Low-lying states of ^{121}Sb studied in the ^{123}Sb(p,t) reaction

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Angular distributions of tritons from the ^{123}Sb$(p,t)^{121}$Sb reaction induced by 26 MeV protons have been measured up to an excitation energy of about 3 MeV using a Q3D spectrometer. Many previously unknown levels of ^{121}Sb have been observed. Microscopic calculations of the ^{123}Sb$(p,t)^{121}$Sb reaction cross sections, using the quasiparticle-phonon model, give a reasonably good description of the fragmentation of the (*p*,*t*) cross sections and the lack of (*p*,*t*) strength above 2.7 MeV of excitation energy. The experimental results from the ^{122}Sn$(p,t)^{120}$Sn reaction have been used to discuss the role of the unpaired quasiparticle in ^{121}Sb in determining the properties of its levels.

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I. INTRODUCTION

The weak coupling model has been used in spectroscopic studies of odd-*A* nuclei [1,2] to further the understanding of their spectra. The simplest form of this model foresees that a class of states in odd-*A* nuclei will arise from the coupling of the odd particle with a basically undisturbed state of the $(A-1)$ even-even nucleus. The coupling of the odd spectator particle with an excited state of the core generates a multiplet of homologous states with spin J which varies from $|J_p-J_c|$ to (J_p+J_c) where $J_p(J_c)$ is the spin of the particle (core). According to this approach the excitation probability for the members of the multiplet is proportional to $(2J+1)$.

The concept of homologous states has been experimentally investigated via $(\vec{p},\alpha)$ reactions in the regions with $A\approx 208$ [3–5] and $A\approx 90$ [6,7]. Recently we have also done more detailed theoretical studies on the properties of homologous states in the lead region [8].

The aim of the present experiment is to compare the cross sections of (*p*,*t*) reactions induced on adjacent ^{122}Sn and ^{123}Sb target nuclei in order to extract the properties of levels in ^{121}Sb whose configurations can be described by the coupling of the $1g_{7/2}$ proton with the even-even ^{120}Sn core. The lighter member of the chosen pair of target nuclei has a magic proton shell so that the additional proton in the heavier member occupies a higher proton shell. Comparison of the cross sections of the two reactions can thus provide information on the role of the extra unpaired proton.

The level structure of the ^{121}Sb nucleus has been investigated in many ways: the ^{121}Sn β decay [9–11]; the ^{121}Te $\beta-\gamma$ decay [12]; Coulomb excitation studies [13–15]; the ^{120}Sn(p,p) reaction using the isobaric analog resonances (IAR) with unpolarized [16] and polarized protons [17,18]; inelastic scattering with the (d,d') [13] and (α,α') reactions [19]; and in $(\gamma,\ \gamma)$ and (γ,γ') studies [20–22]. The following reactions have been studied using in-beam γ-ray spectroscopy: ^{121}Sb$(n,n'\gamma)^{121}$Sb [23,24], ^{120}Sn$(p,\gamma)^{121}$Sb [24] and ^{120}Sn$(^7$Li$,\alpha 2n\gamma)$ [25]. Single-particle proton states have been studied by means of the ^{120}Sn$(^3$He$,d)^{121}$Sb reaction [13,26] and proton hole states by means of the ^{122}Te$(t,\alpha)^{121}$Sb reaction [27]. The experimental results are summarized in Nuclear Data Sheets (NDS) [28].

^{121}Sb has also been studied in the two-nucleon transfer reaction ^{123}Sb$(p,t)^{121}$Sb [29], but only partial results are presented [29,30]. For this reason we have performed a new investigation of the ^{123}Sb$(p,t)^{121}$Sb reaction by means of a high resolution experiment at 26 MeV incident proton energy. 33 of the 66 levels observed in the present (*p*,*t*) experiment up to an excitation energy of ~2.7 MeV are not reported in NDS [28].

There have been several theoretical investigations [24,31] of ^{121}Sb. A comprehensive review of the odd-proton nuclei near $Z=50$ has been given by Heyde *et al.* [32].

Although such a wide variety of reactions, with a high degree of selectivity and a relatively high resolution, has been used to study ^{121}Sb levels, spin and parity assignments for the levels above 2 MeV are still incomplete.

The density of complex configurations rapidly increases with the excitation energy. In odd nuclei, complex configurations have the structure [quasiparticle $\otimes$ *n* phonons] with different total angular momenta J^{π}. The interaction between them, and with the simpler [one-quasiparticle] configurations, should result in a rather complex structure of nuclear excitations in odd-mass nuclei, even at an excitation energy of a few MeV. This means that the validity of a simple approach, which treats an unpaired quasiparticle as a specta-

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tor, should be verified and its predictions compared with the results of more advanced nuclear models which take into account the interplay between simple and complex configurations. Experimental data from (*p*,*t*) reactions on adjacent nuclei, in which many levels can be observed, provide an excellent opportunity to clear up to what extent the spectator approach may be applied, and what its shortcomings are.

To accomplish this task, the measured ^{123}Sb$(p,t)^{121}$Sb cross sections will be compared with the theoretical predictions employing two approaches for nuclear structure calculations. The first one is the spectator model, already mentioned. The second is the quasiparticle-phonon model (QPM) [33], which accounts for the interaction between simple and complex configurations of nuclear excitations. QPM has been rather successful in describing the fragmentation of the simplest components of nuclear wave functions [33–36]. Within QPM, phonons of different multipolarities and parities are obtained by solving quasiparticle random-phase approximation equations. The single particle spectrum and phonon basis are determined from the calculations on the neighboring even-even nuclear core. On the other hand, the QPM analysis can be easily transformed into the spectator approach by switching off the interaction between different configurations in the model space.

The paper is organized as follows. In Sec. II A, the experimental method and apparatus are described. In Sec. II B, measured cross section angular distributions are compared with the distorted wave Born approximation (DWBA) analysis with conventional Woods-Saxon potentials. Section III is devoted to the QPM analysis of the experimental results. Section IV presents a summary of our conclusions.

II. EXPERIMENTAL METHOD AND RESULTS

A. The experiment

We have measured the angular distributions of the two-neutron pick-up reaction ^{123}Sb$(p,t)^{121}$Sb using the proton beam of the Garching HVEC MP Tandem at the proton incident energy $E_p = 26$ MeV, with a beam current ranging from ~500 nA up to 800 nA.

An isotopically enriched ^{123}Sb (98%) target, with a thickness of 100 μg/cm^2 on 7 μg/cm^2 carbon backing, has been used. Outgoing tritons have been detected in the focal plane of the Q3D magnetic spectrograph by using the position and angle resolving light ion detector, with single wire proportional detectors and cathode periodic readout [37]. Cross-section angular distributions have been measured from 5° and 65° in steps of 5° in the excitation energy range from 0 to 2.7 MeV, with an energy resolution of 8 keV full width at half maximum. The setting of spectrograph entrance slits provided a solid angle of 2.978 msr at $\theta = 5°$ and of 11.038 msr at $\theta \geqslant 10°$.

