CONF-9409230--

LA-UR-94-3104

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

TITLE: **Experience At Los Alamos With Use Of The Optical Model For Applied Nuclear Data Calculations**

AUTHOR(S): Young, P.G., T-2

SUBMITTED TO: International Atomic Energy Agency 1st Research Co-ordination Meeting on "Development of Reference Input Parameter Library for Nuclear Model Calculations of Nuclear Data" Cervia near Ravenna, Italy, 19-23 September 1994

By acceptance of this article, the publisher recognizes that the U. S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form this contribution, or to allow others to do so, for U.. S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.. S. Department of Energy.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EXPERIENCE AT LOS ALAMOS WITH USE OF THE OPTICAL MODEL FOR APPLIED NUCLEAR DATA CALCULATIONS

P. G. Young
Los Alamos National Laboratory

ABSTRACT

While many nuclear models are important in calculations of nuclear data, the optical model usually provides the basic underpinning of analyses directed at data for applications. An overview is given here of experience in the Nuclear Theory and Applications Group at Los Alamos National Laboratory in the use of the optical model for calculations of nuclear cross section data for applied purposes. We consider the direct utilization of total, elastic, and reaction cross sections for neutrons, protons, deuterons, tritons, ^{3}He and alpha particles in files of evaluated nuclear data covering the energy range of 0 to 200 MeV, as well as transmission coefficients for reaction theory calculations and neutron and proton wave functions in direct-reaction and Feshbach-Kerman-Koonin analyses. Optical model codes such as SCAT and ECIS and the reaction theory codes COMNUC, GNASH, FKK-GNASH, and DWUCK have primarily been used in our analyses. A summary of optical model parameterizations from past analyses at Los Alamos will be given, including detailed tabulations of the parameters for a selection of nuclei.

I. INTRODUCTION

The optical model frequently provides the basis for theoretical analyses and/or data evaluations that are used in providing nuclear data for applied purposes. In addition to offering a convenient means for calculation of reaction, shape elastic, and (neutron) total cross sections, optical model potentials are widely used in quantum-mechanical preequilibrium and direct-reaction theory calculations and, most importantly, in supplying particle transmission coefficients for Hauser-Feshbach statistical-theory analyses used in nuclear data evaluations. This paper collects and reviews optical model potentials developed over the last several years for applied nuclear data analyses in the Nuclear Theory and Applications Group at Los Alamos National Laboratory.

Section II outlines the methodology used for determining many of the potentials described here. Section III includes tabulations of a selection of spherical optical model potentials that have been utilized at Los Alamos in nuclear data calculations, and Section IV gives a similar summary for coupled-channels optical model potentials. Finally, conclusions and recommendations are given in Section V.

II. METHODOLOGY

In the sections that follow a standard form is used for the optical model potential and the various components of the potential.[1] In particular, the potential is represented by a combination of Woods-Saxon volume and surface derivative terms with (V_R, r_R, a_R), (W_V, r_V, a_V), (W_D, r_D, a_D), and (V_{SO}, r_{SO}, a_{SO}) indicating the real central, volume imaginary, surface derivative imaginary, and real spin-orbit components. In the parameterizations given below, the abbreviations

$$\eta = \frac{N-Z}{A} = 1 - \frac{2Z}{A} \tag{1}$$

and

$$\Delta V_c = 0.4\frac{zZ}{A^{1/3}} \tag{2}$$

are employed in the isospin and coulomb correction terms, respectively. In Eqs. (1) and (2) the quantities N, Z, and A are the neutron, proton, and atomic mass numbers of the target nucleus, respectively, and z is the charge number of the projectile. Note that when plus or minus signs are used with the isospin terms in general expressions for proton or neutron potentials, the minus sign is used for neutrons and the positive sign for protons.

For our calculations we typically use the spherical optical model codes SCAT2 by Bersillon[2] or SNOOPY8 by Schwandt.[3] In the case of SCAT2, we have extended the option to call built-in parameterizations to include many additional global and regional parameterizations. For coupled-channels calculations we use either the ECIS code by Raynal[4] or the JUPITOR code, as modified by Rebel et al.[5] In cases where detailed neutron optical model analyses are required, we typically combine the SPRT method[6] (fitting experimental values of s- and p-wave neutron strengths, potential scattering radii, and low energy neutron total cross sections) with fits to differential elastic scattering data at higher energies. We often combine analyses of neutron and proton data using a simple Lane model. In cases where accuracy requirements are not too demanding, we use existing global or regional parameterizations in calculations.

III. SPHERICAL OPTICAL MODEL POTENTIALS

A. Global Potentials at Incident Energies Below 50 MeV

A number of global optical model potentials have been developed for nuclear physics calculations at incident energies below ~ 50 MeV, especially for neutrons. A review of neutron global parameters is given in Ref. 1, and the older review by Percy and Percy[7] is still useful for charged-particle potentials. A global neutron potential developed since the 1985 review that has proven useful for calculations of nuclear data for fusion reactions is a modification by Yamamuro[8] of the surface imaginary term in the Walter and Guss[9] potential below an incident neutron energy of 20 MeV, as follows:

$$\begin{aligned} W_D\,(\mathrm{MeV}) &= 5.0 - 14.94\,\eta + 0.271\,E_n & 0 \le E_n \le 10\ \mathrm{MeV} \\ &= 7.71 - 14.94\,\eta & 10 \le E_n \le 20\ \mathrm{MeV} \end{aligned} \tag{3}$$

All other parameters are taken from the Walter and Guss potential, and that potential is used intact at neutron energies above 20 MeV. We have found the Yamamuro/Walter potential to be quite useful in cases where detailed optical model analyses are not available.

B. Global Potentials at Incident Energies Above 50 MeV

Possibilities for global optical model parameterizations above 50 MeV are considerably more restricted. Starting from a global proton potential by Schwandt et al.,[10] Madland[11] developed a potential that covers a wider energy range and that is generalized for neutrons and protons through the Lane model. The Madland potential was developed by analyzing data for 3 nuclides in the mass range $27 \leq A \leq 208$ and the energy range 50 MeV $\leq E_{n,p} \leq$ 400 MeV. We have incorporated a form of the Madland potential[12] modified for nonrelativistic calculations over the range 50 MeV $\leq E_{n,p} \leq$ 140 MeV into the SCAT2 code; this potential is listed in Table 1.

