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Calculation and analysis for p + ^{50,52,53,54,nat}Cr reactions

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ABSTRACT

All cross sections, elastic and inelastic scattering angular distributions, energy spectra and double differential cross sections of six outgoing particles (n, p, d, t, helium-3 and α) for p + ^{50,52,53,54,nat}Cr reactions are calculated and analyzed at incident proton energies below 150 MeV. The optical model, the intra-nuclear cascade model, evaporation model, Hauser–Feshbach theory with width fluctuation correction, exciton model which includes the improved Iwamoto–Harada model and distorted Born approximation theory are involved in the calculation. The calculated results are compared with existing experimental data.

1. Introduction

Besides of a general interest in basic nuclear physics, cross-sections for nuclear reactions induced by medium-energy protons are of increasing importance for a wide variety of applications. The development of ADS requires much accurate nuclear data, which include not only the common cross sections, but also the energy spectra and double differential cross section of outgoing particles (neutron, proton, deuteron, triton, helium-3, and alpha) of the reaction induced by neutron or proton.

The development of high-quality nuclear data for Cr is particularly important due to its role as an important adding substance in the structure material of many accelerator-driven system designs. Its percentage content is usually more than 13%). Nature chromium is consisted of four isotopes including ^{50}Cr (4.345%), ^{52}Cr (83.789%), ^{53}Cr (9.501%), and ^{54}Cr (2.365%).

In this work, the optical model potential parameters are obtained by reproducing the experimental data of non-elastic cross-sections and elastic scattering angular distributions for p + ^{48}Ti, p + ^{51}V and p + ^{52}Cr reactions. All the proton-induced cross-sections, angular distributions, energy spectra as well as double differential cross sections for neutron, proton, deuteron, triton, helium and alpha particle emissions are consistently calculated by nuclear theoretical models which integrate optical model, intra-nuclear cascade model, direct reaction, pre-equilibrium and equilibrium reaction theories.

An introduction of the theoretical models and parameters used in this work is given in Section 2. The analysis and comparison of the calculated results with existing experimental data is given in Section 3. And some conclusions are shown in Section 4.

2. Theoretical models and parameters

2.1. Optical model and optical potential parameters

The optical model (Becchetti and Greenlees, 1969; Woods and Saxon, 1954) is used to analyze the measured proton-induced non-elastic reaction cross sections, elastic scattering angular distributions, and calculate the transmission coefficient of the compound nucleus and pre-equilibrium emission process. About the optical potential, a Woods–Saxon (Becchetti and Greenlees, 1969) form is considered for the real part. And for the imaginary parts corresponding to the volume and surface absorptions, the Woods–Saxon form and derivative Woods–Saxon form are taken into account, respectively. The spin–orbit potential is taken as a Thomas form.

The optical potential can be expressed as

$$V(r) = V_r(r) + i[W_s(r) + W_v(r)] + V_{so}(r) + V_{so}(r) + V_c(r), \quad (1)$$

where $V_r(r)$ is the real part potential, $W_s(r)$ and $W_v(r)$ are surface and volume absorption of the imaginary parts, $V_{SO}(r)$ is the spin–orbit part, and $V_c(r)$ is the Coulomb potential.

The form factor of Woods–Saxon is

$$f_i(r) = [1 + \exp(r - R_i)/a_i]^{-1}, \quad i = r, s, v, so, \quad (2)$$

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where $R_i = r_i A^{1/3}$, $i = r, s, v, so$ and $a_k = a_{k0} + a_{k1}(N - Z)/A$, $k = s, v, r_r, r_s$, r_v and r_{so} are radii of the real part, the surface and volume absorption of imaginary part, the spin–orbit part and the coulomb part, respectively. a_r, a_s, a_v and a_{so} are diffusive widths of them, respectively. Z, N and A are charge, neutron, and mass number of the target nucleus, respectively. E is the incident proton energy in laboratory system.

The real part potential is

$$V_r(r) = -V_r(E) f_r(r). \tag{3}$$

The imaginary surface absorption is

$$W_s(r) = -4 a_s W_s(E) \frac{df_s(r)}{dr}. \tag{4}$$

The imaginary volume absorption is

$$W_v(r) = -W_v(E) f_v(r). \tag{5}$$

The spin–orbit potential is

$$V_{so}(r) = -\frac{2V_{so}}{a_{so} r} \frac{df_{so}(r)}{dr} \tag{6}$$

The Coulomb potential is

$$V_c r = \begin{cases} 0.7720448 \frac{Z}{R_c}\left(3 - \frac{r^2}{R_c^2}\right) & \text{if } r < R_c \\ \frac{1.440975Z}{r} & \text{if } r \geqslant R_c \end{cases}. \tag{7}$$

In Eqs. (3)–(5), the items $V_r(E)$, $W_s(E)$ and $W_v(E)$ related to the incident energy can be written as following:

$$V_r(E) = V_0 + V_1 E + V_2 E^2 + V_3(N - Z)/A + V_4 Z/A^{1/3}. \tag{8}$$

$$W_s(E) = \max\{0, W_0 + W_1(E) + W_2(N - Z)/A\}. \tag{9}$$

$$W_v(E) = \max\{0, U_0 + U_1 E + U_2 E^2\} \tag{10}$$

V_0, V_1, V_2, V_3, V_4, W_0, W_1, W_2, U_0, U_1, U_2, r_r, r_s, r_v, r_{so}, r_c, a_r, a_{s0}, a_{s1}, a_{v0}, a_{v1} and a_{so} are adjustable parameters. The unit of potential parameters including V_r, W_s, W_v, V_{so} and V_C is in MeV. The unit of length parameters including r_r, r_s, r_v, r_{so}, r_c, a_r, a_{s0}, a_{s1}, a_{v0}, a_{v1} and a_{so} is in *fm*.

