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# Energy dependence of the $^{124}$Sn$(p,t)$ reaction to the $3^-$—$10^+$ two-quasiparticle states of $^{122}$Sn at incident energies of 34.9, 45.1, 54.7, and 65.0 MeV

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Angular distributions for the $^{124}$Sn$(p,t)$ reaction to low-lying $3^-$, $4^+$, $5^-$, $6^+$, $7^-$, $8^+$, and $10^+$ two-quasiparticle 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. The shapes of the angular distributions are reasonably well reproduced with the zero-range theory using one average optical potential set and the deduced enhancement factors are almost constant with smoothly decreasing zero-range normalization constants as a function of the incident energy.

[NUCLEAR REACTIONS $^{124}$Sn$(p,t)$, $E_p=34.9$, 45.1, 54.7, and 65.0 MeV; measured $\sigma(E_t,\theta)$ absolute. DWBA analysis, zero-range, energy dependence of enhancement factors. Enriched target.]

## I. INTRODUCTION

The energy dependence of $(p,t)$ reactions at medium incident energies has been recently investigated by a group at the University of Colorado[1] and by others.[2] They show that the cross sections decrease as a function of the incident energy more rapidly than expected by the zero-range distorted-wave Born approximation (DWBA) theory. In Ref. 1, Kunz *et al.* investigated the energy dependence of the $^{54}$Fe$(p,t)$ reaction with exact finite range DWBA calculations. Their results show that the energy dependence over the incident energy range from 25 to 80 MeV is not well reproduced and the shape of the angular distribution of $3^-$ and $4^+$ transitions is poorly accounted for, in contrast to the ground and $2_1^+$ state transitions. They added a comment that a strong energy dependence seemed to occur primarily between 25 and 50 MeV for the $^{54}$Fe$(p,t)$ reaction. These results suggest two problems. First, there were many sources for the experimental data so that the systematic errors between the data from different sources may strongly affect the final conclusions. Second, the reproduction of the DWBA calculations for the $3^-$ and $4^+$ transitions in Ref. 1 was not good with the zero- and finite-range DWBA formalisms, while that of the zero-range DWBA calculations for $3^-$, $5^-$, and $7^-$ states in the Te$(p,t)$ reactions at 52 MeV was better in Ref. 3.

To systematically discuss the problems mentioned above, 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 incident energies where data are relatively scarce and to analyze them 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 and the coupling effect between the ground and $2_1^+$ states may be weak.[4] In Ref. 2, the differential cross sections of the ground and $2_1^+$ (1.141 MeV) states are analyzed and the smooth energy dependence of the zero-range normalization constant $D_0{}^2$ is confirmed in the several tens of MeV region of the incident energy.

In the present paper, the transitions to the $3^-$, $4^+$, $5^-$, $6^+$, $7^-$, $8^+$, and $10^+$ states of $^{122}$Sn are analyzed with the zero-range DWBA theory. These states are considered to be two-quasiparticle states in the single particle major shells in $^{122}$Sn as discussed below.

## II. EXPERIMENTAL PROCEDURES

The proton beams of 34.9, 45.1, 54.7, and 65.0 MeV produced by the AVF cyclotron at the Research Center for Nuclear Physics (RCNP), Osaka University, 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-sextupole-dipole-quadrupole spectrograph RAIDEN (Ref. 5) with a focal plane detector system[6] which consists of a 1.52 m single-wire position-sensitive proportional counter, two $\Delta E$ proportional counters, and an $E$ plastic scintillation counter.

A typical momentum spectrum of tritons is shown in Fig. 1. The energy resolutions of the triton peaks are 13—18 keV depending on the bombarding energy, which were sufficient to resolve the overlap peaks in the excitation energy region of 2.0—3.0 MeV. As is well understood from the figure, the $3^-$, $4^+$, $5^-$, $6^+$, $7^-$, $8^+$, and $10^+$ states are excited selectively in the excitation energy of 2.0—3.0 MeV and these states are considered to be two-quasiparticle states in the single particle major shells in $^{122}$Sn.[3,7,8]

The excited states studied and the predicted transferred $L$ values are tabulated in Table I. In the present work, the angular distributions of the strongly excited 2.146 MeV $4_1^+$, 2.252 MeV $5^-$, 2.337 MeV $4_2^+$, 2.417 MeV $7^-$, 2.499 MeV $3^-$, 2.560 MeV $6^+$, 2.695 MeV $8^+$, and 2.775 MeV $10^+$ states are analyzed by the zero-range DWBA formalism, and are shown in Fig. 2(a)—(l) together with those of the 2.089 MeV $0^+$, 2.657 MeV, 2.679 MeV $0^+$, and 2.752 MeV ($5^-$,$6^+$) states. Absolute cross sections are determined first by the measurement of the target thickness with weighing and with measuring the energy loss of $\alpha$ particles, and further confirmed by the normalization method with the optical model. The same target foil was used for the measurements at all the bombarding energies, and the uncertainty in the overall normalization was estimated to be less than 25%.