Table 1. Global spherical optical model potentials for incident neutrons and protons over the incident energy range 50 MeV $\leq E_{n,p} \leq$ 140 MeV and for the mass range $24 \leq A \leq 208$

<u>NEUTRONS</u>

Well Depth (MeV)	Geometry (fm)
$V_R = 105.5 - 16.5\eta - 0.4*Z/A^{1/3} - 17.14375 \ln(E_n)$	$r_R = 1.125 + 0.001 E_n$ $a_R = 0.675 + 0.00031 E_n$
$W_D = 0.0$	
$W_V = 2.4346 + 0.1016 E_n - (9.288E\text{-}4) E_n^2 + (3.87E\text{-}6) E_n^3$	$r_V = 1.650 - 0.0024 E_n$ $a_V = 0.328 + 0.00244 E_n$
$V_{SO} = 19.0 + 3.75\eta - 3.154 \ln(E_n)$	$r_{SO} = 0.920 + 0.0305 A^{1/3}$ $= 0.98\ (A \leq 40)$ $a_{SO} = 0.768 - 0.0012 E_n$

<u>PROTONS</u> ($r_c = 1.25$ fm)

Well Depth (MeV)	Geometry (fm)
$V_R = 105.5 + 16.5\eta - 17.14375 \ln(E_p)$	$r_R = 1.125 + 0.001 E_p$ $a_R = 0.675 + 0.00031 E_p$
$W_D = 0.0$	
$W_V = 2.4346 + 0.1016 E_p - (9.288E\text{-}4) E_p^2 + (3.87E\text{-}6) E_p^3$	$r_V = 1.650 - 0.0024 E_p$ $a_V = 0.328 + 0.00244 E_p$
$V_{SO} = 19.0 + 3.75\eta - 3.154 \ln(E_p)$	$r_{SO} = 0.920 + 0.0305 A^{1/3}$ $= 0.98\ (A \leq 40)$ $a_{SO} = 0.768 - 0.0012 E_p$

For deuterons, tritons, ^{3}He and alpha particles, we have modified the SCAT2 code to include a simplified Watanabe model[13] to derive potentials at medium energies. Details of the Watanabe transformation are also described by Madland.[11]

Other techniques for simplifying and facilitating development of optical model potentials are summarized in Ref. 1. These include the method of approximating an odd-A rotational nucleus in coupled-channels calculations by using appropriately chosen fictitious levels in an adjacent even-A (K=0) nucleus.[14] This procedure can reduce the computer time required to perform coupled-channels calculations for odd-A rotational nuclei, although some penalty in accuracy and setup time must be paid. Another technique that has good potential but that has had little use is the method outlined by Madland and Young[15] that permits the adaptation of spherical optical model potentials for coupled-channels calculations by simply scaling the imaginary surface potential by the relation

$$\frac{W_D a_D}{W'_D a'_D} = \alpha \ , \tag{4}$$

where the primed and unprimed quantities refer to the spherical and deformed potentials, respectively, and α is a constant that can be optimally adjusted but which is typically ≈ 0.7.[1]

C. Regional and Local Potentials

1. Neutron, Proton, and Alpha Potentials for Analysis of n + ^{27}Al Reactions

A reaction theory analysis of neutron cross sections on ^{27}Al has been carried out with the FKK-GNASH code in some detail to 40 MeV for a planned update of the ENDF/B-VI data file, and in less detail to 100 MeV for comparison with high-resolution γ-ray measurements.[16] In this study the neutron potential of Petler et al.[17] was found to reproduce the available experimental data up to 60 MeV or so, and at higher energies the Madland potential[11] appeared to reliably track the total and reaction cross sections to above 100 MeV. For proton channels a form of the Perey proton potential[18] was used for proton energies below 30 MeV, with the following modification to the imaginary surface potential:

$$W_D(\text{MeV}) = 13.5 - 0.15\, E_p \, . \tag{5}$$

In the energy range 30 MeV ≤ E_p ≤ 100 MeV, the Madland global potential[11] was employed for protons. The alpha-particle potential was taken from an analysis of n + ^{54,56}Fe reactions[19] (see next section) and was used up to 100 MeV.

These potentials produce good agreement with elastic scattering, (n,p), (n,n'), (n,α), and nonelastic cross sections over the range of available data, and give reasonable agreement with neutron, proton, and alpha-particle emission spectrum measurements at 14 MeV. Additionally, reasonable agreement is observed in calculations of discrete gamma-ray production cross sections for (n,n'γ) and (n,2nγ) reactions to 60 MeV.[16] The optical model potentials for neutrons and alpha particles are given in Table 2.

Table 2. Spherical optical model potentials for ^{27}Al + n calculations over the incident neutron energy range 1 keV $\leq E_n \leq$ 100 MeV. For $E_n > 60$ MeV, the global potential of Madland[11] was used for neutrons (Table 1).

NEUTRONS

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 51.55 - 0.308\ E_n$	$0 < E_n < 60$	$r_R = 1.18$	$a_R = 0.64$
W_D	$= 6.07$	$0 < E_n < 15$	$r_D = 1.26$	$a_D = 0.58$
	$= 6.07 - 0.10\ (E_n - 15)$	$15 \leq E_n \leq 60$		
W_V	$= 0.00$	$0 < E_n < 15$	$r_V = 1.26$	$a_V = 0.58$
	$= -2.625 + 0.175\ E_n$	$15 \leq E_n \leq 60$		
V_{SO}	$= 6.0$	$0 < E_n < 60$	$r_{SO} = 1.01$	$a_{SO} = 0.50$

ALPHA PARTICLES ($r_c = 1.4$ fm)

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 193.0 - 0.15\ E_\alpha$	$0 < E_\alpha < 100$	$r_R = 1.37$	$a_R = 0.56$
W_D	$= 0.00$	$0 < E_\alpha < 100$		
W_V	$= 21.0 + 0.25\ E_\alpha$	$0 < E_\alpha < 100$	$r_V = 1.37$	$a_V = 0.56$

B. Neutron, Proton, and Alpha Potentials for Analysis of n + ^{54,56}Fe Reactions

Starting from an analysis of reactions on ^{54,56}Fe and nearby nuclei,[19] an optical model parameterization was developed for use in calculating neutron and proton reactions to 100 MeV.[20] These parameters have been used recently to calculate n + ^{56}Fe cross sections to 40 MeV for a planned update of ENDF/B-VI and to compare with experimental measurements of alpha particle spectra from the Weapons Neutron Research (WNR) facility.[21] Calculated cross sections agree reasonably with the available experimental data, including ^{56}Fe(p,n) and (p,2n) measurements as well as (n,xγ) data and neutron elastic angular distributions. The neutron, proton, and alpha particle optical model parameters are included in Table 3.