To provide the energy calibration of the ^{121}Sb spectra, the ^{122}Sn$(p,t)^{120}$Sn reaction data [38] have been used to establish a correlation between measured channels and excitation energies. This procedure was used to compensate for the lack of reference levels with precisely measured excitation energies in the ^{121}Sb adopted level scheme [28], above ~1.8 MeV. The ^{122}Sn$(p,t)^{120}$Sn and the ^{123}Sb$(p,t)^{121}$Sb reactions were measured in the same experimental conditions. Our quoted energies are hence estimated to have an uncertainty of ±3 keV.

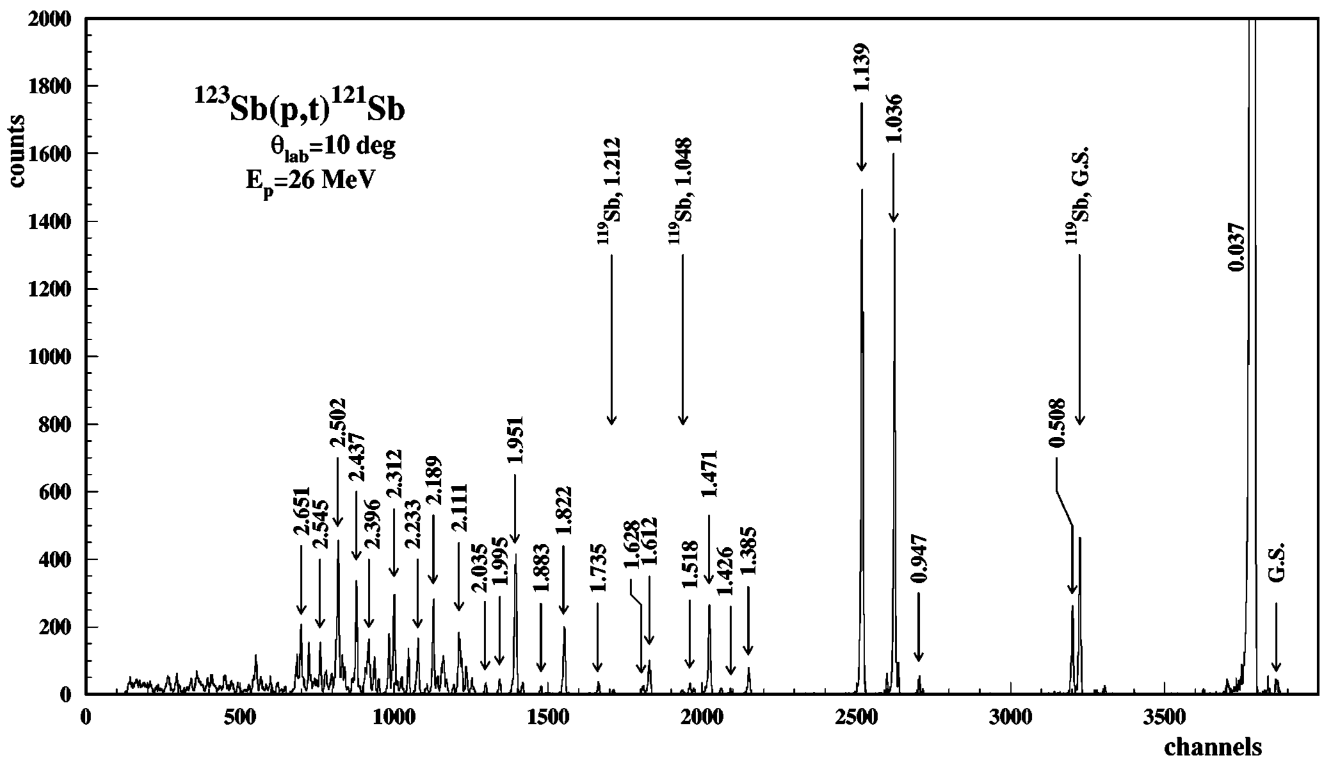

FIG. 1. The triton spectrum at 10° is shown and the excitation energies of the most prominent peaks are indicated, together with the positions of the ^{119}Sb ground state, 1.048 MeV and 1.212 MeV levels.

The triton spectra were analyzed with the AUTOFIT shape-fitting code [39]. The errors in the absolute cross sections are mostly determined by the uncertainties regarding the target thickness, solid angle, collected charge, background subtraction at higher excitation energies, and counting statistics, giving an overall value of ~15%, while the dead time was completely negligible.

Most of the 33 states detected for the first time in the present experiment are weakly excited. They have been observed due to the use of the high resolving power of the Q3D magnetic spectrograph and a large solid angle. This large number of weak transitions is a confirmation of the selectivity of (p,t) reactions which gives a small number of intense transitions. To avoid the presence of contaminant peaks from the ^{121}Sb$(p,t)^{119}$Sb reaction, few forward angle spectra have been measured in the same experimental conditions.

The measured triton spectrum at $\theta_{lab}=10°$ for the ^{123}Sb$(p,t)^{121}$Sb reaction is shown in Fig. 1. The excitation energies are indicated for the most excited levels and the contribution of the visible levels from the ^{121}Sb$(p,t)^{119}$Sb reaction is also given.

Table I reports the spectroscopic information on ^{121}Sb, deduced from the present experiment and compared with information available in the literature [28]. The integrated experimental cross sections and the relative spectroscopic factors are also given in the last two columns. We have observed 66 excited states in all, up to an excitation energy of $\simeq$2.7 MeV, of which 33 were unknown before.

B. The experimental results

Most of the existing data on two-neutron transfer reactions such as (p,t) are concentrated on studies with even-even target nuclei. Starting from a 0^+ initial state and assuming that the neutrons are transferred in a state of relative angular momentum zero, only natural-parity states in the final nucleus will be populated in a one-step transfer process, with a unique L transfer. In this case, the determination of the L transfer directly gives both spin and parity of the observed level.

For odd target nuclei, generally more than one L transfer may contribute to the excitation of a given final state. A more favorable situation is obtained when only one L transfer dominates a given transition amplitude. This behavior can be observed in (p,t) reactions on odd-A nuclei for a certain class of states, arising from coupling the odd particle with the states of the $(A-1)$ even-even core [1,2].