## III. ANALYSIS AND DISCUSSION

Zero-range DWBA calculations were carried out for the eight states of $^{122}$Sn at four incident energies using the code DWUCK.[9]

### A. Optical potentials

The optical potential used in the calculations was of a standard type,

$$V(r)=V_c(r)-V(e^{x}+1)^{-1} -i\left[W-4W_D a'\frac{d}{dr}\right](e^{x'}+1)^{-1} +\left[\frac{\hbar}{m_\pi c}\right]^2 V_{S\cdot O}\frac{1}{r}\frac{d}{dr}(e^{x''}+1)^{-1}\sigma\cdot l\ , \tag{1}$$

where

TABLE I. Experimental results for $^{124}$Sn($p,t$) reactions. Parentheses in the excitation enregy indicate the error at the last digit.

| Ex[a] (MeV) | $L$[a] | $J^{\pi a}$ | Ex[b] (MeV) | $J^{\pi b}$ | Ex[c] (MeV) | $J^{\pi c}$ | Ex[d] (MeV) | $j^{\pi d}$ |
|---|---|---|---|---|---|---|---|---|
| 0.0 | 0 | $0^+$ | 0.0 | $0^+$ | | | 0.0 | $0^+$ |
| 1.141 | 2 | $2^+$ | 1.135(10) | $2^+$ | | | 1.1411 | $2^+$ |
| 2.089(5) | 0 | $0^+$ | 2.10 | $0^+$ | | | 2.09 | ($0^+$) |
| 2.146(5) | 4 | $4^+$ | 2.16 | $4^+$ | | | 2.144 | ($4^+$) |
| 2.252(5) | 5 | $5^-$ | 2.250(15) | $5^-$ | | | 2.248 | ($5^-$) |
| | | | | | | | 2.26 | |
| 2.337(5) | 4 | $4^+$ | 2.335(15) | $4^+$ | | | 2.335 | ($4^+$) |
| | | | | | | | 2.40 | ($7^-$) |
| 2.417(5) | 7 | $7^-$ | 2.415 | $2^+$ | | | 2.42 | ($2^+$) |
| 2.499(5) | 3 | $3^-$ | 2.495 | $3^-$ | | | 2.49 | $3^-$ |
| 2.560(5) | 6 | $6^+$ | | | 2.56 | $6^+$ | 2.56 | ($8^+$) |
| 2.657(10) | | | | | | | 2.65 | |
| 2.679(10) | 0 | $0^+$ | 2.67 | $0^+$ | | | 2.68 | ($0^+$) |
| 2.695(10) | 8 | $8^+$ | | | 2.69 | $8^+$ | | |
| 2.752(10) | 5–6 | ($5^-$,$6^+$) | | | 2.74 | $5^-$ | 2.75 | |
| 2.775(10) | 10 | $10^+$ | | | 2.78 | $10^+$ | | |

[a] Present work, ($p,t$) reactions at 35, 45, 55, and 65 MeV.

[b] Reference 7, ($p,t$) reactions at 20 MeV.

[c] Reference 8, ($p,t$) reactions at 55 MeV.

[d] *Table of Isotopes*, 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978), p. 590.