C. Neutron, Proton, and Alpha Potentials for Analysis of n + ^{59}Co Reactions

Similar to the above calculations on Fe, reaction theory analyses that were made earlier for n + ^{59}Co reactions[22] have been modified slightly for a planned extension of the ENDF/B-VI library to 40 MeV and for calculations of alpha particle spectra to compare with recent measurements from WNR.[23] Again, these parameters result in good agreement with the available total, elastic, nonelastic, inelastic, and (n,2n) cross section measurements and reasonable agreement with (n,p) and (n,α) data. The parameters are listed in Table 4. It should be noted that reaction theory calculations using these parameters have only been performed to ~ 50 MeV but reasonable total and reaction cross sections are calculated out to 100 MeV. Also note that the earlier set of alpha parameters given in Ref. 22 also give good results, especially at lower neutron energies.

Table 3. Spherical optical model potentials for ^{54,56}Fe + n calculations over the incident neutron energy range 1 keV $\le E_n \le$ 100 MeV. Above 62 MeV for neutrons and 28 MeV for protons, the Madland global potential[11] is used (Table 1).

NEUTRONS TO 62 MeV

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 49.747 - 0.297 E_n - 0.0003 E_n^2$	$0 < E_n < 62$	$r_R = 1.287$	$a_R = 0.56$
W_D	$= 6.00 + 0.42 E_n$	$0 < E_n < 6$	$r_D = 1.345$	$a_D = 0.47$
	$= 8.52 - 0.224 (E_n - 6)$	$6 \le E_n \le 62$		
W_V	$= 0.00$	$0 < E_n < 8.9$	$r_V = 1.287$	$a_V = 0.56$
	$= -1.60 + 0.18 E_n$	$8.9 \le E_n \le 62$		
V_{SO}	$= 6.20$	$0 < E_n < 62$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

PROTONS TO 28 MeV ($r_c = 1.25$ fm)

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 58.384 - 0.55 E_p$	$0 < E_p < 28$	$r_R = 1.25$	$a_R = 0.65$
W_D	$= 13.5 - 0.15 E_p$	$0 < E_p < 28$	$r_D = 1.25$	$a_D = 0.47$
W_V	$= 0$	$0 < E_p < 28$		
V_{SO}	$= 7.5$	$0 < E_p < 28$	$r_{SO} = 1.25$	$a_{SO} = 0.47$

ALPHA PARTICLES ($r_c = 1.4$ fm)

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 193 - 0.15 E_\alpha$	$0 < E_\alpha < 100$	$r_R = 1.37$	$a_R = 0.56$
W_D	$= 0.00$	$0 < E_\alpha < 100$		
W_V	$= 21.0 + 0.25 E_\alpha$	$0 < E_\alpha < 100$	$r_V = 1.37$	$a_V = 0.56$

D. Neutron, Proton, and Alpha Potentials for Analysis of n + ^{64,66,68}Zn Reactions

A set of optical model parameters for Zn isotopes was developed in support of 14.8-MeV activation measurements of the ^{64}Zn(n,p)^{64}Cu and ^{64}Zn(n,2n)^{63}Zn cross sections, covering the incident neutron energy range up to 20 MeV.[24] The parameters were obtained by fitting elastic angular distribution and total cross section measurements, and were validated in calculations of activation cross sections for neutron reactions on ^{64,66,68}Zn and for (p,n) reactions on ^{63}Cu and ^{65}Cu. The optical model parameters that resulted are given in Table 5.

E. Neutron and Proton Potentials for Analysis of Neutron Reactions on Sr, Y, and Zr Isotopes

Results of a detailed analysis of neutron and proton reactions on Sr, Y, and Zr isotopes at incident energies from 50 keV to 20 MeV were reported in 1980.[25] The optical model parameters obtained in that study were thoroughly tested against experimental data over that energy range.

Since that time, the optical model analyses and reaction theory calculations have been extended to higher energies. Calculations of neutron-induced reactions on ^{89}Y have been compared with higher energy (n,xγ) measurements from WNR.[26] Similarly, in the case of ^{90}Zr proton-induced reactions were calculated to 160 MeV for the recent NEA-sponsored intermediate energy data calculations.[27] The optical model potentials for protons and neutrons used in these studies are given in Table 6.

Table 4. Spherical optical model potentials for ^{59}Co + n calculations over the incident neutron energy range 1 keV $\leq E_n \leq$ 100 MeV. Above 62 MeV for neutrons and 23 MeV for protons, the Madland global potential[11] is used.

NEUTRONS

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 47.604 - 0.3636\,E_n - 0.0003\,E_n^2$	$0 < E_n < 62$	$r_R = 1.2865$	$a_R = 0.561$
W_D	$= 8.047 + 0.0805\,E_n$	$0 < E_n < 6$	$r_D = 1.3448$	$a_D = 0.473$
	$= 8.530 - 0.2509\,(E_n - 6)$	$6 \leq E_n \leq 62$		
W_V	$= 0.00$	$0 < E_n < 0.5$	$r_V = 1.3448$	$a_V = 0.473$
	$= -0.0721 + 0.1475\,E_n$	$0.5 \leq E_n \leq 62$		
V_{SO}	$= 6.20$	$0 < E_n < 62$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

PROTONS TO 23 MeV ($r_c = 1.25$ fm)

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 57.175 - 0.55\,E_p$	$0 < E_p < 23$	$r_R = 1.25$	$a_R = 0.65$
W_D	$= 13.5 - 0.15\,E_p$	$0 < E_p < 23$	$r_D = 1.25$	$a_D = 0.47$
W_V	$= 0$	$0 < E_p < 23$		
V_{SO}	$= 7.5$	$0 < E_p < 23$	$r_{SO} = 1.25$	$a_{SO} = 0.47$

ALPHA PARTICLES ($r_c = 1.4$ fm)

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 217.0 - 0.15\,E_\alpha$	$0 < E_\alpha < 100$	$r_R = 1.416$	$a_R = 0.493$
W_D	$= 0.00$	$0 < E_\alpha < 100$		
W_V	$= 24.0$	$0 < E_\alpha < 100$	$r_V = 1.416$	$a_V = 0.493$

Table 5. Optical Model Parameters for Neutron Reactions with Zn Isotopes.

