FAST-NEUTRON REACTION ANALYSIS FOR FUSION LOW-ACTIVATION MATERIALS

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Objectives: 1. Improved nuclear model calculation methods for nuclear activation data.

Milestones: A. Completion of fast-neutron reaction analysis for stable Ni isotopes: $^{60,62,64}$Ni
   B. $(\alpha,\alpha)$ analysis at incident energies around Coulomb barrier on A~100 nuclei
   C. Completion of fast-neutron reaction analysis for Mo isotopes: $^{92,94,95,96,97,98,100}$Mo

Progress of work
Improved nuclear model calculation methods for nuclear activation data have been carried out by using the exciton and the Geometry-Dependent Hybrid (GDH) semi-classical models for pre-equilibrium emission (PE) and the Hauser-Feshbach statistical model (SM) within the computer code STAPRE-H95. The points on which we have focused our work are:
   (i) description of the $(n,p)$ and $(n,\alpha)$ reaction excitation functions above the common 15 MeV value, which was recently proved to be not suitable provided by the usual semi-classical PE models;
   (ii) the angular-momentum distribution of the nuclear-level density described, e.g. within the wide-used back-shifted Fermi gas (BSFG) model, by the nuclear moment of inertia $I$ which was found rather recently to be equal with only half of the rigid-body value $I_r$ (usually it is still used, e.g. Ref.\(^3\), the value $I=I_r$);
   (iii) optical model potential (OMP) providing the $\alpha$-particle transmission coefficients, which is yet an open question of reaction cross-section calculations while best approach for its description could be only microscopic.\(^6\)

The development in the meantime at IFIN-HH of a novel partial level-density formalism, e.g. the recent IAEA Reference Input Parameter Library (RIPL)\(^8\), and an improved version of corresponding computer code PLD\(^9\) have contributed to progress on the above item (a). Work concerning the items (b,c) is described hereafter in connection with the main tasks of the former Subgroup 1 of the WPEC of OECD/NEANSC, namely\(^10\) to compare the JENDL-3, JEF-2 and

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\(^4\)S.F. Mughabghab and C. Dunford, Phys. Rev. Lett. 82,4083 (1998)
\(^6\)* * * The Model Code Meeting, May 21-22, 2002, EC/JRC/IRMM, Geel, Belgium.
ENDF/B-VI evaluations and to recommend further studies. The \((n, \alpha)\) reaction and the nuclear level density were underlined as generic problems while possible reasons for the well-known differences among the evaluated \((n, \alpha)\) cross sections have been considered (i) competition of other channels, (ii) alpha-particle optical model potential, (iii) level density, and (iv) pre-formation factors in the pre-equilibrium emission (PE) model. Moreover, the main recommendation from Subgroup 1 concerns the formation of a new Subgroup on Level Densities for Structural Materials, looking especially for new calculation fitting all other cross sections and data. It was also pointed out that any near-term revision for \(^{58}\text{Ni}\)(\(n, \alpha\)) should consider all measured data, and the evaluator should consider \(^{60}\text{Ni}\)(\(n, \alpha\)) simultaneously in order to use new data for natural nickel.

The last motivation of above has been both superseded and extended by the first measurement at LASL-Los Alamos and comprehensive study\(^{11,12}\) of the alpha-production by neutrons on \(^{58,60}\text{Ni}\) as well as \(^{59}\text{Co}\) from threshold to 50 MeV. However, the new data\(^{11}\) have not supported any of the three above-mentioned evaluations while latest analyses still consider the large uncertainties in the \((n, \alpha)\) cross sections as a general problem, in conjunction also with LD approaches\(^{13,14}\). On the other hand recent measurements\(^{15,16}\) at IRMM-Geel and FZ-Jülich of cross-sections for other channels in competition with these \((n, \alpha)\) reactions, especially at incident energies between 14 and 21 MeV, make possible an enlarged analysis of the fast-neutron interactions around the atomic mass number \(A=60\).

Since the neutron-induced alpha emission represents a small fraction of the total reaction cross section, it is considered that a successful analysis depends on the use of accurate level densities (LD) and optical potentials (e.g. Ref.\(^{11}\)). While the proper treatment of the latter item is considered\(^{6}\) the semi-microscopic calculation using the double-folding method for the real potential (e.g. Ref.\(^{17}\)), until now we have used or adjusted the phenomenological optical model potential (OMP) proved able to describe alpha emission\(^{18}\). Thus it has been the level density the first subject of our major interest\(^{19}\), due to the latest achievements in the field and remaining question marks above-mentioned under point (ii). Nevertheless, the unitary account of a whole body of related experimental for isotope chains of neighboring elements has been considered for validation of the calculation method.

