

The first universal formula for spallation reaction cross sections was suggested by Rudstam [8] and later improved by many authors, notably by Silberberg and Tsao [9]. These five-parameter systematics are well known, widely used, and often reviewed (see, e.g., [6, 7, 10, 39]). The Silberberg and Tsao formula is extensively used in applications, due to, among others, its realization in the code SPALL published by Routti and Sandberg [10]. In subsequent years Silberberg and Tsao performed a number of changes and refinements of their systematics [11], extended it to the description of heavy-ion reactions as well [12], and now a new recent code version YIELD of these systematics is available (citation under Michel et al. [25]).

Fig. 4 (taken from Michel et al. [25]) shows, as an example, the ratios of proton-induced sppalation cross sections calculated under Silberberg and Tsao systematics versus Michel et al. experimental data [25] for proton energies of 800 MeV and 2600 MeV.

On can see that most of the individual ratios are within a factor of 2 from unity and only seldomly there are reactions for which the ratios go up to a factor of 10.

The five-parameter Rudstam formula was extensively used to analyze also data on high-energy photospallation, and new sets of parameters for these reactions were obtained (see, e.g., [26] and references therein).

Further, some authors developed similar but simpler formulae for spallation cross sections. So, Gupta et al. [27] proposed a four-parameter systematics, while Foshina et al. [28] derived a simpler one, three-parameter formula.

Recently, several investigators obtained similar simple but universal systematics for spallation cross sections which may be applied to describe both proton- and nucleus-nucleus interactions [29, 30] (see also the new Silberberg and Tsao formulae [12] cited above).

So, the Sümmerer et al. parametrization [29] is very simple, does not pretend to describe such processes as multifragmentation, intermediate-mass fragments and fission products and was developed with an emphasis on heavy targets (or projectiles) nuclei; therefore, it should be applied to fragments from targets (or projectiles) with masses larger than approximately A=40.

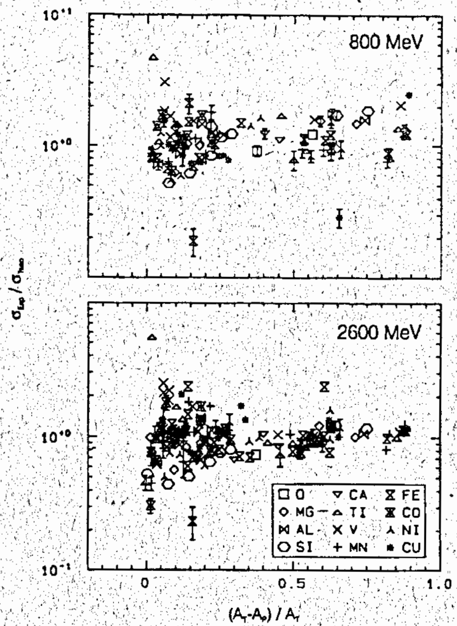

Fig. 4. Ratios of theoretical cross sections calculated by the semiempirical formulae of Silberberg and Tsao [11, 12] and experimental cross sections from the work by Michel et al. [25] as a function of the relative mass difference between target and product for 800 and 2600 MeV. Different targets are shown with different symbols, as indicated. The figure is taken from Michel et al. [25].

An example of prediction of Sümmerer et al. parametrization [29] for charge distributions of residual nuclei with the mass number $A = 72$ from proton-induced reactions on ^{96}Ru, ^{96}Mo, and ^{96}Zr at incident energy of 1.8 GeV is shown in Fig. 5 (taken from Ref. [29]). One can see that the agreement is quite good.

On the contrary, new systematics presented in a series of recent papers by Webber et al. [30] were developed with the aim to describe interactions of light nuclei (with light targets) with $Z = 4 - 28$ and $A = 7 - 60$ for energies ≥ 200 MeV/nucleons and claim for an accuracy

"of 10 % or better". These new semiempirical systematics were fitted in a form of a product of three essentially independent terms [30], first describing the elemental cross sections; second, the isotopic cross sections, and the third term describing the energy dependence. In addition to these basic terms in the expression for cross sections, there are specialized terms for neutron and proton stripping reactions and a special treatment of cross section for production of "difficult" Be isotopes. The complete details of these systematics, including tables and plots of cross sections are available "in limited quantities" on a PC compatible diskette by writing the authors [30].

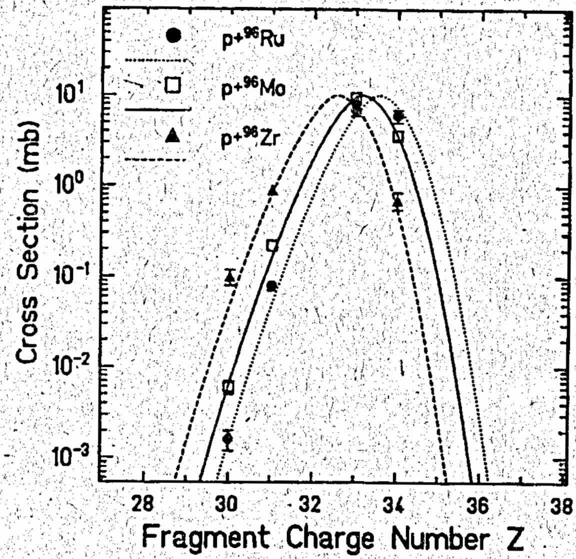

Fig. 5. Cross sections for $A = 72$ isobars from reaction of 1.8 GeV protons with ^{96}Ru, ^{96}Mo, and ^{96}Zr. The symbols are experimental data and the curves are from Sümmerer et al. emperical description with the memory effect parametrized according to Eq. (13) from Ref. [29]. The figure is taken from Sümmerer et al. [29].