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 49.11 - 16\,\eta - 0.376E$	$0 \leq E_n \leq 20$	$r_R = 1.295$	$a_R = 0.58$
W_D	$= 8.545 - 8\eta$	$0 \leq E_n \leq 20$	$r_D = 1.295$	$a_D = 0.48$
W_V	$= -0.094 + 0.197E$	$0 \leq E_n \leq 20$	$r_V = 1.295$	$a_V = 0.58$
V_{SO}	$= 6.2$	$0 \leq E_n \leq 20$	$r_{SO} = 1.12$	$a_{SO} = 0.48$

Table 6. Spherical optical model potentials for proton and neutron reactions on Sr, Y, and Zr isotopes in the vicinity of $A = 90$. At energies above the maxima indicated, the global potential of Madland[11] was used for protons and neutrons.

n + ^{89}Y

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 49.5 - 0.28\ E_n$	$0 < E_n < 21$	$r_R = 1.24$	$a_R = 0.62$
W_D	$= 4.63 + 0.3\ E_n$	$0 < E_n < 10$	$r_D = 1.26$	$a_D = 0.58$
	$= 7.63 - 0.13\ E_n$	$10 \le E_n < 21$		
W_V	$= 0$	$0 < E_n \le 10.9$	$r_V = 1.24$	$a_V = 0.62$
	$= -1.42 + 0.13\ E_n$	$10.9 < E_n < 21$		
V_{SO}	$= 6.2$	$0 < E_n < 21$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

n + ^{90}Zr

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 49.0 - 0.28\ E_n$	$0 < E_n < 20$	$r_R = 1.24$	$a_R = 0.62$
W_D	$= 3.4 + 0.3\ E_n$	$0 < E_n < 10$	$r_D = 1.26$	$a_D = 0.58$
	$= 6.4 - 0.13\ E_n$	$10 \le E_n < 20$		
W_V	$= 0$	$0 < E_n \le 10.9$	$r_V = 1.24$	$a_V = 0.62$
	$= -1.42 + 0.13\ E_n$	$10.9 < E_n < 21$		
V_{SO}	$= 6.2$	$0 < E_n < 20$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

p + Sr

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 56.4 + 24\eta + \Delta V_c - 0.32\ E_p$	$0 < E_p < 21$	$r_R = 1.20$	$a_R = 0.68$
W_D	$= 3.0 + 0.60\ E_p$	$0 < E_p < 17.5$	$r_D = 1.225$	$a_D = 0.40$
	$= 13.5 - 0.15\ E_p$	$17.5 \le E_p < 21$		
W_V	$= 0$	$0 < E_p < 21$		
V_{SO}	$= 6.4$	$0 < E_p < 21$	$r_{SO} = 1.03$	$a_{SO} = 0.63$

p + Y

	Well Depth (MeV)	Range (MeV)	Geometry (fm)	
V_R	$= 56.4 + 24\eta + \Delta V_c - 0.32\ E_p$	$0 < E_p < 21$	$r_R = 1.20$	$a_R = 0.73$
W_D	$= 4.0 + 0.5\ E_p$	$0 < E_p < 17.5$	$r_D = 1.30$	$a_D = 0.40$
	$= 12.75 - 0.15\ E_p$	$17.5 \le E_p < 21$		
W_V	$= 0$	$0 < E_p < 21$		
V_{SO}	$= 6.4$	$0 < E_p < 21$	$r_{SO} = 1.03$	$a_{SO} = 0.63$

IV. REGIONAL AND LOCAL COUPLED-CHANNELS OPTICAL MODEL POTENTIALS

A. Incident Neutron and Proton Potentials for Nuclides in the Region $63 \leq Z \leq 82$

A number of coupled-channels optical model analyses have been performed at Los Alamos for use in reaction theory calculations, including several rare earth and transition elements. In all cases modified SPRT[6] approaches were used to determine the neutron parameters, requiring reasonable agreement with low-energy resonance data and neutron total cross sections, as well as with elastic and inelastic scattering measurements if available. Inclusion of proton data in most cases was accomplished using a simple Lane model.

An analysis was performed of neutron-induced reactions with ^{165}Ho and ^{169}Tm to establish reasonable optical parameters for reaction theory calculations on Tm isotopes.[28] The parameters are based mainly on fits to ^{169}Tm low-energy resonance and total cross section data, and to a neutron elastic scattering angular distribution measurement for ^{165}Ho at 11 MeV. The parameters are listed in Table 7.

In preparation for a major update of the ENDF/B-V cross sections, a coupled-channels optical model analysis was performed on the W isotopes.[28] That analysis included high-resolution neutron elastic and inelastic scattering data below 4 MeV, neutron total cross sections, 16-MeV (p,p') differential cross sections, and low-energy resonance data. A set of neutron parameters specific to each major isotope was obtained in the analysis, and the potentials produce good agreement with the available data to 20 MeV. Since that time, a general form of the potential was extended to higher energies and was used to calculate data libraries to 100 MeV for incident neutrons and protons.[20] The generalized potential is included in Table 8.

Table 7. Coupled-Channels Optical Model and Deformation Parameters for Proton and Neutron Reactions with ^{165}Ho and ^{169}Tm.

	Well Depth (MeV)	Range(MeV)	Geometry (fm)	
V_R	$= 49.8 \pm 16\eta + \Delta V_c - 0.25E$	$0 \leq E \leq 100$	$r_R = 1.26$	$a_R = 0.63$
W_D	$= 5.020 \pm 8\eta + 0.51E$	$0 \leq E \leq 6.5$	$r_D = 1.26$	$a_D = 0.48$
	$= 8.335 \pm 8\eta - 0.092(E-6.5)$	$6.5 \leq E \leq 100$		
W_V	$= 0$	$0 \leq E \leq 8.3$	$r_V = 1.26$	$a_V = 0.63$
	$= -1.0 + 0.12E$	$8.3 \leq E \leq 100$		
V_{SO}	$= 6.0$	$0 \leq E \leq 100$	$r_{SO} = 1.26$	$a_{SO} = 0.63$
	$\beta_2\,(^{165}\mathrm{Ho}) = 0.30$	$\beta_4\,(^{165}\mathrm{Ho}) = -0.02$	(3 States Coupled)	
	$\beta_2\,(^{169}\mathrm{Tm}) = 0.29$	$\beta_4\,(^{169}\mathrm{Tm}) = -0.01$	(5 States Coupled)	

Table 8. Deformed optical potential for proton and neutron reactions on W isotopes over the energy range 10 keV to 100 MeV.