Based on the experimental data of non-elastic cross sections and elastic scattering angular distributions for p + ^{48}Ti, p + ^{51}V and p + ^{52}Cr reactions (Lamba et al., 1968; Fulmer, 1962; Peterson, 1969; Shore et al., 1961; Lombardi et al., 1972; Fulmer and Goodman, 1960; Varner, 1986; Sakaguchi, 1982; Sakaguchi et al., 1979; Antropov et al., 1976, 1974; Demay et al., 1967; Comparat et al., 1974; Maripuu, 1970; Rao et al., 1994; Woo et al., 1984; Maripuu et al., 1970; Noro et al., 1981) at incident proton energies below 150 MeV, a set of optical potential parameters for p + ^{52}Cr reaction is obtained using the code APMN (Shen, 2002), as shown in Table 1. The best optical potential parameters are reached by minimizing the quantity called χ^2 which represents the deviation of the calculated results from the experiment data. Since the optical potential depths are dependence of mass number A and neutron number N, this set of optical potential parameters can also be used for p + ^{50,53,54}Cr reactions. The neutron optical potential parameters are taken from the reference (Han, 2005). The deuteron optical potential parameters are taken from the reference (Han et al., 2006). We take global phenomenological optical potential for ^{3}He from the reference (Xu et al., 2011), and the optical potential for t and alpha particle are the same as that for ^{3}He.

Table 1
Optical model potential parameters.

V_0	53.2535	r_r	1.1852
V_1	−0.3724	r_s	1.3087
V_2	0.00006429	r_v	1.3375
V_3	23.1103	r_{so}	1.01
V_4	0.4215	r_c	1.25
W_0	11.9163	a_r	0.6974
W_1	−0.2426	a_{s0}	0.4203
W_2	10.4859	a_{v0}	0.4946
U_0	−1.16175	a_{so}	0.75
U_1	0.2260	a_{s1}	0.70
U_2	−0.0008091	a_{v1}	0.70
V_{so}	6.20		

2.2. Direct inelastic scattering for discrete levels

Direct inelastic scattering cross sections and angular distributions in the low-lying excited states are very important. Direct reaction cross sections are calculated using the code DWUCK4 (Kunz, 1994) based on the distorted wave Born approximation theory. In the calculation, the obtained optical potential parameters are used. The discrete energy levels from the ground state (0^+) to the 27th excited state (4.1297^+) are considered for ^{50}Cr, ground state (0^+) to the 21th excited state (4.6274^+) for ^{52}Cr, ground state ($0.5640\,1/2^-$) to the 16th excited state ($2.2332\,9/2^-$) for ^{53}Cr, ground state (0^+) to the second excited state ($0.8349\,2^+$) for ^{54}Cr. Since there is much overlapping at high excited state, its level density has to be taken into account.

2.3. The pre-equilibrium and equilibrium processes

The pre-equilibrium statistical theory based on exciton model, evaporation models and Hauser–Feshbach theory with width fluctuation correction (Griffin, 1966; Mantzouranis et al., 1976; Sun et al., 1982), and intra-nuclear cascade model (Chen et al., 1968) are used to describe the nuclear reaction pre-equilibrium and equilibrium decay processes, respectively.

The nuclear reaction theoretical models code MEND (Cai, 2006) can give all kinds of reaction cross-sections and energy spectra for six outgoing particles (n, p, d, t, ^{3}He and α) and various residual nuclei, was developed. It includes the optical model, intra-nuclear cascade model, equilibrium and pre-equilibrium reaction theories. The contribution of direct reaction is treated as a part of input file to MEND code. The improved Iwamoto–Harada model (Iwamoto and Harada, 1982; Zhang et al., 1992) for composite particle (d, t, ^{3}He and α) emissions and Pauli principle in the calculation of exciton state densities are accommodated. The angular dependent part of double differential cross sections for six outgoing particles (n, p, d, t, ^{3}He and α) are obtained from Kalbach phenomenological approach. It is based on a systematical study of a wide variety of experimental data.

The Kalbach systematical parameter K used in two body reaction residual interaction plays an important role in nuclear reaction, which determines the contribution of equilibrium and pre-equilibrium decay processes. According to the experimental data of reaction cross-sections, K is 1500 MeV^3 in this work. The level density adopts Gilbert–Cameron formula (Gilbert and Cameron, 1965) in lower energies region, and the Ignatyuk model (Ignatyuk et al., 1975), which includes the washing out of shell effects with increasing excitation energy, is matched continuously onto low-lying experimental discrete level in the higher energies region. The level density parameters a and pair correction parameter$\Delta$of the back-shifted Fermi gas level density are given in Tables 2.1 and 2.2 for low energy are adjusted to more fit with experimental data of cross sections.

3. Calculated results and analysis

The comparison of the calculated results of non-elastic cross section with experimental data (Menet et al., 1971) for p + ^{52}Cr