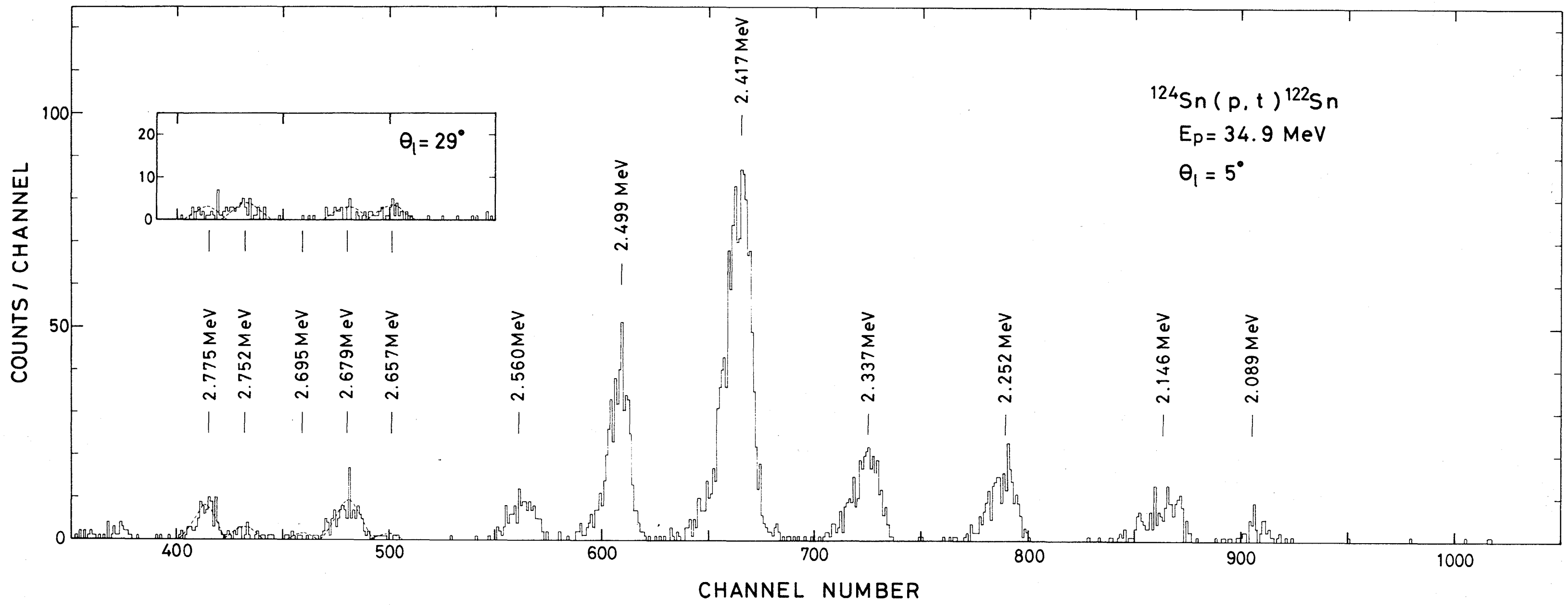

FIG. 1. Momentum spectrum of tritons from the $^{124}$Sn$(p,t)^{122}$Sn reaction to the excitation energy region of 2.0—3.0 MeV at 5°. A part of the 29° spectrum is inserted for comparison.

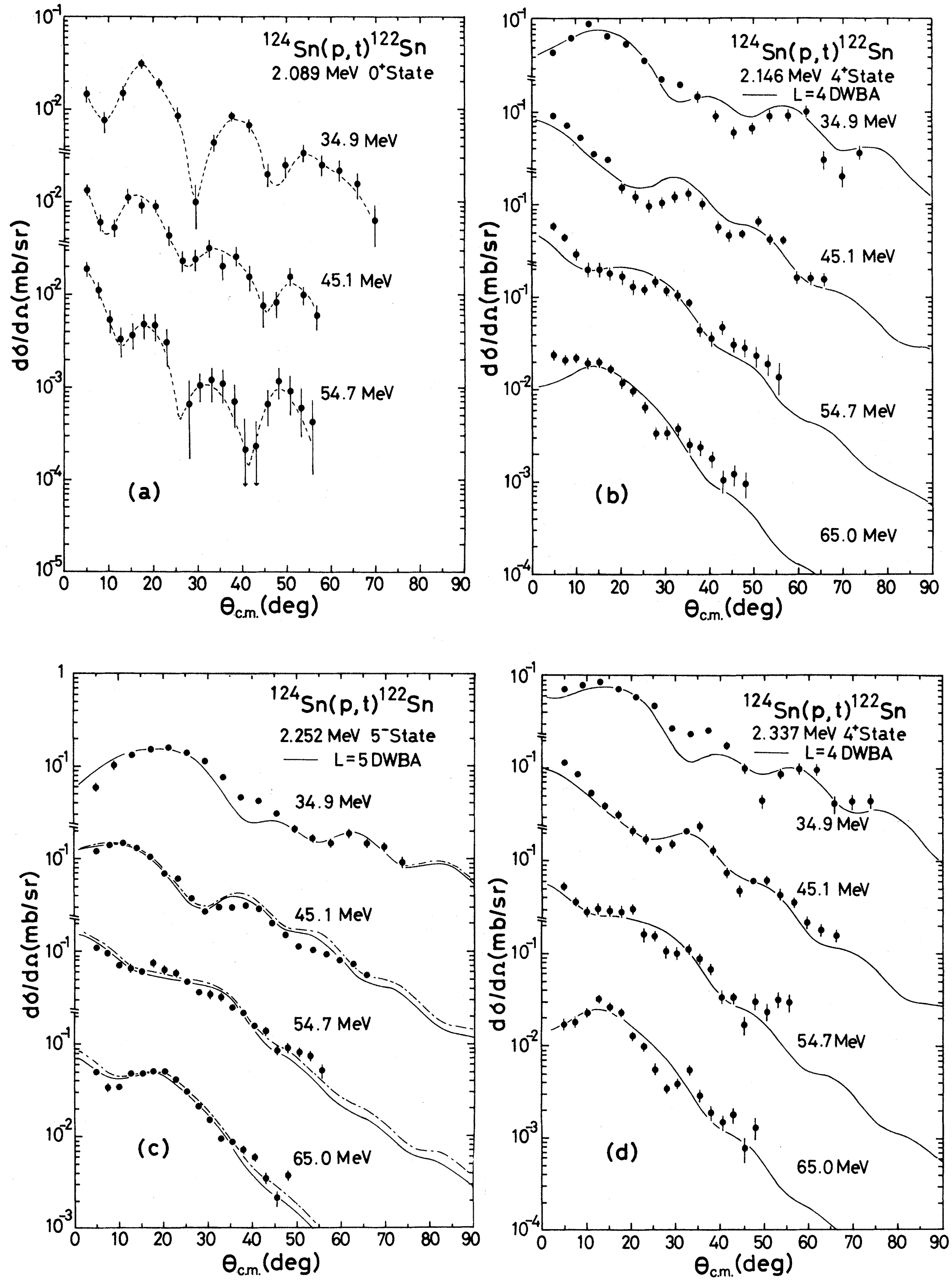

FIG. 2. Angular distributions of the $^{124}$Sn($p,t$) reaction to the (a) 2.089 MeV $0^+$, (b) 2.146 MeV $4^+$, (c) 2.252 MeV $5^-$, (d) 2.337 MeV $4^+$, (e) 2.417 MeV $7^-$, (f) 2.499 MeV $3^-$, (g) 2.560 MeV $6^+$, (h) 2.657 MeV, (i) 2.679 MeV $0^+$, (j) 2.695 MeV $8^+$, (k) 2.752 MeV ($5^-$,$6^+$), and (l) 2.775 MeV $10^+$ states at incident energies of 34.9, 45.1, 54.7, and 65.0 MeV. Solid and dotted-dashed curves show the zero-range DWBA predictions with the energy-independent and energy-dependent triton optical potentials, respectively. Dashed curves are drawn only to guide the eye. See text.