For the transitions populating the states in ^{121}Sb, DWBA analyses have been performed assuming a semimicroscopic dineutron cluster pickup mechanism. Angular distributions for the observed levels are shown in Figs. 2–7 where they are compared with the calculations performed using the code TWOFNR [40]. The DWBA calculations have been performed in a finite-range approximation using a proton-di-neutron interaction potential of Gaussian form $V(r_{p2n})=V_0\exp-(r_{p2n}/\xi)^2$ with $\xi=2$ fm. The parameters for the proton entrance channel, deduced from a systematic survey of elastic scattering by Perey [41] and for the triton exit channel by Fleming *et al.* [42], have been slightly adjusted in order to improve the agreement with the experimental angular distributions. Alternative proton [43] and triton [44] potentials have been tried, using the ground state transition as a test case, but they give poorer fits.

Table II summarizes the optical model parameters for the proton and triton continuum wave functions, and the geometric parameters used for evaluating the bound-state wave function of the transferred dineutron cluster. The optical model parameters shown in Table II have been also used to analyze the angular distributions of the ^{122}Sn$(p,t)^{120}$Sn reaction, measured at 20 MeV [42] and 26 MeV [38,45], giving good agreement between experimental results and DWBA calculations. Therefore we assume that multistep processes, which are not taken into account in the DWBA analyses and which could affect the extracted strengths, are small in these nuclei.

The transferred L values have been assigned by comparing the shapes of the experimental angular distributions with the calculated ones. DWBA curves are quite different for different L transfers, except for the $L=4$ and $L=5$ shapes, which are fairly similar. We are able to fit rather satisfactorily the angular distributions for all the observed levels assuming only one L-transfer. The g.s. and 1.932 MeV level angular distributions cannot be fitted with a unique L transfer. In the NDS [28] the g.s. is listed as $J^\pi=5/2^+$. In this case, the allowed L transfers are 2, 4, and 6. The results of DWBA calculations for the allowed L transfers have been incoherently added with relative intensities proportional to $2L+1$, following the suggestions of Ref. [46], as already done in analyzing the ^{91}Zr$(p,t)^{89}$Zr [47] reaction. The resulting curve is rather featureless, although each L-transfer distribution displays noticeable angular structure. The agreement between experimental and predicted shapes is rather good.

In the case of the 1.932 MeV level, no *a priori* argument exists to choose an L-transfer mixing. The angular distribution is similar to the g.s. angular distribution. Thus, we have used also for this level a combination of $L=2+4+6$, weighted with the $2L+1$ factor. For this level too, the angular distribution is well reproduced.

For the levels up to 1139 keV, we confirm the parity assignments reported in the adopted level scheme [28], while the adopted spin values are in the range allowed by the L-transfer values indicated by the present experiment. For the 37 keV level, the $7/2^+$ spin and parity values are confirmed, because the transition to this level is observed to exhibit an angular distribution with $L=0$ shape.

In the adopted level scheme [28], a level at 1447.5 keV is listed as $1/2^-$, $3/2^-$. We see a level at 1.447 MeV with an angular distribution well reproduced by a pure $L=2$ transfer. Consequently the parity of our level is positive and the angular momentum can range from 3/2 to 11/2. Presumably this level does not coincide with the level at 1447.5 keV, quite strongly excited in the ^{122}Te$(t,\alpha)^{121}$Sb reaction via an $L=1$ pickup [27].

In the present experiment we see a level at 1.995 MeV whose angular distribution is accurately reproduced by assuming an $L=2$ transfer $(3/2^+\leqslant J^\pi\leqslant 11/2^+)$. It might not be the state reported in NDS [28] at 1994.6 keV, to which spin

TABLE I. The adopted energies, spins and parities [28] of the ^{121}Sb levels in comparison with the results of the present work: the energies, the transferred angular momentum L, the spin and parity range, and the integrated cross sections from 5° to 65°. Our quoted energies are estimated to have an uncertainty of ± 3 keV. Absolute cross sections are estimated with a systematic uncertainty of $\pm 15\%$. In column 7 are reported the relative spectroscopic factors, defined as $S_r = [(d\sigma/d\Omega)_{exp}/N(d\sigma/d\Omega)_{DW}]$, where $(d\sigma/d\Omega)_{DW}$ is calculated by finite range DWBA theory, using the TWOFNR code; N is chosen to give $S_r = 1$ for the first excited state.

Levels of ^{121}Sb						
Adopted		Present experiment				
E_{exc} (keV)	J^π	E_{exc} (MeV)	L	J_π	σ_{int} (μb)	S_r
0.0	$5/2^+$	0.0	$2+4+6$	$(5/2-11/2)^+$	3.198	
37.133	$7/2^+$	0.037	0	$7/2^+$	1950.048	1
507.597	$3/2^+$	0.508	2	$(3/2-11/2)^+$	30.738	0.0180
573.142	$1/2^+$	0.573	4	$(1/2-15/2)^+$	0.519	0.0005
946.991	$9/2^+$	0.947	2	$(3/2-11/2)^+$	0.958	0.0004
1024.00	$7/2^+$	1.025	2	$(3/2-11/2)^+$	8.754	0.0054
1035.433	$9/2^+$	1.036	2	$(3/2-11/2)^+$	139.048	0.0902
1139.292	$(11/2)^+$	1.139	2	$(3/2-11/2)^+$	171.271	0.1011
1144.66	$9/2^+$					
1322.0	$(11/2)^+$					
1385.5		1.385	2	$(3/2-11/2)^+$	8.704	0.0058
1407.28						
1427.3		1.426	3	$(1/2-13/2)^-$	5.102	0.0072
1447.5	$1/2^-,3/2^-$					
		1.447	2	$(3/2-11/2)^+$	2.586	0.0018
1471.2		1.471	2	$(3/2-11/2)^+$	29.808	0.0181
1474.4		1.474	2	$(3/2-11/2)^+$	5.410	0.0027
1509.0		1.509	2	$(3/2-11/2)^+$	2.254	0.0018
1519.2		1.518	2	$(3/2-11/2)^+$	4.404	0.0032
1575.4						
1612.6		1.612	2	$(3/2-11/2)^+$	13.503	0.0072
1627.7		1.628	2	$(3/2-11/2)^+$	3.981	0.0025
1647.5	$(13/2)^+$					
1659	$1/2^-,3/2^-$					
1736.3		1.735	2	$(3/2-11/2)^+$	5.133	0.0032
		1.759			1.009	
1810.9		1.810	2	$(3/2-11/2)^+$	1.014	0.0006
		1.822	2	$(3/2-11/2)^+$	31.331	0.0202
		1.868	4	$(1/2-15/2)^+$	1.613	0.0018
		1.883	2	$(3/2-11/2)^+$	4.004	0.0025
		1.932	$2+4+6$	$(5/2-11/2)^+$	5.842	
		1.951	2	$(3/2-11/2)^+$	53.529	0.0361
1983						
1994.6	$(15/2)^+$					
		1.995	2	$(3/2-11/2)^+$	6.784	0.0040
		2.035	4	$(1/2-15/2)^+$	11.959	0.0130
2048						
		2.068			1.773	
2075		2.075	5	$(3/2-17/2)^-$	14.317	0.0386
2097		2.090	3	$(1/2-13/2)^-$	21.363	0.0217
		2.104	3	$(1/2-13/2)^-$	27.215	0.0282
		2.111	2	$(3/2-11/2)^+$	20.498	0.0152
2129		2.128	5	$(3/2-17/2)^-$	13.807	0.0386
2137						
		2.148	3	$(1/2-13/2)^-$	9.340	0.0119

TABLE I. (*Continued*).