**A. Completion of fast-neutron reaction analysis for stable Ni isotopes: \(^{60,62,64}\text{Ni}\).**

The completion of previous analysis\(^{16}\) of the \((n, p)\) reaction in the case of target nucleus \(^{60}\text{Ni}\) concerns the \((n, \alpha d)\) reaction, following thus the WPEC earlier recommendations to consider the analysis of the \(^{60}\text{Ni}\)(\(n, \alpha\))\(^{57}\text{Fe}\) reaction at the same time with discussion of the \(^{58}\text{Ni}\) target\(^{10,11}\). The recent analysis of the latter case is described elsewhere\(^{16}\), including all open reaction channels, as well as a similar work for the target nucleus \(^{59}\text{Co}\), due to many common isotopes involved in the de-excitation of the compound nuclei \(^{60}\text{Co}\) and \(^{59,61}\text{Ni}\). Results of the similar analysis for the target nuclei \(^{60}\text{Ni}\) and \(^{61,62,64}\text{Ni}\) are shown in Figs. 1 and 2, respectively.

The particular case of the \((n, \alpha)\) reaction on target nuclei \({}^{58,60,62,64}\text{Ni}\) is shown in Fig. 3. The logarithmic representation of the first 4-6 MeV of these excitation functions proves the suitability of the \(\alpha\)-particle OMP involved in this work. It was obtained by decreasing the OMP real-potential well diffuseness\(^{18}\) from about 0.78 fm to 0.71 fm. On the other hand, in Fig. 4 there are shown the effects of the \(D_0\)-value uncertainties used for LD parameter establishment for target \({}^{60}\text{Ni}\) and residual nucleus \({}^{57}\text{Fe}\). These effects are shown separately as well as summed up for the \((n, \alpha)\) reaction and total \(\alpha\)-particle production. Beyond their significant magnitude, one may see also the effective thresholds of the continuum populated in the two distinct excited nuclei. One could see thus the lower incident energy of about 6 MeV at which the target-nucleus LD starts to be important while \(\alpha\)-channel nucleus LD plays the same role only above 9 MeV.

A by-product of this work has been the \((n, \alpha)\) and \((n, p)\) reaction cross section calculation for target nucleus \({}^{60}\text{Ni}\) in the keV-range (Fig. 5) of interest for shut-down dose rate analysis\(^{20}\).

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Fig. 2. Comparison of experimental and calculated activation cross sections for fast neutrons on ${}^{61}$, ${}^{62}$, and ${}^{64}$Ni.
Fig. 3. Comparison of experimental and calculated (n,xα) cross sections for target nuclei $^{58}$Ni, $^{60}$Ni, $^{62}$Ni, $^{64}$Ni.
Fig. 4. Comparison of experimental and calculated cross sections for \((n,x\alpha)\) reactions on the target nucleus \(^{60}\text{Ni}\), including the effect of uncertainties of resonance data used for LD parameter establishment.

Fig. 5. Comparison of experimental and calculated fast-neutron cross sections on \(^{58}\text{Ni}\) from keV-region.
Another related analysis of actual interest\textsuperscript{21} for fusion neutronics has been the case of $^{51}$V($n,n'$\alpha$)$^{47}$Sc reaction above 20 MeV. Results of the previous analysis\textsuperscript{22} for fast-neutron induced reactions on the target nucleus $^{51}$V up to 21 MeV have had thus to be extended to higher energies. While the correctness of $\alpha$-particle OMP is still an open question especially at low energies, we have extended only the analysis of the neutron OMP which was already validated\textsuperscript{23} for incident-neutron energies $E$ from 8 to 13.9 MeV by the corresponding description of neutron-emission spectra measured\textsuperscript{24} at PTB-Braunschweig. The total neutron cross sections\textsuperscript{25} which are available only up to 32 MeV were used in this respect (Fig. 6). Finally the $^{51}$V($n,n'$\alpha$)$^{47}$Sc reaction cross sections have been calculated in the incident energy range up to 32 MeV by using the realistic LD approach\textsuperscript{19} as well as only the BSFG model (Fig. 6). The differences are below 5% in this case, especially due to presence of an $\alpha$-particle in the emergent channel. On the other hand, the shape of the excitation function thus obtained is quite different with respect to the IEAF-2001 evaluated data. The latest major uncertain quantity seems to remain the $\alpha$-particle OMP just above Coulomb barrier, where e.g. the dispersion relations may provide distinct behavior than within first MeVs of the ($n,\alpha$) excitation functions.