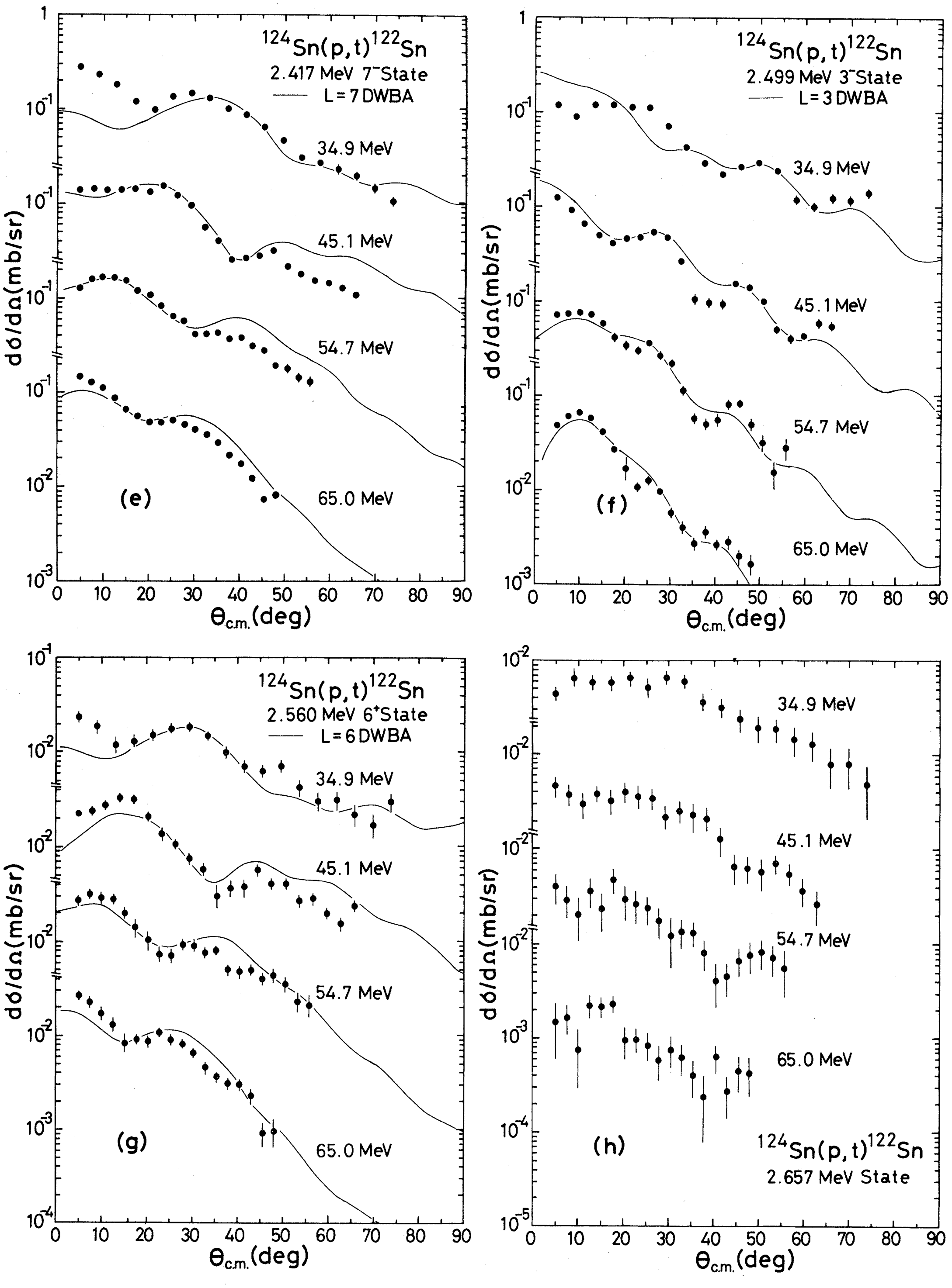

FIG. 2. (*Continued.*)

$$x=(r-R_0)/a_0\ ,$$

$$x'=(r-R')/a'\ ,$$

$$x''=(r-R'')/a''$$

with $R_0=r_0A^{1/3}$, etc., and the Coulomb potential $V_c$ is that for a uniformly charged sphere of radius $R_c=r_cA^{1/3}$. For the protons, the average potential parameters of Fulmer *et al.*[10] are used. For the tri-