Besides the need for spallation and fragmentation cross sections at intermediate and high energies widely evaluated with the systematics cited above, a lot of simpler excitation functions, like (n,n′), (n,n′γ), (n,2n), (n,3n), (n,p), (n,t), (n,α), (n,γ) etc. at lower energies are required for solving safety and technical problems of fusion and thermonuclear reactors, as well as for other important applications and science [1]-[3]. To fill the gap of data needed and to extend the available Large Evaluated Data Files and Libraries (see, e.g., [1]-[3]), a variety of systematics were developed by many authors for (n,2n) (see [31, 37, 38] and references therein), (n,p) [31, 32, 35, 36], (n,t) [33, 35, 36], (n,α) [34]-[36], (n,Charge-Particle) [31]-[36] that are used along with calculations in the framework of different models of nuclear reactions.

As an example, below we show only very simple but quite reliable systematics for incident energies less than 20 MeV and mass numbers of targets between 30 and 210 which have recently been obtained by Badikov et al. [31] for $\sigma(n,p)$ and $\sigma(n,3n)$ (in mb) by fitting experimental data with Forrest and Lu-Fink formulae (see references in [31]):

$$\sigma(n,p) = 5.2093(A^{1/3}+1)^2 exp(-23.486s - 85.044s^2 + 0.25406A^{1/2}),$$
$$\sigma(n,2n) = 47.015(A^{1/3}+1)^2(1 - 3.9777exp(-24.116s)). \quad (7)$$

Here A and s are the mass number and asymmetry parameter of the target nucleus.

Other useful systematics for excitation functions may be found in [31]-[38] and references therein.

It should be stressed that several fortran codes written according to some systematics for neutron-induced excitation functions are available at present from the OECD NEA Data Bank [42, 43]. So, there are Chinese codes: NX-1 (IAEA0918/01) for calculation of (n,p) and (n,α) excitation functions for $23 \le A \le 197$ and $T_n < 20$ MeV [36]; NX-2 (IAEA0919/01) for (n,d) and (n,^{3}He) for the same energies and targets [36]; and the code SC2N3N (IAEA0917/02) [37] for $(n,3n)$ and (n,2n) cross sections in the incident energy region up to 25 MeV and targets in the region $23 \le A \le 238$. There is also BNL code THRES2 (NESCO0504/01) by Pearlstein [38] intended for calculation of 19 channels of neutron-induced reaction cross sections from 0 to 20 MeV, namely: 2n, 3n, p, d, t, ^{3}He, ^{4}He, np, nd, nt, n^{3}He, n^{4}He, pn, 2p, p^{4}He, ^{4}Hen, ^{4}Hep, dn, and fission spectrum averages.

At the end of this section we would like to refer to a general remark by Michel et al. [25] about the quality of predictability of semiempirical systematics: "Semiempirical formulas will be quite successful if binding energies are the crucial parameters dominating the production of the residual nuclides, i.e., for nuclides far from stability. In the valley of stability, the individual properties of the residual nuclei, such as level densities and individual excited states, determine the final phase of the reactions. Thus, the averaging approach of all semiempirical formulas will be inadequate."

V. SUMMARY

Now, that we have come to the end, our readers may ask us: What are the best systematics from hundreds available or from a dozen cited above? There is no a unique answer to this question. It depends on our concrete task. In many cases, for quick estimations it may be enough to use simple systematics by Fotina et al. [16] to estimate inelastic cross sections or double differential spectra, the Silberberg and Tsao[11, 12] ones recently realized as the code versions YIELD to estimate spallation cross sections, or even such simple formulae as (7) to evaluate excitation functions.

On the contrary, to analyze "delicate" characteristics, calculations using more complicated systematics like the proposed in Refs.[17, 22, 23, 30], or even in the framework of sophisticated models of nuclear reactions may be necessary.

From our standpoint, the intercomparisons organized systematically during the last years by NEA OECD (see, e.g., [4]) are very useful for authors of models and systematics serving as a guidance for further development. These exercises are quite useful also for users as their results help interested parties to choose the most appropriate models, systematics or codes for their concrete tasks. We strongly recommend our colleagues to use in their work these reports as well as other valuable NEA OECD information [42] available by E-mail (send a mail to **nearobot@nea.fr**, put **HELP** in the message); by FTP (ftp to **ftp.nea.fr**, login as **anonymous**); by telnet (telnet to **nos.nea.fr**, login as **neadb** then enter **guest**); or by WWW (open URL **http://www.nea.fr/**).

We also address our readers to the Computer Program Abstracts (see, e.g., [43]) issued periodically by NEA OECD which contains a short description of the codes of nuclear models and systematics available from the OECD NEA Data Bank collection.

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