Levels of ^{121}Sb						
Adopted		Present experiment				
E_{exc} (keV)	J^{π}	E_{exc} (MeV)	L	J_{π}	σ_{int} (μb)	S_r
		2.159	5	$(3/2-17/2)^-$	37.886	0.1083
		2.165	1	$(5/2-9/2)^-$	8.550	0.0090
		2.176	3	$(1/2-13/2)^-$	10.223	0.0126
		2.189	0	$7/2^+$	25.107	0.0126
2209		2.209	3	$(1/2-13/2)^-$	7.158	0.0079
2234		2.233	0	$7/2^+$	8.497	0.0049
		2.239	5	$(3/2-17/2)^-$	8.350	0.0245
2259		2.266	4	$(1/2-15/2)^+$	30.651	0.0361
2275						
		2.288	4	$(1/2-15/2)^+$	15.097	0.0181
		2.302	3	$(1/2-13/2)^-$	12.181	0.0144
		2.312	1	$(5/2-9/2)^-$	35.455	0.0323
2329		2.328	2	$(3/2-11/2)^+$	22.446	0.0166
2352.6	$(17/2)^+$					
		2.362	4	$(1/2-15/2)^+$	10.440	0.0126
2371		2.377	2	$(3/2-11/2)^+$	17.407	0.0108
2398		2.396	4	$(1/2-15/2)^+$	40.081	0.0484
		2.407	4	$(1/2-15/2)^+$	16.873	0.2040
		2.426	4	$(1/2-15/2)^+$	5.434	0.0066
2435		2.437	0	$7/2^+$	27.490	0.0162
		2.452	4	$(1/2-15/2)^+$	11.960	0.0145
2461		2.467	4	$(1/2-15/2)^+$	5.696	0.0069
		2.477	3	$(1/2-13/2)^-$	19.949	0.0256
		2.488	3	$(1/2-13/2)^-$	25.027	0.0325
		2.502	0	$7/2^+$	45.655	0.0271
		2.523	3	$(1/2-15/2)^+$	20.543	0.0289
		2.545	1	$(5/2-9/2)^-$	17.073	0.0108
2558		2.565	4	$(1/2-15/2)^+$	38.678	0.0480
		2.580	4	$(1/2-15/2)^+$	17.648	0.0217
		2.599	3	$(1/2-13/2)^-$	6.767	0.0090
		2.607	5	$(3/2-17/2)^-$	46.629	0.1730
		2.625	4	$(1/2-15/2)^+$	13.434	0.0165
2639		2.636	4	$(1/2-15/2)^+$	65.191	0.0816
		2.651	2	$(3/2-11/2)^+$	19.969	0.0144

and parity $J^{\pi}=(15/2)^+$ are attributed on the basis of the study of the ^{120}Sn(^{7}Li,$\alpha 2n\gamma$) reaction.

We attribute $J^{\pi}=7/2^+$ to the levels at 2189, 2233, 2437, and 2502 keV on the basis of the $L=0$ transfer that satisfactorily reproduces the forward angles in their angular distributions. The second and the third of these are reported in the adopted level scheme [28]. The other two have been observed for the first time.

III. THEORETICAL ANALYSIS

Since it is not possible to identify unequivocally the spin of most of the excited levels in ^{121}Sb from the analysis of angular distributions of the (p,t) cross section, theoretical support is needed for a better understanding of the experimental results. To this purpose, microscopic calculations of the ^{123}Sb$(p,t)^{121}$Sb reaction cross sections have been performed.

First, calculations were done for the neighboring even-even ^{120}Sn nucleus. The model parameters were fixed at this stage. The calculations in ^{121}Sb include no other free parameters because all matrix elements of the interaction between different configurations in the model space of ^{121}Sb are calculated on a microscopic footing, making use of a model Hamiltonian and an internal fermion structure of phonons of the core excitation. With this approach the properties of phonons, i.e., their internal fermion structure and excitation energies, are obtained by solving the quasiparticle-RPA equations. The occupation numbers for particles and holes and the quasiparticle spectrum are calculated from the BCS equations.

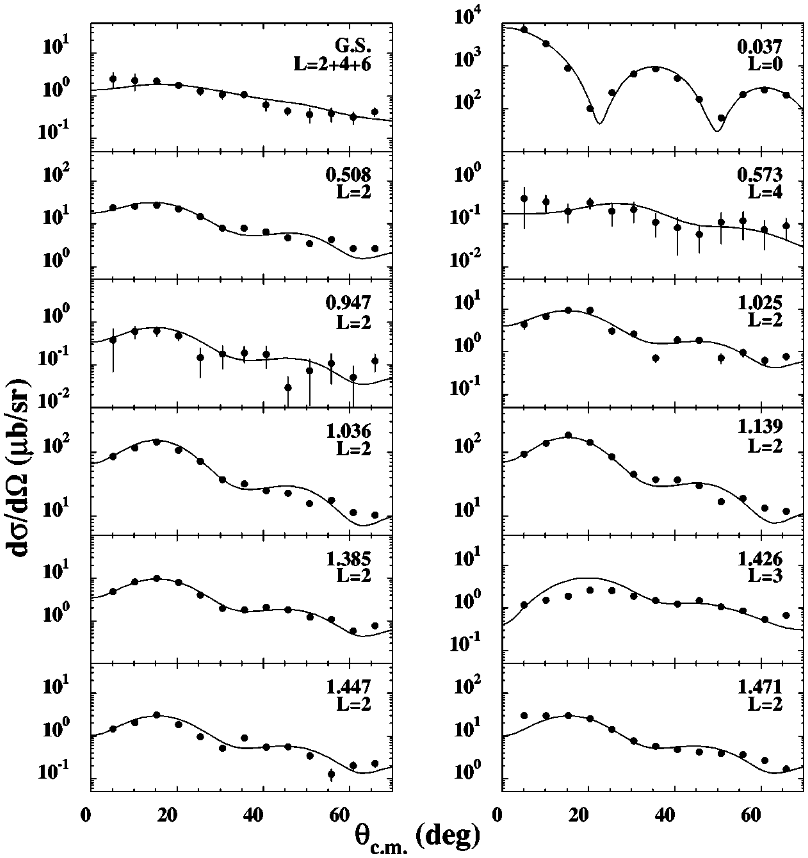

FIG. 2. Angular distributions for the transitions to the ^{121}Sb levels whose excitation energy (MeV) and *L*-transfer value are indicated. The dots represent the experimental data, the solid lines the theoretical estimates obtained with DWBA calculations. The energies attributed to the observed levels are those given in the present work.