Well Depth (MeV)		Range(MeV)	Geometry (fm)	
V_R	$= 49.73 \pm 16\eta + \Delta V_c - 0.25E$	$0 \leq E \leq 100$	$r_R = 1.26$	$a_R = 0.61$
W_D	$= 4.95 \pm 8\eta + 0.76E$	$0 \leq E \leq 4.5$	$r_D = 1.24$	$a_D = 0.45$
	$= 8.37 \pm 8\eta - 0.10(E - 4.5)$	$4.5 \leq E \leq 100$		
W_V	$= 0$	$0 \leq E \leq 5.8$	$r_V = 1.26$	$a_V = 0.61$
	$= -0.70 + 0.12\ E$	$5.8 \leq E \leq 100$		
V_{SO}	$= 7.5$	$0 \leq E \leq 100$	$r_{SO} = 1.26$	$a_{SO} = 0.61$
		(3 States Coupled)	$r_c = 1.20$	

$\beta_2(^{182}W) = 0.223$ $\beta_4(^{182}W) = -0.054$

$\beta_2(^{183}W) = 0.220$ $\beta_4(^{183}W) = -0.055$

$\beta_2(^{184}W) = 0.209$ $\beta_4(^{184}W) = -0.056$

$\beta_2(^{186}W) = 0.195$ $\beta_4(^{186}W) = -0.057$

Because of a need to provide radiative capture cross section calculations for Eu and Re isotopes, very similar coupled-channels potentials were developed for the two systems covering the neutron energy range up to 20 MeV. The results were utilized in (n,γ) cross section calculations for ^{151,153}Eu[29] and ^{185,187}Re.[30] The parameterizations are included in Tables 9 and 10. Similarly, a requirement to perform (n,xγ) calculations on ^{197}Au led to an investigation of coupled-channels potentials for that system. In that case the potential of Delaroche[31] was found to be highly suitable and was used to perform extensive calculations to 20 MeV.[32] The potential, which was later used to calculate data for the ENDF/B-VI evaluation, is given in Table 11.

An optical model potential coupling in vibrational states was developed for n + ^{208}Pb reactions, primarily for use in analyzing high-resolution (n,xγ) measurements[33] and in performing calculations for the NEA intermediate energy data calculations.[27] Beginning with the coupled-channels neutron potential by Shamu and Young[34] (obtained for experimental neutron data in the range 8.5 to 10 MeV), the potential was modified and extended to both lower and higher neutron energies by matching the available experimental neutron total, elastic scattering, and nonelastic scattering data. The collective model assumed for ^{208}Pb was a first-order vibrational model with complex coupling. Excited states included in these calculations were all the ^{208}Pb states below 10 MeV excitation energy known from various alpha-particle, proton and/or electron inelastic scattering experiments to be highly collective, as follows: discrete states at 2.615(3^-), 4.085(2^+), 4.323(4^+), 4.424(6^+), and 4.610(8^+) MeV; and a low-energy octupole resonance (LEOR) state, centered at 5.38 MeV (3^-). The β_L used for the discrete states were adopted proton values,[35] except at $E_x = 2.615$ MeV where $\beta_3 = 0.115$, and $E_x = 5.38$ where $\beta_3 = 0.10$ was used. The potential that resulted, which is presented in Table 12, gives a reasonable representation of the available neutron total, elastic, and nonelastic scattering data to approximately 200 MeV.

Table 9. Coupled-Channels Optical Model and Deformation Parameters for ^{151,153}Eu Isotopes

	Well Depth (MeV)	Range(MeV)	Geometry (fm)	
V_R	$= 49.8 \pm 16\eta + \Delta V_c - 0.325E_n$	$0 \le E_n \le 20$	$r_R = 1.28$	$a_R = 0.63$
W_D	$= 4.02 \pm 8\eta + 0.51E_n$	$0 \le E_n \le 10$	$r_D = 1.28$	$a_D = 0.48$
	$= 9.12 \pm 8\eta - 0.09(E_n - 10)$	$10 \le E_n \le 20$		
W_V	$= 0$	$0 \le E_n \le 8$	$r_V = 1.28$	$a_V = 0.63$
	$= -2.0 + 0.1E_n$	$8 \le E_n \le 20$		
V_{SO}	$= 6.0$		$r_{SO} = 1.28$	$a_{SO} = 0.63$

$\beta_2(^{151}\text{Eu}) = 0.16$ $\beta_2(^{153}\text{Eu}) = 0.30$ $\beta_4(^{151,153}\text{Eu}) = 0$ (3 States Coupled)

Table 10. Coupled-Channels Optical Model and Deformation Parameters for Neutron Reactions with ^{185,187}Re

	Well Depth (MeV)	Range(MeV)	Geometry (fm)	
V_R	$= 49.8 \pm 16\eta + \Delta V_c - 0.30E_n$	$0 \le E_n \le 20$	$r_R = 1.26$	$a_R = 0.61$
W_D	$= 4.02 \pm 8\eta + 0.75E_n$	$0 \le E_n \le 9$	$r_D = 1.26$	$a_D = 0.47$
	$= 10.77 \pm 8\eta - 0.05(E_n - 9)$	$9 \le E_n \le 20$		
W_V	$= 0$	$0 \le E_n \le 9$	$r_V = 1.26$	$a_V = 0.61$
	$= -1.8 + 0.2E_n$	$9 \le E_n \le 20$		
V_{SO}	$= 7.5$	$0 \le E_n \le 20$	$r_{SO} = 1.26$	$a_{SO} = 0.61$

$\beta_2(^{185}\text{Re}) = 0.22$ $\beta_4(^{185}\text{Re}) = -0.085$ (3 States Coupled)
$\beta_2(^{187}\text{Re}) = 0.21$ $\beta_4(^{187}\text{Re}) = -0.085$ (3 States Coupled)

Table 11. Deformed optical potential for proton and neutron reactions on ^{197}Au over the energy range 10 keV to 57 MeV.

	Well Depth (MeV)	Range(MeV)	Geometry (fm)	
V_R	$= 49.9 \pm 18\eta + \Delta V_c - 0.25E$	$0 \le E \le 57$	$r_R = 1.26$	$a_R = 0.64$
W_D	$= 4.20 \pm 9\eta + 0.50E$	$0 \le E \le 10$	$r_D = 1.26$	$a_D = 0.47$
	$= 9.20 \pm 9\eta - 0.18(E - 10)$	$10 \le E \le 57$		
W_V	$= 0$	$0 \le E \le 10$	$r_V = 1.26$	$a_V = 0.63$
	$= -8.54 + 2.7\sqrt{E}$	$10 \le E \le 57$		
V_{SO}	$= 6.2$	$0 \le E \le 57$	$r_{SO} = 1.12$	$a_{SO} = 0.47$
			$r_c = 1.10$	

$\beta_2 = 0.30$ $\beta_4 = -0.02$ (3 States Coupled)

Table 12. Coupled-channels optical model potential for ^{208}Pb + n calculations over the neutron energy range 1 keV $\leq E_n \leq$ 200 MeV