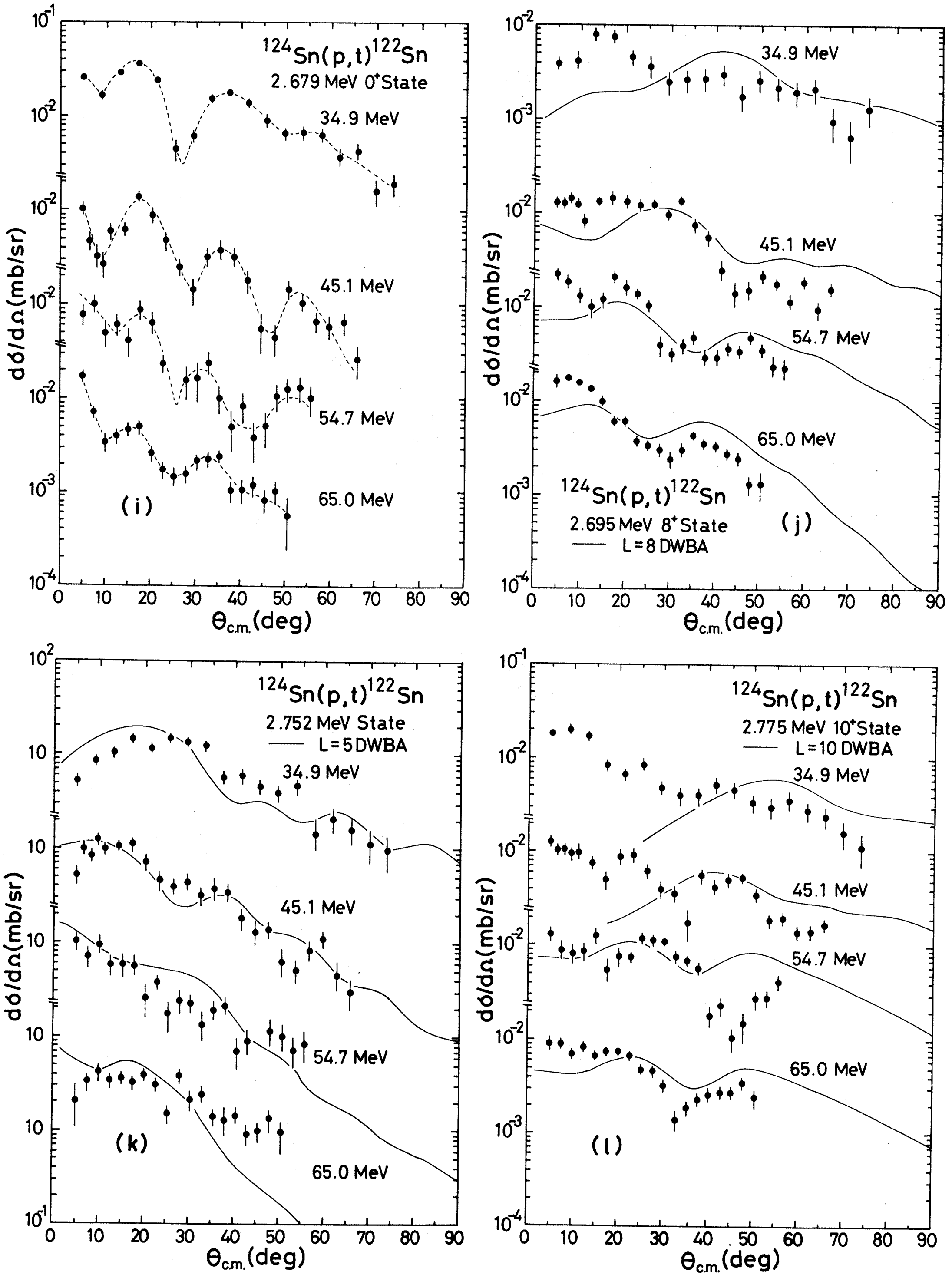

FIG. 2. (*Continued.*)

tons, the potential of Flynn *et al.*[11] was used for all the incident energies, since the energy dependence of the triton optical potential is not known at present. The idea of using only one triton potential set for all the incident energies is in part supported by the fact that the ($p,t$) reactions on $^{54}$Fe and $^{208}$Pb at 80 MeV (Ref. 12) are reasonably reproduced by using the potentials having a similar volume integral of about

TABLE II. Optical model parameters.

| Projectile | $E$ (MeV) | $V$ (MeV) | $W$ (MeV) | $W_D$ (MeV) | $V_{S\cdot O}$ (MeV) | $r_0$ (fm) | $a_0$ (fm) | $r'$ (fm) | $a'$ (fm) | $r''$ (fm) | $a''$ (fm) | $r_c$ (fm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p^{a}$ | 35–65 | $58.94-0.215E$ | 6.0 | 2.88 | 6.04 | 1.16 | 0.75 | 1.37 | 0.63 | 1.064 | 0.74 | 1.25 |
| $t^{b}$ | 27–57 | 166.3 | 15.2 | 0.0 | 0.0 | 1.16 | 0.752 | 1.498 | 0.817 | | | 1.25 |
| $t^{c}$ | 27–57 | $169.1-0.14E$ | $16.0-0.04E$ | 0.0 | 0.0 | 1.16 | 0.752 | 1.498 | 0.817 | | | 1.25 |

[a] Reference 10.

[b] Reference 11.

[c] Reference 21 and present work.