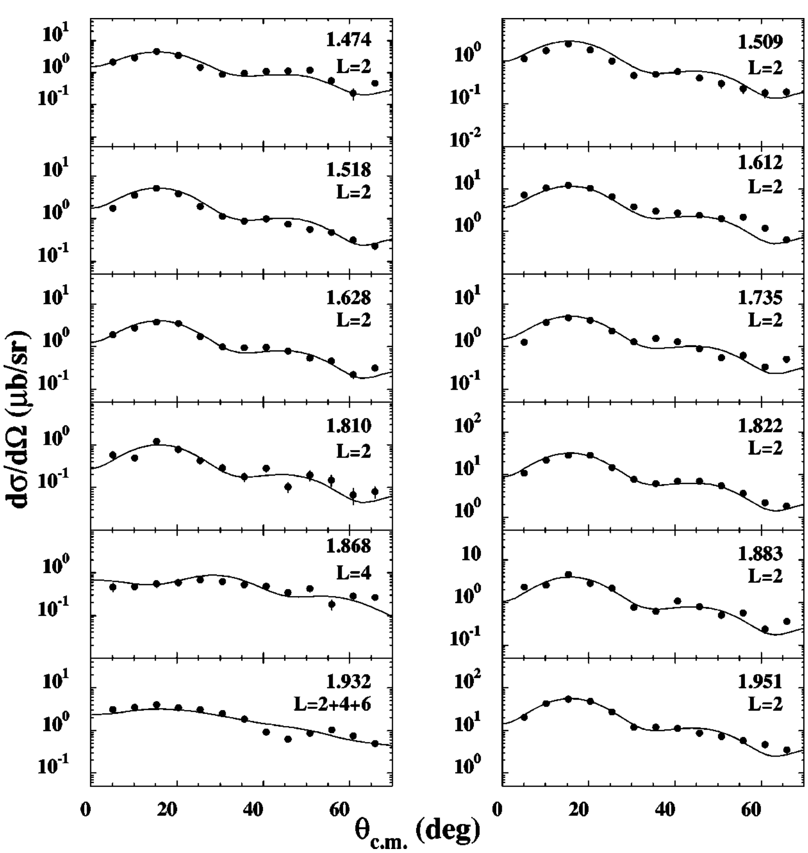

FIG. 3. Same as Fig. 2.

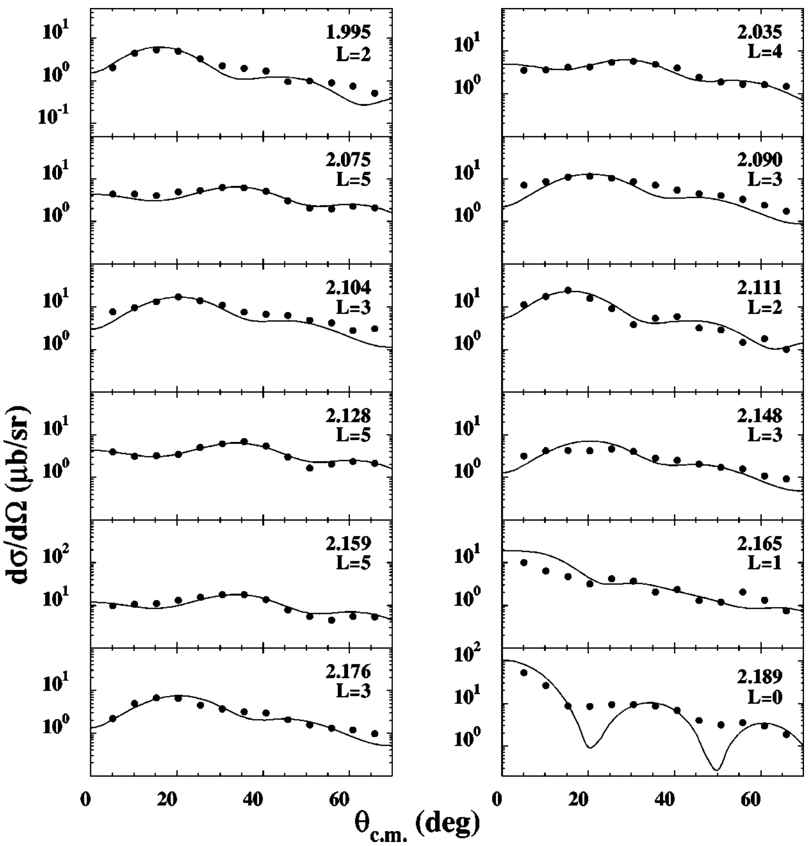

FIG. 4. Same as Fig. 2.

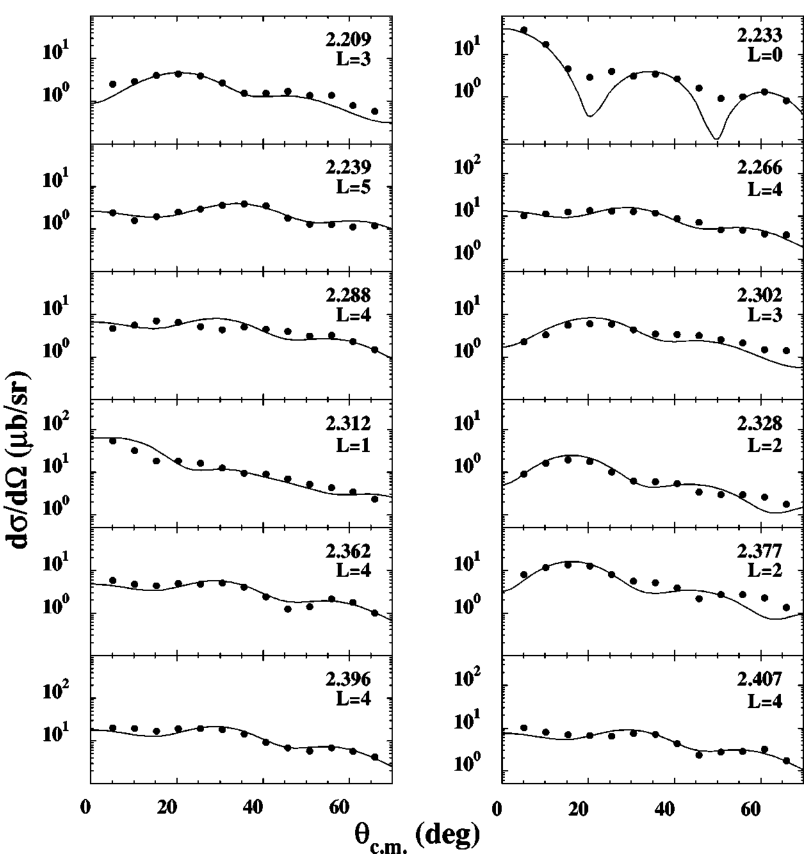

FIG. 5. Same as Fig. 2.

