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26 MeV Protons and FKK Model Analysis**

Y. Watanabe, A. Aoto, H. Kashimoto, S. Chiba,
T. Fukahori, K. Hasegawa, M. Mizumoto
S. Meigo, M. Sugimoto, Y. Yamanouti, N. Koori,
P.E. Hodgson, M.B. Chadwick

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MEASUREMENT OF DOUBLE DIFFERENTIAL CHARGED-PARTICLE EMISSION CROSS SECTIONS FOR REACTIONS INDUCED BY 26 MEV PROTONS AND FKK MODEL ANALYSIS

Y. Watanabe, A. Aoto, and H. Kashimoto

Department of Energy Conversion Engineering, Kyushu University, Kasuga, Fukuoka 816, Japan

S. Chiba, T. Fukahori, K. Hasegawa, M. Mizumoto, S. Meigo, M. Sugimoto and Y. Yamanouti
Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-11, Japan

N. Koori

Faculty of Integrated Arts and Sciences, The University of Tokushima, Tokushima 770, Japan

M.B. Chadwick

Nuclear Data Group, Lawrence Livermore National Laboratory, Livermore, California 94551, U.S.A.

P.E. Hodgson

Nuclear Physics Laboratory, Physics Department, University of Oxford, Oxford, OX1 3RH, UK

ABSTRACT

Double differential charged-particle emission cross sections of proton-induced reactions have been measured for ^{nat}C , ^{27}Al , ^{nat}Si , ^{98}Mo , ^{106}Pd , ^{159}Tb and ^{181}Ta at energies around 26 MeV. Several (p,p') and (p,n) data for ^{98}Mo and ^{106}Pd in the incident energy range from 12 to 26 MeV are analysed in terms of the Feshbach-Kerman-Koonin model, in order to study preequilibrium nucleon emission from nucleon-induced reactions.

I. INTRODUCTION

The quantum-mechanical theory of Feshbach, Kerman and Koonin¹ (FKK) has been successfully applied² to preequilibrium nucleon emission from nucleon-induced reactions at incident energies up to 200 MeV and is regarded as one of the most promising models for intermediate energy nuclear data evaluation. To apply it to future nuclear data evaluation, we shall need further studies to provide a reliable set of the model parameters involving the strength V_0 of effective N-N interaction which is treated as the only free parameter. Thus we measured double differential charged-

particle emission cross sections (DDXs) of proton-induced reactions for several targets at energies around 26 MeV, in order to investigate the sensitivity to the model parameters and the dependence of the V_0 values on the incident energy and target mass number. The results of analyses of the (p,p') data for ^{98}Mo and ^{106}Pd are reported, together with those of the earlier (p,p') data^{3,4} for the same targets at lower energies from 12 to 18 MeV and the (p,n) data^{5,6} for both targets at the same incident energies.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experiment was performed using a proton beam from the JAERI tandem accelerator. The details of the experimental procedure and the data processing have been reported elsewhere⁷. Energy distributions of protons, deuterons, tritons, and alphas emitted from proton-induced reactions were measured for the following targets and incident energies: ^{nat}Si and ^{98}Mo at 25.6 MeV, and ^{nat}C , ^{27}Al , ^{106}Pd , ^{159}Tb , and ^{181}Ta at 26 MeV. All targets were self-supporting foils with their thickness of 0.1 to 1.05 mg/cm², depending on the targets. A ΔE -E counter telescope consisting of three silicon surface barrier detectors of 20 μm , 300 μm and 5000

Fig.1 The DDXs of (p,xp), (p,xd), and (p,xα) reactions for ^{106}Pd at 26 MeV. Each line illustrated in (a) is the calculated result with the FKK-GNASH code. See text for details of the calculation.

μm thick was used for these measurements at outgoing angles in intervals of 10° between 30° or 40° and 150° .

Some typical examples of the energy spectra are shown for $^{106}\text{Pd}(p, xp)$, (p, xd) , and $(p, x\alpha)$ measured at 70° in Fig.1. It should be noted that protons and deuterons with outgoing energies below about 7 MeV and 9 MeV, respectively, are not detected because of the threshold energy restricted by the thickness ($300\ \mu\text{m}$) of the ΔE -detector.