B. \((\alpha,\alpha_0)\) analysis at incident energies around Coulomb barrier on A~100 nuclei

The \(\alpha\)-particles double-folded (DF) microscopic real potential analysis carried out within previous report proved that additional work has been necessary below 20 MeV in order to provide OMPs for nuclear data evaluation. A fit of \(\alpha\)-particle elastic scattering data at energies below 35 MeV has been restricted in the first phase to the mass range A~100 since Atzrott et al.\(^{26}\) shown that the \(\alpha\)-nucleus OMP real part becomes rather independent of the target mass for nuclei with masses A\(\geq\)90. The \(\alpha\)-induced or \((n,\alpha)\) reaction cross sections have been not yet taken into account in this respect, in order to avoid the question marks due to the rest of the statistical-model parameters (e.g. the shaded areas in Figs. 4-9 of Ref.\(^{27}\)). A two-step analysis of the \((\alpha,\alpha_0)\) angular distributions on \(^{89}\)Y, \(^{90,91}\)Zr, \(^{92,94,96,98,100}\)Mo, \(^{107}\)Ag, and \(^{116,122,124}\)Sn has been carried out\(^{28}\) by (i) fit of an energy-dependent phenomenological imaginary part while the DF real potential is used (e.g. Fig. 7), and (ii) a real phenomenological OMP parameters have been adopted by fit of the same data keeping fixed the imaginary part (e.g. Fig. 8). A method validation concerns application of these potentials in case of \(^{90}\)Zr data\(^{29}\) at 40 MeV (Fig. 9).

Fig. 7. Semi-microscopic analysis of \(\alpha\)-particle elastic scattering on A~100 nuclei\(^{30}\) at energies below 25 MeV by using only DF method for OMP real part and also including the dispersion (DR) correction.

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\(^{28}\)M. Avrigeanu, W. von Oertzen, A.J.M. Plompen, and V. Avrigeani, to be published.

Fig. 8. Phenomenological analysis of $\alpha$-particle elastic scattering on $A\sim 100$ nuclei below 25 MeV.

Fig. 9. Semi-microscopic and phenomenological analysis of 40 MeV $\alpha$-particle elastic scattering on $^{90}$Zr.
D. Completion of fast-neutron reaction analysis for Mo isotopes: $^{92,94,95,96,97,98,100}$Mo

This completion of the analysis of fast-neutron induced reaction on Mo isotopes, carried out previously\textsuperscript{31} has concerned now inclusion of the measurements of activation cross sections of Mo isotopes which were performed at the same time at IRMM-Geel for neutron energies from 16 to 20.5 MeV. Their comparison\textsuperscript{32} could be considered a blind exercise and thus proves the accuracy of the calculation approach. The main change with respect to previous calculation\textsuperscript{31} concerned the formalism of the partial level density\textsuperscript{9} including surface effects. On the other hand, we have taken the advantage of new $^{93}$Nb($p,\gamma$)$^{94}$Mo reaction cross-section measurements below 5 MeV reported in the meantime\textsuperscript{33} and used them for additional validation of the proton OMP involved in our calculation. Our presents results (Fig. 10) solved the discrepancies reported\textsuperscript{33} for the model description of the ($p,\gamma$) data above 3.5 MeV, at the same time with a good agreement obtained with the ($p,n$) reaction data. The actual revision of these calculations by taking into account also the new IRMM data proved both (i) the usefulness of the activation cross sections at neutron energies just above the common value of 15 MeV, and (ii) the prediction power as well as the accuracy limits of the present calculations, mainly related to the decay schemes in the case of the isomer ratio calculations.

**Fig. 10.** Comparison of experimental\textsuperscript{33} and calculated ($p,\gamma$) and ($p,n$) reaction cross sections.

**Forecast progress for the next six months**
- Analysis of ($n,\alpha$)reaction cross sections in order to check the global OMP based\textsuperscript{28} on the use of the DF method.

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