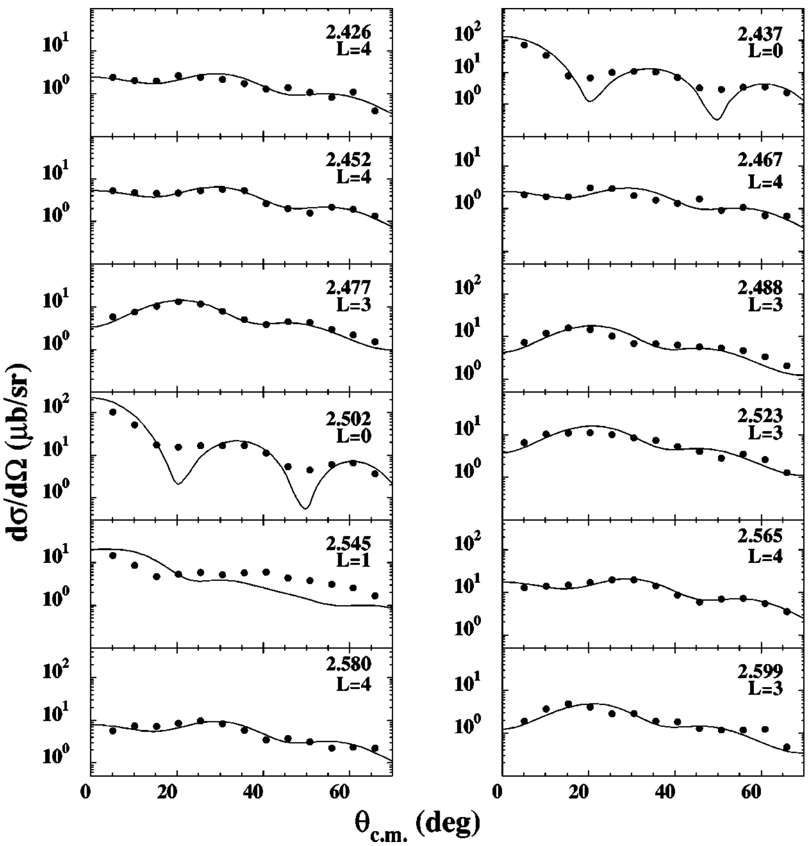

FIG. 6. Same as Fig. 2.

Excited states in ^{120}Sn have been described by wave functions which include one- and two-phonon configurations. The parameters of the Woods-Saxon potential for an average field for protons and neutrons of the model Hamiltonian, as well as the strength parameters for monopole pairing, are taken from Ref. [48]. The strength parameters of the multipole residual interaction have been adjusted to reproduce the properties of low-lying collective states. The particle-particle channel of the residual interaction is very important for a correct description of the excitation of low-lying states in two-nucleon transfer reactions.[1] An interplay between particle-hole and particle-particle channels of the residual interaction has been studied in detail within QPM in the case of Nd isotopes in Ref. [50]. These studies have shown that a consistent description of the (p,t) reaction cross sections and of data from inelastic proton and deuteron scattering is achieved when the strength of the particle-particle residual interaction is 0.9 times the isoscalar part of the particle-hole residual interaction. We have kept this ratio in the present study. Thus, the only variable parameters in these calculations are the strengths of the residual interaction. They have been fixed to reproduce the energies of the low-lying states in ^{120}Sn.

The ground and excited states of ^{121}Sb have been described by wave functions of the form

$$\Psi^{\nu}(\mathrm{JM})=\left\{C^{\nu}(J)\alpha^{+}_{\mathrm{JM}}+\sum_{j\lambda i}S^{\nu}_{j\lambda i}(J)[\alpha^{+}_{j}Q^{+}_{\lambda i}]_{\mathrm{JM}}+\sum_{j\beta_1\beta_2 l}\frac{D^{\nu}_{j\beta_1\beta_2}(J)[\alpha^{+}_{j}[Q^{+}_{\beta_1}Q^{+}_{\beta_2}]l]_{\mathrm{JM}}}{\sqrt{1+\delta_{\beta_1\beta_2}}}\right\}|^{120}\mathrm{Sn}\rangle_{\mathrm{g.s.}}, \tag{1}$$

where α^{+}_{jm} is a quasiparticle (qp) creation operator and Q^{+}_{β} is a phonon (ph) creation operator. Square brackets in Eq. (1) denote angular momentum coupling, i.e., $[\alpha^{+}_{j}Q^{+}_{\beta}]_{\mathrm{JM}}=\Sigma_{m\mu}C^{\mathrm{JM}}_{jm\lambda\mu}\alpha^{+}_{jm}Q^{+}_{\lambda\mu i}$, etc. where $C^{\mathrm{JM}}_{jm\lambda\mu}$ are the Clebsch-Gordan coefficients. Quasiparticles with shell quantum numbers $jm\equiv(n,l,j,m)$ have half-odd-integral angular momenta. The index β of the phonon operator means a combination of (λ, μ, i) where i is used to distinguish between one-phonon states of the same multipolarity λ, but with different excitation energies. In QPM, phonons are composed of different two-quasiparticle configurations. Thus, the wave function (1) may be also considered as a mixture of one-, three-, and five-quasiparticle configurations. When odd nuclei with an unpaired proton are considered, both $1\pi2\nu$ and 3π configurations contribute to the second term of wave function (1), etc.

In the actual calculations we have used several of the lowest RPA states for each multipolarity $\lambda=0-7$ corresponding to natural parity excitations of the ^{120}Sn core

[1]The states excited in the two-nucleon transfer reactions are described theoretically by introducing ‘‘particle-removal’’ phonons. See Refs. [49,50] for more details on their mixing with particle-hole phonons near the Fermi level in open- and closed-shell nuclei.