III. THEORETICAL ANALYSIS WITH FKK MODEL AND DISCUSSIONS

We have analysed preequilibrium nucleon emission from proton-induced reactions on ^{98}Mo and ^{106}Pd at energies from 12 to 26 MeV using the FKK-GNASH code⁸, applying the subtraction method⁹ to isolate the multistep direct (MSD) component alone by taking the forward and backward difference in the cross sections for complementary C.M. angle pairs, e.g. 30° and 150° . Only the one-step direct process is taken into account, since the MSD components involving more than two-step process were found to be negligibly small at low incident energies of our interest. The strength V_0 of a Yukawa potential with 1 fm range is regarded as the only free parameter in the FKK calculation.

Fig.2 The results of the subtraction method analysis for the (p,p') and (p,n) on ^{98}Mo at 25.6 MeV. The experimental (p,n) data are taken from ref. 5. For details see text.

Fig.3 The extracted strength V_0 as a function of incident energy.

The following values were used as the other parameters: the optical potential parameters of Walter and Guss¹⁰, the single particle level density parameter $g=A/13$, the spin cut-off parameter given in ref.¹¹, no pairing correction, and nonlocality correction¹² with the range $\beta = 0.85\ \text{fm}$.

The results for $^{98}\text{Mo}(p,p')$ and (p,n) reactions at 25.6 MeV are shown in Fig.2. Both the calculated spectra are in excellent agreement with the experimental ones in the continuum except for the high energy parts. We extract the strength V_0 by averaging the best fit V_0 s for all angle pairs. Similar analysis for ^{93}Nb was applied to some (n,n') reactions¹³ in the same incident energy range and the (p,p') reaction³ at 18 MeV.

In Fig.3, all the extracted strength V_0 s are plotted as a function of incident energy. First, the V_0 values for (p,p') are approximately proportional to $E_{\text{inc}}^{-1/2}$, where E_{inc} is the incident energy, as was found in an earlier work for (n,n') at low energies⁸ and a more recent work¹⁴ for higher proton energies up to 200 MeV using the same code. In the present work, however, the V_0 s for (n,n') have a little weaker dependence and smaller values than those for (p,p') . This might be related to the difference in the kinetic energies of incident nucleons near the surface region of nucleus where direct inelastic scattering occurs strongly, originating from the Coulomb effect and the asymmetry term of optical potentials. Next, the V_0 values extracted from the (p,n) reactions are about a half those from the (p,p') reactions for the same targets and incident energies. This is because a 1-component state density is used for both calculations. If a 2-component state density treating protons and neutrons separately is used, both values are expected to become closer because of the difference by a factor of about two in the number of 1p-1h residual states between (p,p') and (p,n) reactions as was considered in ref. 14,15.

The calculated total nucleon emission spectra including multistep compound (MSC) and equilibrium components are compared with the experimental ones in Fig.1(a) and Fig.4. Collective excitation to the first 2^+ and 3^- states is also taken into account by a DWBA calculation using collective form factors with experimental deformation parameters. The

Fig.4 The experimental angle-integrated (p,xp) and (p,xn) for ^{98}Mo at 25.6 MeV and the calculated ones with the FKK-GNASH code.

measured angle-integrated (p,p') and (p,n) spectra for ^{98}Mo are reproduced well using the FKK-GNASH code, although there is some underestimate at low outgoing energies below 10 MeV. The disagreement might be due to enhanced proton emission from T_2 states of the composite nucleus under the isospin conservation^{4,16} or possible preequilibrium nucleon emission from MSC stages following the so-called P to Q transition. Further detailed consideration will be required to find the reason of the disagreement.

The details of the above-mentioned analysis will be given elsewhere.

IV. CONCLUDING REMARKS

The DDXs from proton-induced reactions were measured for several nuclei with the mass number ranging from natC to ^{181}Ta at incident energies around 26 MeV. The FKK model was applied to the analysis of (p,p') and (p,n) reactions on ^{98}Mo and ^{106}Pd at incident energies ranging from 12 to 26 MeV, as well as the ^{93}Nb (n,n') reactions. The strength V_0 of effective N-N interaction was extracted using the subtraction method, and was found to have the same energy dependence as in the previous analyses with the same FKK-GNASH code. In addition, we found that there is a distinct difference in the V_0 s between (p,p') and (p,n) even at the same energy and target and the V_0 s for (p,p') are larger than those for (n,n') at low incident energies below 18 MeV. In the future, it will be necessary to determine a reliable systematics of the free parameter V_0 over a wide range of incident energy and mass number through FKK analyses of various data using the same code with the consistent parameter set.

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