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Calculation and evaluation of neutron-induced reactions on ^{60}Ni below 150 MeV

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Abstract

Based on the experimental data of total, nonelastic, elastic cross section and elastic-scattering angular distributions for n+^{60}Ni reactions, a set of neutron optical model potential parameters is obtained in the region of incident neutron energy from 0.456 MeV to 150 MeV. The reaction cross sections, angular distributions, energy spectra, gamma-ray production cross sections, gamma-ray production energy spectra, are calculated and evaluated by optical model, distorted wave Born approximation theory, Hauser–Feshbach theory, exciton model and cascade mechanism inside nucleus. The theoretical model code UNF and MEND are used in the neutron incident energies below 20 MeV and $20 < E_n \leqslant 150$ MeV, respectively. The results are compared with existing experimental data and other evaluated data from ENBF/B-6 and JENDL-3 and in agreement with each other within the uncertainties of these evaluation and measurements. Finally the covariances for the important neutron cross sections are estimated using SPC code based on the available experimental data.
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1. Introduction

Nickel is one of the very important structure material in nuclear engineering. With the development of the reactor physics and the clean nuclear power systems that employ accelerator-driven technologies (ADS), more accurate nuclear data are needed. To meet these needs, the nuclear reaction data of cross sections, angular distributions, energy spectra and gamma-ray production cross sections are necessary to calculate and evaluate up to 150 MeV. On the other hand, with the development of computer technology, the covariance matrix of nuclear data becomes more and more important. The covariance data can describe not only the accuracy of the data but also the correlation of them.

In this work, the theoretical model codes UNF and MEND are used to calculate and evaluate all neutron-induced cross sections and energy spectra for energies below 20 MeV and $20 < E_n \leqslant 150$ MeV, respectively. The optical model potential parameters are obtained from experimental data of total, nonelastic elastic cross sections and elastic-scattering angular distributions. The direct inelastic scattering cross sections and angular distributions for discrete levels are calculated by the distorted wave Born approximation theory. For energy above 20 MeV, the double differential cross sections of emission neutrons and protons are obtained from Kalbach systematics. The covariances of the important neutron cross sections are estimated using SPC code based on the available experimental data.

2. Theoretical calculation and parameter adjusting

To obtain a set of neutron optical model potential parameters, the APMN [1] code was used in present work. With this code, the best potential neutron optical model parameters can be automatically searched to fit with the relevant experimental data of total cross sections, nonelastic scattering

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cross sections, elastic-scattering cross sections and elastic-scattering angular distributions. The optical model potentials considered here are the Woods–Saxon form for the real part and the Woods–Saxon and derivative Woods–Saxon form for the imaginary parts corresponding to the volume and surface absorptions, respectively and the Thomas form for the spin–orbit part.

The experimental data of total cross sections, nonelastic elastic scattering cross sections and elastic-scattering angular distributions are taken from the EXFOR library. Since there are no any experimental data of nonelastic-scattering cross sections and total cross sections above energies of 28 MeV, the experimental data above energies of 28 MeV for natural Ni are used. There are some experimental data of elastic scattering cross sections and elastic-scattering angular distributions for ^{60}Ni given in energies up to 24 MeV. For total cross sections, the data were mainly taken from [2–6]. For nonelastic elastic scattering cross sections above 20 MeV, Pearlstein's systematics [7] and evaluation of ENDF/B-6 are referred.

The total cross sections, nonelastic elastic-scattering cross sections and elastic-scattering angular distributions mentioned above were used to obtain a set of neutron optical model potential parameters of ^{60}Ni in incident neutron energies from 0.456 MeV to 150 MeV. The optical model potential parameters for charged particles are taken from [8]. The optical model potential parameters are adjusted to minimize a quantity called χ^2, which represents the deviation of the theoretical calculated results from the experimental values.