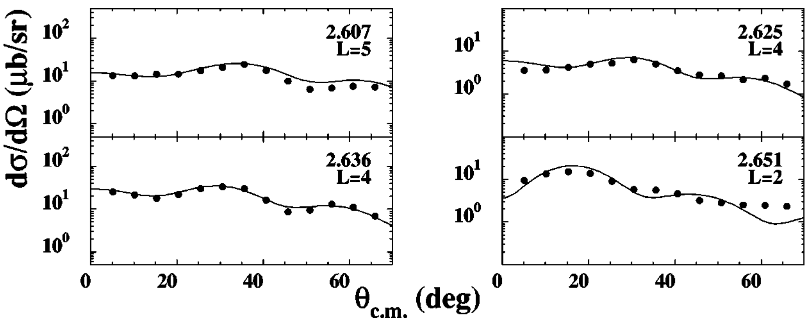

FIG. 7. Same as Fig. 2.

nucleus. To make realistic calculations possible, we have been obliged to truncate the basis of complex configurations. This has been done assuming that the configurations at high excitation energies have marginal influence on the properties of low energy excited states. In the present calculations, we have included all [qp×1ph] configurations up to 4.0 MeV, and all [qp×2ph] configurations up to 5.75 MeV, which do not violate the Pauli principle. Calculations have been performed for excited states in ^{121}Sb with J^{π} ranging from $1/2^{\pm}$ to $19/2^{\pm}$, up to 3.5 MeV.

Coefficients C, S, and D in Eq. (1), and energy eigenvalues, are obtained by diagonalizing the model Hamiltonian on the set of wave functions (1). The index ν is used to distinguish between different excited states with the same J^{π}. For more details of the QPM application to the description of excited states in odd-mass nuclei, we refer to [51–53].

DWBA calculations employing spectroscopic amplitudes calculated from microscopic wave functions for the different configurations of the transferred nucleons are rather complex. On the other hand, the spins of most observed levels could not be unambiguously assigned to establish a one-to-one correspondence between observed levels and calculated excited states. Thus the main interest is not to compute the absolute value of the (p,t) cross section for each level in ^{121}Sb, but rather to consider the general features of the fragmentation of the (p,t) cross section in this nucleus. That is why we did not perform DWBA calculations with the QPM spectroscopic amplitudes. Instead we used the experimentally measured ''transition amplitudes'' of the ^{122}Sn$(p,t)^{120}$Sn reaction from Ref. [38] in the QPM calculations of the ^{123}Sb$(p,t)^{121}$Sb cross sections. The procedure was the following. The L-transfer values deduced from the DWBA analysis of the ^{122}Sn$(p,t)^{120}$Sn cross sections allow an unambiguous assignment of spin and parity to the ^{120}Sn observed levels because of $J^{\pi}_{\mathrm{g.s.}}=0^{+}$ for ^{122}Sn. It is possible to establish a correspondence up to about 3 MeV between the set of observed levels with definite J^{π} and the one-phonon states in ^{120}Sn of the same spin and parity in the QPM calculations taking into account the excitation energy and collectivity of the states (see Fig. 8).[2] After this correspondence has been established the square root of the experimental cross section has been taken as the transition amplitude for the J_i^{π} one-phonon state in ^{120}Sn.

The procedure applied for the transition amplitudes does not allow us to determine their relative signs. However these signs become very important for the calculations in ^{121}Sb, where interference effects among the different components of the wave function (1) take place. To determine the signs, a simplified calculation for each J_i^{π} one-phonon configuration in ^{120}Sn was performed. The transition amplitude is proportional to $\Sigma_k f_k \psi_i^k(J)$, where k goes over different possible two-neutron configurations coupled to angular momentum J, f_k is the transition amplitude to excite the k two-neutron configuration, and $\psi_i^k(J)$ is a contribution of this configuration to the wave function of the one-phonon state J_i^{π}. The assumption $f_k=$const, as recommended in Ref. [49] and checked in Ref. [50], is sufficient to determine the *sign* of the J_i^{π} transition amplitude.

When ^{121}Sb is excited in the ^{123}Sb$(p,t)^{121}$Sb reaction the same set of phonons of the core ^{120}Sn is involved. The unpaired proton of antimony does not influence the excitation process in a one-step transfer. For this reason, the reaction amplitudes $(A_{\lambda i})$ of the $0^{+}_{\mathrm{g.s.}}(^{122}\mathrm{Sn})\rightarrow Q^{+}_{\lambda i}(^{120}\mathrm{Sn})$ transitions may be used to describe the $1g_{7/2}(^{123}\mathrm{Sb})\rightarrow[1g_{7/2}\times Q^{+}_{\lambda i}]_{J^{\pi}}(^{121}\mathrm{Sb})$ transitions. In addition, the reaction amplitude (A_0) of the $0^{+}_{\mathrm{g.s.}}(^{122}\mathrm{Sn})\rightarrow 0^{+}_{\mathrm{g.s.}}(^{120}\mathrm{Sn})$ transition for the excitation of the ground state in ^{120}Sn should correspond to the excitation of the $7/2^{+}$ quasiparticle configuration in ^{121}Sb, i.e., for the $1g_{7/2}(^{123}\mathrm{Sb})\rightarrow 1g_{7/2}(^{121}\mathrm{Sb})$ transition. Thus, the excitation cross section of the states (1) in ^{121}Sb are calculated using

$$\sigma_{\nu}(J)=\left|C^{\nu}(J)A_0+\sum_{\lambda i} S^{\nu}_{7/2+\lambda i}(J)A_{\lambda i}\right|^2. \qquad (2)$$

This means that the $[\alpha_j^{+}Q^{+}_{\lambda i}]_{\mathrm{JM}}$ components of the wave function (1) with $j\neq 7/2^{+}$ make no contribution to the transition amplitudes in the present calculations. Indeed, these configurations may be excited only in the next order of perturbation theory due to the internal fermion structure of phonons. Thus, their excitation amplitudes are a few orders of magnitude smaller than $A_{\lambda i}$, and may be neglected. Nevertheless, these configurations are essential to the calculations because they are responsible for the fragmentation of the excitation strength.

The $1g_{7/2}$ quasiparticle configuration has an amplitude of 0.97 in our calculated ^{123}Sb ground state. Thus the two-

[2]For a few levels in ^{120}Sn observed in the (p,t) reaction with very small cross sections, we did not find corresponding one-phonon states in the calculation. Probably these levels have mostly a two-phonon structure. They are not presented in Fig. 8.

TABLE II. The Woods-Saxon optical model parameters for the incident proton, the outgoing triton, and the geometrical parameters for the bound state of the transferred dineutron cluster.

	V_r (MeV)	r_r (fm)	a_r (fm)	W_v (MeV)	r_v (fm)	a_v (fm)	W_d (MeV)	r_d (fm)	a_d (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_c (fm)
p	50.0	1.25	0.65				10.0	1.30	0.60	3.00	1.25	0.70	1.25
t	176.0	1.14	0.72	18.0	1.61	0.82				8.00	1.10	0.80	1.30
B.S.		1.30	0.50										

neutron transition amplitudes determined from ^{122}Sn$(p,t)^{120}$Sn must be multiplied by 0.97 in order to have a correct relative normalization of the ^{122}Sn$(p,t)^{120}$Sn and ^{123}Sb$(p,t)^{121}$Sb reactions.

