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Energy dependence of the zero-range normalization constant for the (p,t) reaction at incident energies of 34.9, 45.1, 54.7, and 65.0 MeV

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Angular distributions of ^{124}Sn(p,t) reactions to low-lying states of ^{122}Sn were measured at $E_p=34.9$, 45.1, 54.7, and 65.0 MeV and analyzed with zero-range distorted-wave Born approximation theory. It is found that the zero-range normalization constant D_0^2 is smoothly decreasing as a function of the incident proton energy in the several tens of MeV region of bombarding energy.

[NUCLEAR REACTIONS ^{124}Sn(p,t), $E=34.9$, 45.1, 54.7, and 65.0 MeV; measured (E_t,θ_t); DWBA analysis; deduced zero-range normalization factor.]

For the direct (p,t) reaction, there appears in the zero-range distorted-wave Born approximation expression for the amplitude a universal normalization constant D_0^2 which depends principally on the structure factor of the incident and outgoing projectiles and on the nucleon-nucleon interaction. The determination of this constant is important not only for the discussion of the reaction mechanism, but also for the nuclear structure studies with (p,t) reactions as a probe. Empirical normalization constants deduced previously fall in the range between $(10-50)\times10^4$ fm^3 MeV^2.[1–6]

Recent investigations of (p,t) reactions on ^{12}C, ^{56}Fe, ^{208}Pb,[7] and Sn isotopes[8] at $E_p=80-90$ MeV have shown that the theoretical cross section values are factors of 3 to 10 smaller than the estimated values in the 40 MeV region, where a D_0^2 value of $22-25$ was used. This experimental fact implies small D_0^2 values at $80-90$ MeV bombarding energy.

In all the previous studies, the data were taken with different experimental conditions. The analyses also differed from each other in the choice of the optical model parameters, the structure factor, and the method of constructing the form factor.

To discuss systematically the energy dependence of this constant, we have decided to measure the differential cross sections of (p,t) reactions on one target nucleus under the same experimental condition between 35 and 65 MeV bombarding energy where data are relatively scarce, and to analyze the data on the same theoretical basis. For the target nucleus, ^{124}Sn is chosen because the wave functions for the low-lying states are well known and the value of the deformation parameter of the 2_1^+ state is the smallest in this mass region. This latter fact results in rather weak two-step processes such as (p,p',t) and (p,t',t) reactions.[9] The incident proton energy was varied from 35 at 65 MeV in 10 MeV steps, which connects three energy regions, i.e., $E_p=20$, 40, and 80 MeV, where previous results have been reported. The experiments were performed at the AVF cyclotron facility of Osaka University.

The accelerated protons were momentum-analyzed and bombarded an enriched ^{124}Sn metal target of 0.7 mg/cm^2 thickness. Emitted tritons were analyzed using the quadrupole-dipole-multipole-dipolar-quadrupole spectrograph RAIDEN[10] with a focal plane detector system[11] which consists of a 1.52 m single-wire position-sensitive proportional counter, two ΔE proportional counters, and an E plastic scintillation counter. The data were measured for the ground state to the 10_1^+ state at 2.775 (10) MeV. In the present paper, the differential cross sections of the ground 0^+ and the first excited 2^+ states (1.140 MeV) are analyzed by the

DWBA formalism.

The measured angular distributions of ^{124}Sn(p,t) reactions to the ground and the first excited 2^+ states at the incident energies of 34.9, 45.1, 54.7, and 65.0 MeV are shown in Fig. 1. The shape of these angular distributions at the forward angle region changes strongly as a function of the incident energy, although the oscillating pattern in the angular region beyond ~20 degrees changes smoothly.

The (p,t) reaction cross sections are calculated with the zero-range DWBA formalism using the code DWUCK.[12] The wave functions of the ground 0^+ and the first excited 2^+ states are constructed with the BCS random-phase-approximation model.[13] The pairing parameters are taken to be 26/nucleon and the strengths of the Q-Q and P_2-P_2 force are set to reproduce the energy of the first excited state as in the usual procedure.[13] The single particle orbits considered are $0g_{9/2}$, $1d_{5/2}$, $0g_{7/2}$, $2s_{1/2}$, $1d_{3/2}$, and $0h_{11/2}$ for neutrons, and $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$, $0g_{9/2}$, $1d_{5/2}$, and $0g_{7/2}$ for protons. For the proton optical potentials the average parameters of Becchetti and Greenlees[14] and Fulmer *et al.*[15] are used. Since the energy dependence of the triton optical potential is not known at present, the Flynn's potential[16] ($V=166.3$ MeV, $W=15.2$ fm, $r=1.16$ fm, $r'=1.498$ fm, $a_r=0.752$ fm, $a_i=0.817$ fm, and $r_c=1.25$ fm) is used at all incident energies. The idea of using only one potential set for all the incident energies is in part supported by the fact that the (p,t) reactions on ^{56}Fe and ^{208}Pb at 80 MeV (Ref. 7) are reasonably reproduced by using the triton potentials having a similar volume integral of about 420 MeV fm^3 as that in the low energy region. The fact that the energy dependence of the ^{3}He optical potentials in this en-