The energy dependencies of the potential depths and optimum neutron optical potential parameters of ^{60}Ni are expressed as follows:

The real part of the optical potential:

$$V = V_0 + V_1 E + V_2 E^2 + V_3 (N - Z)/A. \tag{1}$$

The imaginary part of the surface absorption:

$$W_s = W_0 + W_1 E + W_2 (N - Z)/A. \tag{2}$$

The imaginary part of the volume absorption:

$$W_v = U_0 + U_1 E + U_2 E^2, \tag{3}$$

where Z, N and A are the charge, neutron and mass numbers of the target, respectively and E is the incident neutron energy.

The spin–orbit couple potential: U_{so}.

The radius and the diffusive width of the real part, the surface absorption, the volume absorption and the spin–orbit couple potential: r_r, r_s, r_v, r_{so}; a_r, a_s, a_v and a_{so}, respectively.

The units of the potential V, W_s, W_v, U_{so} are in MeV, the lengths r_r, r_s, r_v, r_{so}, a_r, a_s, a_v, a_{so} are in fermis, the energy E is in MeV.

The optical model potential parameter obtained for ^{60}Ni is given in Table 1.

The total cross section calculated with the parameters listed in Table 1 is compared with available experimental data and other evaluations, shown in Figs. 1a and 1b. A

Table 1
Optical model potential parameters

	$E \leqslant 20$ MeV	$E > 20$ MeV		$E \leqslant 20$ MeV	$E > 20$ MeV
V_0	53.987732	54.184853	U_{so}	6.2	6.2
V_1	−0.302761	−0.310020	r_r	1.186454	1.180355
V_2	−0.004315	0.000362	r_s	1.276851	1.307949
V_3	−24.0	−24.0	r_v	1.467827	1.200871
W_0	12.018859	12.946355	r_{so}	1.186454	1.180355
W_1	−0.215356	−0.214055	a_r	0.719689	0.625429
W_2	−12.0	−12.0	a_s	0.545279	0.558398
U_0	−1.103158	−2.832649	a_v	0.300000	0.765894
U_1	0.174809	0.163131	a_{so}	0.75	0.75
U_2	−0.004977	−0.000432			

reasonable agreement of the calculations with the experimental data is obtained. It is noted that the experimental data show small structure below 5.0 MeV and the optical model cannot describe those structures, the reasonable calculated results just pass through the experimental data.

Nonelastic elastic-scattering cross sections for natural nickel were used for neutron energies above 4 MeV, as in this energy region the cross section difference between ^{60}Ni and ^{nat}Ni is expected to be smaller than the uncertainty of the measurements. A comparison of the calculated cross sections with experimental data [9] for natural nickel and Pearlstein's systematics is given in Fig. 2 and a good agreement is obtained.

A comparison of calculated results of neutron elastic-scattering angular distribution with experimental data is given in Fig. 3 taking the calculated results above 4.92 MeV as an example. The calculated results fit well experimental data.

These reasonable agreement of mentioned above indicated and allowed us to apply the optical model with the parameters to calculate the total cross sections, nonelastic elastic-scattering cross sections, elastic scattering angular distributions and the transmission coefficient of the compound nucleus and the preequilibrium emission process in the whole energy range.

In order to calculate all neutron-induced cross sections and energy spectra for ^{60}Ni in the energy below 150 MeV, theoretical model code UNF and MEND are used below 20 MeV and $20 < E_n \leqslant 150$ MeV, respectively.

UNF includes optical model, the Hauser–Feshbach theory with width fluctuation correction and the exciton model with parity and angular momentum conservation. Based on the leading particle model, the double differential cross section for all kinds of particles is obtained. UNF provides all reaction cross sections, angular distribution, double differential cross section, gamma-ray production cross sections and gamma-ray production energy spectrum below 20 MeV.

MEND can give all kinds of reaction cross sections and energy spectra for six outgoing light particles (n, p, α, d, t and ^{3}He) and various residual nuclei in the energy range up to 250 MeV. It includes optical model, intranuclear cascade, equilibrium and preequilibrium reaction mechanisms. The double differential cross sections for emission neutrons

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