	Well Depth (MeV)	Range(MeV)	Geometry (fm)	
V_R	$= 50.04 \pm \eta + \Delta V_c - 0.279\, E_n$	$0 < E_n < 60$	$r_R = 1.183$	$a_R = 0.6966$
	$= 111.0925 \pm \eta + \Delta V_c - 19 \ln E_n$	$60 \leq E_n \leq 200$		
W_D	$= 1.000 \pm \eta + 0.2502\, E_n$	$0 < E_n < 14$	$r_D = 1.273$	$a_D = 0.699$
	$= 5.722 \pm \eta - 0.08705\, E_n$	$14 \leq E_n \leq 65.7$		
	$= 0$	$65.7 \leq E_n \leq 200$		
W_V	$= 0$	$0 < E_n < 14.4$	$r_V = 1.273$	$a_V = 0.699$
	$= -2.60 + 0.18\, E_n$	$14.4 \leq E_n \leq 40$		
	$= 2.20 + 0.06\, E_n$	$40 \leq E_n \leq 100$		
	$= 8.20$	$100 \leq E_n \leq 200$		
V_{SO}	$= 6.18$	$0 < E_n < 200$	$r_{SO} = 1.16$	$a_{SO} = 0.677$

B. Actinide Potentials for Incident Neutrons and Protons

Coupled-channels optical potentials have been developed for several actinides in order to provide theoretical analyses[36,37] for ENDF/B-VI evaluations. The analyses use as a starting point the potentials determined by Lagrange,[38] with modifications to enhance agreement with data, especially above 10 MeV. As described above, low-energy resonance data, neutron total and differential elastic and inelastic data were used to optimize the potentials. In this manner potentials have been determined for neutron reactions on ^{235,237,238}U, ^{237}Np, ^{239,242}Pu, and ^{241}Am, and the parameters are listed in Table 13.

In conjunction with our work in extending data libraries to higher energies, a generalized neutron/proton potential was developed for ^{238}U that was used in reaction theory calculations to 100 MeV.[20] This parameterization is included in Table 14.

V. CONCLUSIONS

In this paper a variety of optical model potentials used in reaction theory analyses at Los Alamos National Laboratory have been assembled and presented. While many other potentials have been used that are not included here, the present list is a reasonable sampling of our efforts and includes the systems for which more concentrated efforts have been made. In all cases presented, however, we expect that refinements and improvements can be made. Our hope is that the present parameterizations will be adequate with minimal revision for some applications and will provide an initial basis for future detailed analyses.

The parameterizations included here become progressively less certain as the incident energy increases. In our view substantial additional work is needed at higher energies and into the medium energy region in order to put optical model characterizations on a sound basis. In addition to the Madland potential described here,[11] Kozack and Madland have combined Dirac phenomenology with a relativistic generalization of the Lane model to fit both neutron total cross sections and proton elastic scattering data for ^{208}Pb between 95 and 300 MeV.[39] It is our view that a systematic study utilizing both a Schrödinger and Dirac approach is needed to develop a reliable global nucleon-nucleus optical model potential that extends into the medium energy region.

Table 13. Optical Model and Deformation Parameters Used in the Coupled-Channel Calculations for Actinides

n + ^{235}U Parameters (E_n = 0 - 30 MeV)

Well Depth (MeV)		Range(MeV)	Geometry (fm)	
V_R	$= 46.4 - 0.3E_n$	$0 \leq E_n \leq 30$	$r_R = 1.26$	$a_R = 0.63$
W_D	$= 3.3 + 0.4E_n$	$0 \leq E_n \leq 8$	$r_D = 1.24$	$a_D = 0.50$
	$= 6.5 - 0.046(E_n - 8)$	$8 \leq E_n \leq 30$		
W_V	$= 0$	$0 \leq E_n \leq 7$	$r_V = 1.26$	$a_V = 0.63$
	$= -0.7 + 0.1E_n$	$7 \leq E_n \leq 30$		
V_{SO}	$= 6.2$	$0 \leq E_n \leq 30$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

$\beta_2 = 0.215$ $\beta_4 = 0.075$ (3 States Coupled)

n + ^{237}U Parameters (E_n = 0 - 30 MeV)

Well Depth (MeV)		Range(MeV)	Geometry (fm)	
V_R	$= 46.25 - 0.275E_n$	$0 \leq E_n \leq 30$	$r_R = 1.26$	$a_R = 0.63$
W_D	$= 3.206 + 0.4E_n$	$0 \leq E_n \leq 8$	$r_D = 1.26$	$a_D = 0.52$
	$= 6.406 - 0.046(E_n - 8)$	$8 \leq E_n \leq 30$		
W_V	$= 0$	$0 \leq E_n \leq 8$	$r_V = 1.26$	$a_V = 0.63$
	$= -1.4 + 0.175\ E_n$	$8 \leq E_n \leq 30$		
V_{SO}	$= 6.2$	$0 \leq E_n \leq 30$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

$\beta_2 = 0.195$ $\beta_4 = 0.060$ (6States Coupled)

n + ^{238}U Parameters (E_n = 0 - 30 MeV)

Well Depth (MeV)		Range(MeV)	Geometry (fm)	
V_R	$= 46.2 - 0.275E_n$	$0 \leq E_n \leq 30$	$r_R = 1.26$	$a_R = 0.63$
W_D	$= 3.18 + 0.4E_n$	$0 \leq E_n \leq 8$	$r_D = 1.26$	$a_D = 0.52$
	$= 6.38 - 0.046(E_n - 8)$	$8 \leq E_n \leq 30$		
W_V	$= 0$	$0 \leq E_n \leq 8$	$r_V = 1.26$	$a_V = 0.63$
	$= -1.4 + 0.175\ E_n$	$8 \leq E_n \leq 30$		
V_{SO}	$= 6.2$	$0 \leq E_n \leq 30$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

$\beta_2 = 0.198$ $\beta_4 = 0.057$ (3 States Coupled)

$n + {}^{237}Np$ Parameters (E_n = 0 - 30 MeV)

Well Depth (MeV)		Range(MeV)	Geometry (fm)	
V_R	$= 46.2 - 0.3E_n$	$0 \le E_n \le 30$	$r_R = 1.26$	$a_R = 0.63$
W_D	$= 3.6 + 0.4E_n$	$0 \le E_n \le 8$	$r_D = 1.24$	$a_D = 0.52$
	$= 6.8 - 0.046(E_n - 8)$	$8 \le E_n \le 30$		
W_V	$= 0$	$0 \le E_n \le 7$	$r_V = 1.26$	$a_V = 0.63$
	$= -0.7 + 0.1E_n$	$7 \le E_n \le 30$		
V_{SO}	$= 6.2$	$0 \le E_n \le 30$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

$\beta_2 = 0.214$ $\beta_4 = 0.074$ (3 States Coupled)

$n + {}^{239}Pu$ Parameters (E_n = 0 - 30 MeV)