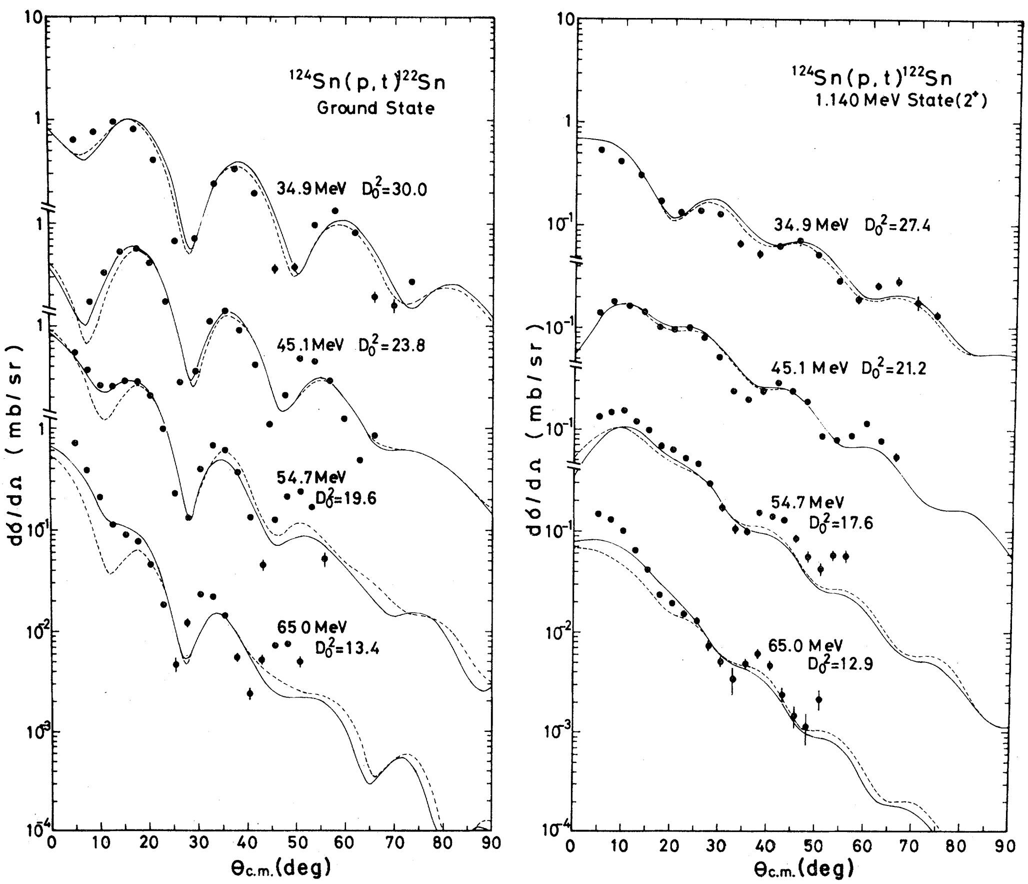

FIG. 1. Angular distributions of ^{124}Sn$(p,t)^{122}$Sn reactions to the ground and the first excited 2^+ states at incident energies of 34.9, 45.1, 54.7, and 65.0 MeV. Solid and dashed curves show the zero-range DWBA predictions with the proton optical potentials of Fulmer *et al.* and Becchetti and Greenlees, respectively. See text.

ergy region is rather weak[17] gives further support to the present treatment.

The zero-range normalization constant D_0^2 for the (p,t) reaction with the code DWUCK is defined[18] by the equation

$$\frac{d\sigma}{d\Omega}=\left[\frac{\pi}{2}\Delta^2\right]^{3/2} D_0^2\left[\frac{\Delta'}{\Delta}\right]^6 (2J+1)^{-1}\frac{d\sigma}{d\Omega}\bigg|_{\text{DWUCK}},$$

where Δ is the rms radius parameter of the triton and Δ' is the parameter which relates the interaction range of the two-body force and the size of the triton.[18] Although Δ' is slightly smaller than Δ, many authors have used equal values for Δ and Δ' in practical calculations. Since the relative normalizations are not affected by the choice of the parameter Δ', we use a Δ' value of 1.7 fm and then the definition of the normalization constant is exactly equal to that used in many references.