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 energy region is rather weak[13] gives further support to the present treatment. The optical potential parameters used are tabulated in Table II. This set of the potential parameters was the best choice for the analysis of $^{124}$Sn$(p,t)^{122}$Sn$_{\text{gr}}$ reaction at 35–65 MeV incident energy.[2] The effect of the energy dependence of the triton potentials will be discussed in Sec. III F.

### B. Zero-range normalization constant

The zero-range normalization constant $D_0{}^2$ for the $(p,t)$ reaction with the code DWUCK is defined[14] by the equation

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

where $\Delta$ is the rms radius parameter of the triton and $\Delta'$ is the parameter which relates the interaction range of the two-body force and the size of the triton. Although $\Delta'$ is thought to be slightly smaller than $\Delta$, many authors have used equal values for $\Delta$ and $\Delta'$ in practical calculations. Since the relative normalizations are not affected by the choice of the parameter $\Delta'$, a $\Delta'$ value of 1.7 fm is adopted in the present analysis.

To compare the experimental results with theoretical predictions, we use, then, the expression

$$\frac{d\sigma}{d\Omega}=9.672\epsilon B(J,jj')^2 D_0{}^2\sigma_{\text{DW}}\ , \tag{3}$$

where $\epsilon$ and $B(J,jj')$ are the enhancement factor and the spectroscopic amplitude for the two-neutron pickup from the $0^+$ target ground state to a two-quasiparticle state of spin $J$ which is constructed from a set of two-quasiparticle states $j,j'$, respectively, and $\sigma_{\text{DW}}$ is the calculated results using the code DWUCK with the unit amplitude for the two-neutron pickup form factor. In Ref. 2, the authors show the energy dependence of the $D_0{}^2$ values as shown in Table III, together with some previously reported values. In Table III, anomalously large or small $D_0{}^2$ values are excluded and the equivalent results from the DWUCK formalism are adopted. For practical

TABLE III. Zero-range normalization constant for $(p,t)$ reactions compiled in Ref. 2.

| $E_p$ (MeV) | $D_0{}^2$ ($10^4$ fm$^3$MeV$^2$) |
|---|---|
| 20.0[a] | 39.7 |
| 34.9[b] | 30.0 |
| 38.0[c] | 27.7 |
| 45.1[b] | 23.8 |
| 54.7[b] | 19.6 |
| 65.0[b] | 13.4 |
| 89.0[d] | 8.3 |

[a] Reference 15.

[b] Reference 2.

[c] Reference 16.

[d] References 17 and 2.

TABLE IV. Parameters for calculating the spectroscopic amplitude for the two-quasiparticle pickup form factor in the $^{124}$Sn$(p,t)$ reaction. [$\Delta=1.22$ (MeV), $\lambda=2.783$ (MeV).]

| $nlj$[a] | $\epsilon_j$[b] (MeV) | $E_j$ (MeV) | $U_j$ | $V_j$ |
|---|---|---|---|---|
| $1d_{5/2}$ | 0.0 | 3.038 | 0.205 | 0.979 |
| $0g_{7/2}$ | 0.22 | 2.838 | 0.220 | 0.975 |
| $2s_{1/2}$ | 1.90 | 1.506 | 0.455 | 0.891 |
| $1d_{3/2}$ | 2.20 | 1.352 | 0.533 | 0.846 |
| $0h_{11/2}$ | 2.80 | 1.220 | 0.712 | 0.702 |

[a] The results for the $0g_{9/2}$, $1f_{7/2}$, and $0h_{9/2}$ orbits which are included in the calculation are not shown here because of the negligible contributions for the spectroscopic amplitude.

[b] Reference 16.

TABLE V. DWBA cross sections of $^{124}\mathrm{Sn}(p,t)^{122}\mathrm{Sn}$ reactions at 35 MeV for the possible configurations in the major shells. The values of 0° cross sections are shown. Configurations underlined in the table are assumed in the DWBA calculations (unit: mb/sr).

| Configuration | $3^-$ | $4^+$ | $5^-$ | $6^+$ | $7^-$ | $8^+$ | $10^+$ |
|---|---|---|---|---|---|---|---|
| $h_{11/2}$-$g_{7/2}$ | 0.025 | | 0.025 | | 0.13 | | |
| $h_{11/2}$-$d_{5/2}$ | 2.40 | | 0.42 | | 0.60 | | |
| $h_{11/2}$-$d_{3/2}$ | | | 0.160 | | 1.30 | | |
| $h_{11/2}$-$s_{1/2}$ | | | 0.84 | | | | |
| $h_{11/2}$-$h_{11/2}$ | | 0.076 | | 0.082 | | 0.019 | 0.0078 |
| $g_{7/2}$-$g_{7/2}$ | | 0.046 | | 0.034 | | | |
| $g_{7/2}$-$d_{5/2}$ | | 0.38 | | 1.30 | | | |
| $g_{7/2}$-$d_{3/2}$ | | 0.38 | | | | | |
| $g_{7/2}$-$s_{1/2}$ | | 1.10 | | | | | |
| $d_{5/2}$-$d_{5/2}$ | | 1.50 | | | | | |
| $d_{5/2}$-$d_{3/2}$ | | 5.0 | | | | | |

purposes, a quadratic least-square fit for these data is given as

$$D_0{}^2 = 56.7 - 0.922E + 0.00421E^2 \tag{4}$$

in the unit of $10^4\ \mathrm{fm}^3\,\mathrm{MeV}^2$, where $E$ is the incident proton energy. In the analysis below, we will always use the estimated values from Eq. (4).