Well Depth (MeV)		Range(MeV)	Geometry (fm)	
V_R	$= 46.2 - 0.3E_n$	$0 \le E_n \le 30$	$r_R = 1.26$	$a_R = 0.63$
W_D	$= 3.3 + 0.45E_n$	$0 \le E_n \le 8$	$r_D = 1.24$	$a_D = 0.50$
	$= 6.9 - 0.046(E_n - 8)$	$8 \le E_n \le 30$		
W_V	$= 0$	$0 \le E_n \le 7$	$r_V = 1.26$	$a_V = 0.63$
	$= -0.7 + 0.1E_n$	$7 \le E_n \le 30$		
V_{SO}	$= 6.2$	$0 \le E_n \le 30$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

$\beta_2 = 0.205$ $\beta_4 = 0.075$ (7 States Coupled)

$n + {}^{242}Pu$ Parameters (E_n = 0 - 20 MeV)

Well Depth (MeV)		Range(MeV)	Geometry (fm)	
V_R	$= 53.016 - 0.344E_n - 24.5\eta$	$0 \le E_n \le 20$	$r_R = 1.203$	$a_R = 0.30 + 1.492\eta$
W_D	$= 8.905 - 0.255E_n - 13.6\eta$	$0 \le E_n \le 20$	$r_D = 1.306$	
			$a_D = 0.25 + (0.733E\text{-}2)E_n + 1.42\eta$	
W_V	$= 0$	$0 \le E_n \le 2.7$	$r_V = 1.306$	
	$= -0.566 + 0.21E_n$	$2.7 \le E_n \le 20$	$a_V = 0.25 + (0.733E\text{-}2)E_n + 1.42\eta$	
V_{SO}	$= 6.2$	$0 \le E_n \le 20$	$r_{SO} = 1.01$	$a_{SO} = 0.75$

$\beta_2 = 0.260$ $\beta_4 = 0.036$ (5 States Coupled)

$n + {}^{241}Am$ Parameters (E_n = 0 - 30 MeV)

Well Depth (MeV)		Range(MeV)	Geometry (fm)	
V_R	$= 46.23 - 0.3E_n$	$0 \le E_n \le 30$	$r_R = 1.25$	$a_R = 0.60$
W_D	$= 3.314 + 0.45E_n$	$0 \le E_n \le 8$	$r_D = 1.24$	$a_D = 0.55$
	$= 6.914 - 0.046(E_n - 8)$	$8 \le E_n \le 30$		
W_V	$= 0$	$0 \le E_n \le 8$	$r_V = 1.24$	$a_V = 055$
	$= -1.6 + 0.2E_n$	$8 \le E_n \le 30$		
V_{SO}	$= 6.2$	$0 \le E_n \le 30$	$r_{SO} = 1.01$	$a_{SO} = 0.75$

$\beta_2 = 0.210$ $\beta_4 = 0.0756$ (5 States Coupled)

Table 14. Coupled-Channels Optical Model and Deformation Parameters for Neutron and Proton Reactions with ^{238}U to 100 MeV

n + ^{238}U Parameters (E$_{n,p}$ = 0 - 100 MeV)

Well Depth (MeV)	Range(MeV)	Geometry (fm)
$V_R = 49.8 \pm 16\eta + \Delta V_c - 0.29E + 0.0005E^2$	$0 \le E \le 30$	$r_R = 1.26$ $a_R = 0.63$
$W_D = 3.18 \pm 8\eta + 0.4E$	$0 \le E \le 8$	$r_D = 1.26$ $a_D = 0.52$
$= 6.38 - 0.046(E - 8)$	$8 \le E \le 30$	
$W_V = 0$	$0 \le E \le 8$	$r_V = 1.26$ $a_V = 0.63$
$= -0.7 + 0.10\,E$	$8 \le E \le 30$	
$V_{SO} = 6.2$	$0 \le E \le 30$	$r_{SO} = 1.12$ $a_{SO} = 0.47$
$\beta_2 = 0.198$ $\beta_4 = 0.057$	(3 States Coupled)	

REFERENCES

1. P. G. Young, "Global and Local Optical Model Parameterizations," Proc. *Specialists' Meeting on Use of the Optical Model for the Calculation of Neutron Cross Sections below 20 MeV*, sponsored by the NEANDC, Nov. 13-15, 1985, Chateau de la Muette, Paris, France, OECD/NEA report NEANDC-222'U' (1986) p. 127.

2. O. Bersillon, "SCAT2 - Un Programme de Modele Optique Spherique," Commissariat a l'Energie Atomique report CEA-N-2227 (1978), and Proc. ICTP Workshop on *Computation and Analysis of Nuclear Data Relevant to Nuclear Energy and Safety*, 10 February - 13 March, 1992, Trieste, Italy.

3. P. Schwandt, Indiana University, private communication to D. Madland, May 1984.

4. J. Raynal, "Optical Model and Coupled-Channel Calculations in Nuclear Physics," International Atomic Energy Agency report IAEA SMR-9/8 (1970) p. 281.

5. H. Rebel et al., Karlsruhe report KFK-1333 (1971).

6. J. P. Delaroche et al., "The Optical Model with Particular Considerations of the Coupled-Channel Optical Model," IAEA-190 (1976) p. 251.

7. C. M. Perey and F. G. Perey, *Atomic Data and Nuclear Data Tables* **17**, 1 (1976).

8. N. Yamamuro, "Nuclear Cross Section Calculations with a Simplified-Input Version of ELIESE-GNASH Joint Program," Proc. *Int. Conf. on Nucl. Data for Sci. and Tech.*, May 30-June 3, 1988, Mito, Japan (LA-UR 88-1618) (Ed. S. Igarasi, Saikon Publ. Co., Ltd., 1988) p. 489.

9. R. L. Walter and P. P. Guss, "A Global Optical Model for Neutron Scattering for A>53 and 10 MeV<E<80 MeV," Proc. Int. Conf. Nuclear Data for Basic and Applied Science, Santa Fe, N.M., May 13-17 1985 [Gordon and Breach Science Pub., Inc. (1986)] p. 1079.

10. P. Schwandt et al., *Phys. Rev. C.* **26**, 55 (1982).

11. D. G. Madland, "Recent Results in the Development of a Global Medium-Energy Nucleon-Nucleus Optical-Model Potential," Proc. Specialists' Mtg. Preequilibrium Nuclear Reactions, Semmering, Austria, 10-12 February 1988 [Ed: B. Strohmaier, NEANDC-245 'U' (1988)] p. 103.

12. D. G. Madland, personal communication, December, 1986.

13. S. Watanabe, *Nucl. Phys.* **8**, 484 (1958).

14. Ch. Lagrange, O. Bersillon, and D. G. Madland, *Nucl. Sci. Eng.* **83**, 396 (1983).

15. D. G. Madland and P. G. Young, "Neutron-Nucleus Optical Potential for the Actinide Region," Proc. *Int. Conf. on Neutron Physics and Nuclear Data for Reactors and Other Applied Purposes*, Harwell, England, Sept. 25-29, 1978 [published by the OECD (1978)], p. 349.