The results of the zero-range DWBA calculations are shown in Fig. 1 and the extracted normalization constants D_0^2 are also inserted in the figure. The solid and dashed curves show the results with the proton optical potentials of Fulmer *et al.*[15] and Becchetti and Greenlees,[14] respectively. The fitting of the theoretical curves to the experimental data are performed at the angular region of about 20°.

When the optical potential sets are changed, the shape of the angular distribution changes considerably. The best choice at present was Fulmer's proton potential and Flynn's triton potential. Slight changes of the real and imaginary depths of the triton potential together with the use of a spin-orbit force[19] give a little better representation. It should be noted that the one-step DWBA theory reproduces all the present experiments reasonably well. The general trend of the forward angle region is predicted especially well by the theory.

The extracted D_0^2 values decrease smoothly as a function of the incident energy. This feature is displayed in Fig. 2 together with some previously obtained results. In Fig. 2, the average D_0^2 values deduced from the analyses of the ground and the first excited 2^+ states in the present work are plotted as closed circles. The dashed curve shows the decreasing trend of D_0^2 values to guide the eye. Open circles and an open square show the previously obtained results. Flynn *et al.*[1] obtained a value of $D_0^2=22.5\times10^4$ fm^3 MeV^2 for the (t,p) reaction at 20 MeV on a number of targets over different regions of the mass table. Ball *et al.*[2] obtained a value of $D_0^2=22$ with the code JULIE, which corresponds to 27.7 (Ref. 4) for DWUCK, from the analysis of (p,t) reactions on the Zr isotopes at 38

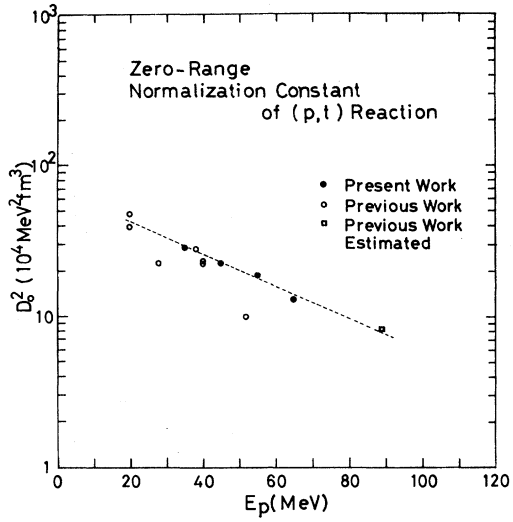

FIG. 2. Zero-range normalization constant of the (p,t) reaction. Solid and open circles show the present and the previously obtained results, respectively. The open square shows the estimated value in the present paper from Ref. 8. The dashed curve shows the trend of the energy dependence of D_0^2 values to guide the eye. See text.

MeV. Broglia *et al.*[3] obtained an average value of $D_0^2=39.7$ from the analysis of (t,p) reactions on Ca, Sn, and Pb isotopes at $E_t=12$ MeV ($E_p\simeq20$ MeV). Hashimoto and Kawai[6] determined D_0^2 values of 48 and 23 from the analyses of (p,t) reactions on the Ca isotopes at 20 and 40 MeV, respectively. Suehiro *et al.*[5] obtained a value of $D_0^2=9.9$ from the analysis of the ^{56}Fe(p,t) reaction at 52 MeV. At 89 MeV, the D_0^2 value is estimated from Ref. 8, where the authors have not obtained the value explicitly, but the ratio of the enhancement factors at 40 and 89 MeV for Sn(p,t) reactions is 0.18/0.48 and $D_0^2=22$ is used in the analysis of 40 MeV data. The present D_0^2 values are, in general, consistent with the previously reported results. The absolute values may change, depending mainly on the nuclear structure factor. In fact, the D_0^2 values obtained from the ground state data are about 10% larger than those from the first excited state data.

It is important to discuss the effects of *p-d-t* two-step processes for the ground to ground states transition.[20] In the present work, two-step *p-d-t* cross sections are calculated by the code TWOSTP using a method similar to that of Ref. 20, which shows the importance of the two-step *p-d-t* processes at 22 MeV. However, the results showed rather poorer agreement with the differential cross sections. At present, it is difficult to estimate the importance of two-step processes in the several tens of

MeV incident energy region.

In summary, zero-range normalization constants are extracted from the $^{124}Sn(p,t)$ reaction to the ground and the first excited 2^+ states at 34.9, 45.1, 54.7, and 65.0 MeV. The extracted values are smoothly decreasing as a function of the incident proton energy. The values extrapolated to the 20 and 90 MeV energy regions are consistent with the previous results.

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