### C. Spectroscopic amplitude

To estimate the spectroscopic amplitude, $B(J,jj')$ of the two-nucleon transfer reaction to a two-quasiparticle state is calculated using the prescription given by Yoshida,[18] i.e., for the transition from the $0^+$ ground state to the quasiparticle state of the spin $J$,

$$B(J,jj') = -(2J+1)^{1/2} V_j V_{j'} , \tag{5}$$

where $V_j$ is the fullness amplituide of a quasiparticle state $j$ for the target nucleus. The $V_j$ values for the single particle orbits $1d_{5/2}$, $0g_{7/2}$, $2s_{1/2}$, $1d_{3/2}$, and $0h_{11/2}$ are calculated and tabulated in Table IV, together with the parameters assumed.[2,19]

### D. Effect of the assumed configuration to the DWBA cross section

The cross section value of the zero-range DWBA calculation for the $(p,t)$ reaction from the ground state to the two-quasiparticle $J$ state depends strongly on the assumed configuration to calculate the two neutron pickup form factor.[3] The 0° differential cross sections of the DWBA calculation $\sigma_{\mathrm{DW}}$ at 35 MeV incident energy are calculated for $3^-$, $4^+$, $5^-$, $6^+$, $7^-$, $8^+$, and $10^+$ states with the possible configurations in the major shell orbits and tabulated in Table V. Clearly, the above conclusion is confirmed again in this table. These features did not change at other incident energies. In the DWBA calculations below, the configuration which gives larger DWBA cross sections is first adopted.

TABLE VI. Extracted enhancement factors for $^{124}\mathrm{Sn}(p,t)$ reactions to $3^-$, $4_1^+$, $4_2^+$, $5^-$, $6^+$, $7^-$, $8^+$, and $10^+$ states in $^{122}$Sn.

| Ex (MeV) | $J^\pi$ | Configuration assumed | Enhancement factor 35 MeV | 45 MeV | 55 MeV | 65 MeV |
|---|---|---|---|---|---|---|
| 2.146 | $4_1^+$ | $h_{11/2}$-$h_{11/2}$ | 7.91 | 6.11 | 6.60 | 5.83 |
| | | $g_{7/2}$-$d_{3/2}$ | 0.69 | 0.62 | 0.80 | 0.94 |
| 2.252 | $5^-$ | $h_{11/2}$-$s_{1/2}$ | 0.59 | 0.51 | 0.62 | 0.62 |
| 2.337 | $4_2^+$ | $g_{7/2}$-$d_{3/2}$ | 0.77 | 0.77 | 0.98 | 1.14 |
| | | $d_{5/2}$-$d_{3/2}$ | 0.25 | 0.25 | 0.28 | 0.36 |
| 2.417 | $7^-$ | $h_{11/2}$-$d_{3/2}$ | 0.73 | 0.64 | 0.62 | 0.52 |
| 2.499 | $3^-$ | $h_{11/2}$-$d_{5/2}$ | 0.77 | 0.81 | 0.93 | 0.96 |
| 2.560 | $6^+$ | $h_{11/2}$-$h_{11/2}$ | 2.01 | 1.98 | 2.48 | 2.48 |
| 2.695 | $8^+$ | $h_{11/2}$-$h_{11/2}$ | 0.69 | 0.79 | 0.87 | 0.79 |
| 2.775 | $10^+$ | $h_{11/2}$-$h_{11/2}$ | 0.78 | 0.57 | 0.68 | 0.53 |

### E. Results of the calculations

States with spin and parity of $5^-$ and $7^-$ in this target mass region have been considered to be, respectively, $h_{11/2}$-$s_{1/2}$ and $h_{11/2}$-$d_{3/2}$ two-quasiparticle states.[3,7] In fact, the two-quasiparticle energies are low and the spectroscopic amplitudes are large in $^{124}$Sn. Then, these configurations for the 2.252 MeV $5^-$ and 2.417 MeV $7^-$ states are, respectively, assumed in the calculations. DWBA cross sections for the above configurations are also so large (as shown in Table V) that these states are quite strongly excited with the $(p,t)$ reaction. For the $3^-$ state transition, there are two possible configurations, i.e., $h_{11/2}$-$g_{7/2}$ and $h_{11/2}$-$d_{5/2}$, as well understood from Table V. The DWBA cross section for the $h_{11/2}$-$g_{7/2}$ pickup configuration is two orders weaker than that for the $h_{11/2}$-$d_{5/2}$ pickup, and so the $h_{11/2}$-$d_{5/2}$ configuration is adopted for the calculations. For $4^+$ and $6^+$ state transitions, no definite assignments for the configurations related to the transitions are found, so that the $h_{11/2}$-$h_{11/2}$ configuration for the 2.146 MeV $4_1^+$ state, the $g_{7/2}$-$d_{3/2}$ for the 2.337 MeV $4_2^+$ state, and the $h_{11/2}$-$h_{11/2}$ for the 2.560 MeV $6^+$ state are assumed for the calculations. It is reasonable to assume $h_{11/2}$-$h_{11/2}$ configurations for the 2.695 MeV $8^+$ and 2.775 MeV $10^+$ states. The results of the fit to the data with the theoretical predictions which are shown by solid lines are displayed in Fig. 2. The fitting of the theoretical curves to the experimental data are performed at the angular region of about 20°. The resultant enhancement factors are tabulated in Table VI.