16. H. Hitzenberger, A. Pavlik, H. Vonach, R. C. Haight, R. O. Nelson, and P. G. Young, "Study of ^{27}Al (n,xγ) Reaction up to $E_n = 400$ MeV," Proc. Int. Conf. on *Nuclear Data for Sci. and Tech.*, 9-13 May 1994, Gatlinburg, Tenn. (LA-UR 93-3808).

17. J. S. Petler, M. S. Islam, R. W. Finlay, and F. S. Dietrich, *Phys. Rev. C* **32**, 673 (1985).

18. F. G. Perey, *Phys. Rev.* **131**, 745 (1963).

19. E. D. Arthur and P. G. Young, "Evaluated Neutron-Induced Cross Sections for ^{54,56}Fe to 40 MeV," Los Alamos National Laboratory report LA-8636-MS (ENDF-304) (1980).

20. P. G. Young, E. D. Arthur, M. Bozoian, T. R. England, G. M. Hale, R. J. LaBauve, R. C. Little, R. E. MacFarlane, D. G. Madland, R. T. Perry, and W. B. Wilson, "Transport Data Libraries for Incident Proton and Neutron Energies to 100-MeV," Los Alamos National Laboratory report LA-11753-MS (July 1990).

21. S. M. Sterbenz, F. B. Bateman, T. M. Lee, R. C. Haight, Rc C. Goeckner, C. E. Brient, S. M. Grimes, H. Vonach, P. Meier-Komor, P. G. Young, and M. B. Chadwick, "The ^{56}Fe(n,xα) Reaction from Threshold to 30 MeV," Proc. Int. Conf. on *Nuclear Data for Sci. and Tech.*, 9-13 May 1994, Gatlinburg, Tenn. (LA-UR-93-3626).

22. E. D. Arthur, P. G. Young, and W. K. Matthes, "Calculation of ^{59}Co Neutron Cross Sections Between 3 and 50 MeV, "Proc. *Symp. on Neutron Cross Sections from 10 to 50 MeV*, BNL (May 1980), p. 751.

23. T. M. Lee, F. B. Bateman, P. G. Young, *et al.*, "The ^{59}Co(n,α) Reaction from Threshold to 30 MeV," Proc. Int. Conf. on *Nuclear Data for Sci. and Tech.*, 9-13 May 1994, Gatlinburg, Tenn. (LA-UR-93-3627).

24. P. G. Young and D. A. Rutherford, "Calculation of Neutron Cross Sections of $^{64, 66, 68}$Zn for Fusion Applications," Proc. *IAEA Advisory Group Mtg. on Nuclear Theory for Fast Neutron Data Evaluation*, 12-16 Oct., 1987, Beijing China (LA-UR 87-3189), International Atomic Energy Agency report IAEA-TECDOC-483 (1988) p. 167.

25. E. D. Arthur, *Nucl. Sci. Eng.* **76**, 137 (1980).

26. H. A. O'Brien, R. O. Nelson, C. M. Laymon, S. A. Wender, and P. G. Young, "Studies of Higher-Order (n,xγ) Reactions in ^{89}Y Targets," Proc. *7th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics*, Asilomar, California, 14-19 October 1990, LA-UR-90-3498 (October, 1990).

27. P. G. Young and M. B. Chadwick, "Calculation of Proton and Neutron Emission Spectra from Proton Reactions with ^{90}Zr and ^{208}Pb to 160 MeV with the GNASH Code", Proc. OECD Nuclear Energy Agency Specialists Meeting on *Intermediate Energy Nuclear Data*, May 30 - June 1, 1994, Issy-les-Moulineaux, France, to be published (LA-UR-94-1830).

28. E. D. Arthur and C. A. Philis, "New Calculations of Neutron-Induced Cross Sections on Tungsten Isotopes," in *Applied Nuclear Data Research and Development, July 1 - Sept. 30, 1980*, Los Alamos Scientific Laboratory report LA-8630-PR (1980) p. 2.

29. R. L. Macklin and P. G. Young, *Nucl. Sci. Eng.* **95**, 189 (1987).

30. R. L. Macklin and P. G. Young, *Nucl. Sci. Eng.* **97**, 239 (1987).

31. J. P. Delaroche, "Potentiel Potique Nucleon-^{197}Au Entre 10 keV et 57 MeV," Proc. *Int. Conf. on Neutron Physics and Nuclear Data for Reactors and Other Applied Purposes*, Harwell, England, Sept. 25-29, 1978 [published by the OECD (1978)], p. 366.

32. P. G. Young and E. D. Arthur, "Analysis of n + ^{197}Au Cross Sections for E_n = 0.01-209 MeV," Proc. *5th Int. Symp. on Capture Gamma Ray Spectroscopy and Related Topics*, Oak Ridge Nat. Lab., Knoxville, Tenn., Sept. 9-14, 1984, AIP Proceedings No. 125, p. 530 (LA-UR-84-2767).

33. H. Vonach, A. Pavlik, M. B. Chadwick, R. C. Haight, R. O. Nelson, S. A. Wender, and P. G. Young, "^{207,208}Pb(n,xnγ) Reactions for Neutron Energies up to 200 MeV," accepted for publication in *Phys. Rev. C* (1994).

34. R. E. Shamu and P. G. Young, *J. Phys. G: Nucl. Part. Phys.* **19**, L169 (1993).

35. M. J. Martin, *Nucl. Data Sheets* **47**, 797 (1986).

36. P. G. Young and E. D. Arthur, "Calculation of ^{235}U(n,n') Cross Sections for ENDF/B-VI, Proc. *Int. Conf. on Nucl. Data for Sci. and Tech.*, May 30-June 3, 1988, Mito, Japan (LA-UR-99-1740) (Ed. S. Igarasi, Saikon Publ. Co., Ltd., 1988), p. 603.

37. P. G. Young and E. D. Arthur, "Theoretical Analyses of (n,xn) Reactions on ^{235}U, ^{238}U, ^{237}Np, and ^{239}Pu for ENDF/B-VI," Proc. Int. Conf. on Nuclear Data for Science and Technology, Jülich, Germany, 13-17 May 1991 (LA-UR-91-1424) [Ed. S. M. Qaim, Springer-Verlag, Germany (1992)], p. 894.

38. G. Haouat, J. Lachkar, Ch. Lagrange et al., *Nucl. Sci. Eng.* **81**, 491 (1982).

39. R. Kozack and D. G. Madland, *Phys. Rev. C.* **39**, 1461 (1990).