### F. Discussion

The predictions of the zero-range DWBA calculations for $3^-$, $4^+$, $5^-$, $6^+$, and $7^-$ states at 35—65 MeV in general reproduce the experimental cross sections quite well. It should be noticed that the change of the shape of the angular distributions as a function of incident energy is interpreted by the theory with only one averages optical potential set. The only exception is the angular distribution of the $3^-$ state at 35 MeV, which shows an out-of-phase pattern at the forward angle region. To resolve this feature, some other reaction mechanism might be considered.

The 2.695 and 2.775 MeV states have been assigned to be the $8^+$ and $10^+$ states with the configuration $h_{11/2}$-$h_{11/2}$.[8] As shown in Fig. 2, their angular distributions at lower incident energies do not show clear $L=8,10$ distributions and the data at 65 MeV give the most definite determination of the transferred $L$ value from the shape of the angular distributions. To study high spin two-quasiparticle states with $(p,t)$ reactions, it is recommended that an incident energy higher than 50 MeV be used.

The 2.089 and 2.679 MeV states show typical $L=0$ angular distributions. In the present work, however, these states are not analyzed. For the 2.752 MeV state, the $L=5$ assignment is proposed in Ref. 8, while the $L=6$ assignment could not be rejected from the present experiment.

All the extracted enhancement factors for the $3^-$—$10^+$ states fall in the range between 0.5 and 1.0, except for the $4^+$ and $6^+$ states with the $h_{11/2}$-$h_{11/2}$ configuration. Since the two-quasiparticle spectroscopic amplitudes depend strongly on the parameters used in the calculation, resultant enhancement factors for $3^-$, $5^-$, $7^-$, $8^+$, and $10^+$ state are quite reasonable. Although the lowest $4^+$ state might be constructed from the $h_{11/2}$-$h_{11/2}$ configuration because it has the lowest quasiparticle energy in this mass region, the experimental cross sections and then the enhancement factors for $4_1^+$ and $4_2^+$ states are too large to conclude the $h_{11/2}$-$h_{11/2}$ assignment. To resolve this problem, better treatment, for example, of the hexadecapole vibration, may be necessary.

In Table VI a slight energy dependence of the enhancement factors is observed in almost all the cases. These energy dependences are, however, weak, and are hard to discuss in detail. This feature suggests that the zero-range normalization factors $D_0{}^2$'s obtained from the $^{124}$Sn$(p,t)^{122}$Sn reactions to lower spin states, i.e., the ground $0^+$ and first excited $2^+$ states, work reasonably for the relatively high spin states in the present incident energy region. Therefore, the problem may reduce now to understanding the energy dependence of the zero-range normalization constant.

It should be checked whether or not the energy dependence of the triton optical potentials have effects on the DWBA calculations. Becchetti and Greenlees[20] have proposed the energy dependent terms of the $^3$He and triton potentials as $dV/dE=-0.17$ and $dW/dE=-0.33$ for the target nuclei $A>40$ in the energy region $E<40$ MeV; Fulmer *et al.*[21] have shown the energy dependent terms of $dV/dE=-0.11$ and $dW_D/dE=-0.04$ for $^3$He on $^{60}$Ni in the energy region of 29.6—71.1 MeV; and Hyakutake *et al.*[22] have shown the energy dependent terms of $dV/dE=-0.173$ and $dW_D/dE=-0.028$ for $^3$He on $^{58}$Ni in the energy region of 90—120 MeV. For the present data in the energy region of $E_t=30$—60 MeV, the energy dependence of Fulmer *et al.* may be the best choice. After absolute depths are determined to reproduce the Flynn potential at 20 MeV (Table II), DWBA cross reactions for all the states investigated are calculated with these triton potentials. The calculated results give slight changes for the cases of higher incident energies. Examples for 2.252 MeV $5^-$ states, for which the best agreements between the experiment and the theory are given, are shown in Fig. 2 with dotted-dashed lines. It may be concluded that the influence of the use of the energy dependent triton potentials is rather weak in the present energy region.

## IV. CONCLUSION

The energy dependence of the $(p,t)$ reaction to $3^- - 10^+$ states, which are thought to be two-quasiparticles states in $^{122}$Sn reactions over the incident energy range from 35 to 65 MeV, is reproduced by the zero-range DWBA calculation with the use of the smoothly decreasing zero-range normalization constant determined from the transition to the ground $0^+$ and first excited $2^+$ states. Only one average optical potential set is used in the calculations. With the results of the present work, the problems of resolving the energy dependence of the zero-range normalization constant with more sophisticated analyses—for example, finite range calculations and/or two-step mechanisms—is left open. The remaining problem that has not been resolved is the strong energy dependence in the $^{208}$Pb$(p,t)$ reaction.

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