The distribution of the $\pi 1g_{7/2}$ quasiparticle configuration over the excited states in ^{121}Sb is very similar to its distribution in ^{123}Sb. 93% of it is concentrated in the first excited state at 40 keV in the present calculations. Since the transition matrix element $1g_{7/2}(^{123}\mathrm{Sb})\rightarrow 1g_{7/2}(^{121}\mathrm{Sb})$ is much larger than the $1g_{7/2}(^{123}\mathrm{Sb})\rightarrow[1g_{7/2}\times Q^{+}_{\lambda i}]_{J^{\pi}}(^{121}\mathrm{Sb})$ matrix elements, this state is the most strongly excited state in ^{121}Sb in the (*p,t*) reaction. An admixture of about 5% for the quasiparticle $\pi 1g_{7/2}$ configuration is found in the $7/2^+$ state which has the $[1g_{7/2}\times 2^+_1]_{7/2^+}$ component of the wave function as a dominant (83%) configuration. In the calculations, this state has an energy of 1.36 MeV and corresponds to the $7/2^+$ level at 1.024 MeV. Indeed, the contribution of 5% of the $\pi 1g_{7/2}$ configuration to the wave function of this state explains why the $7/2^+$ component of the $[1g_{7/2}\times 2^+_1]$ multiplet, which has the largest transition matrix element among the [qp×1ph] configurations is observed to have a small cross section (see Table I). The weak excitation of this state is the result of the destructive interference between a very large transition matrix element $1g_{7/2}(^{123}\mathrm{Sb})\rightarrow 1g_{7/2}(^{121}\mathrm{Sb})$ to a small component of the final state and a moderate transition matrix element $1g_{7/2}(^{123}\mathrm{Sb})\rightarrow[1g_{7/2}\times 2^+_1]_{7/2^+}(^{121}\mathrm{Sb})$ for the main configuration. Some traces of the quasiparticle $\pi 1g_{7/2}$ configuration may be found in $7/2^+$ states at higher energies, but since the contribution does not exceed 0.1%, the excitation of these states in the (*p,t*) reaction is completely determined by the [qp×1ph] components of their wave functions. For this reason the spectroscopic factors of these states will not be discussed in the present analysis.

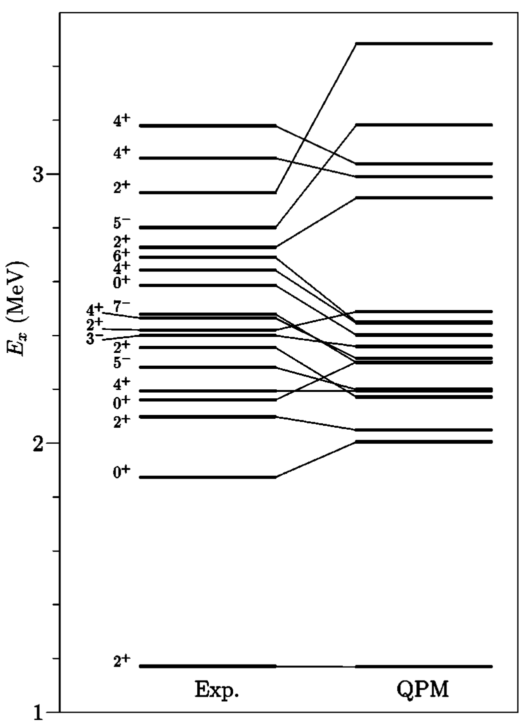

FIG. 8. Correspondence between the levels observed in the ^{122}Sn(p,t) ^{120}Sn reaction and the one-phonon states in ^{120}Sn of the same spin and parity in the QPM calculations.

First, let us consider the $7/2^+$ states whose total spin and parity have been identified because of $L=0$ transfer. There are four levels of this type between 2.1 and 2.5 MeV (see Table I) in addition to the $7/2^+$ level at 37 keV already discussed. The corresponding experimental values are plotted in Fig. 9(a). In the calculations this type of state must have $[1g_{7/2}\times 0^+_i]_{7/2^+}$ configurations as main components of the wave functions. In Fig. 9(b) the theoretical predictions for these four states are shown, while the main components of the wave functions are given in Table III. Only the state at 2.17 MeV has a simple structure: the same as expected in the spectator approach. The structure of other states is much more complex. The agreement between experiment and theory for these states, in position and integrated (*p,t*) cross section, is very good. The calculation also predicts $7/2^+$ state with similar properties at about 1.2 MeV, which has not been observed experimentally. The predicted (*p,t*) cross section for this state, obtained with a destructive admixture of the

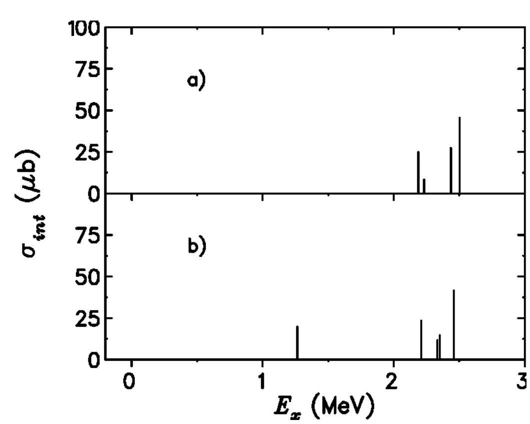

FIG. 9. (a) Experimental and (b) calculated $7/2^+$ states in ^{121}Sb excited by $L=0$ transitions. The 37 keV state is not shown.

TABLE III. Main components (⩾5%) of the wave functions of the 7/2$^+$ states presented in Fig. 9(b).

E_{exc} (MeV)	Configuration	Contribution
1.23	$[1g_{7/2}\times 0_3^+]_{7/2^+}$	34%
	$[1g_{7/2}\times 0_4^+]_{7/2^+}$	12%
	$[1g_{7/2}\times 2_1^+]_{7/2^+}$	46%
2.17	$[1g_{7/2}\times 0_1^+]_{7/2^+}$	97%
2.30	$[1g_{7/2}\times 0_2^+]_{7/2^+}$	77%
	$[1g_{7/2}\times 0_3^+]_{7/2^+}$	5%
	$[1g_{7/2}\times 0_4^+]_{7/2^+}$	14%
2.31	$[1g_{7/2}\times 0_2^+]_{7/2^+}$	14%
	$[1g_{7/2}\times 0_3^+]_{7/2^+}$	15%
	$[1g_{7/2}\times 0_4^+]_{7/2^+}$	27%
	$[1g_{7/2}\times 2_4^+]_{7/2^+}$	15%
	$[1g_{7/2}\times 0_5^+]_{7/2^+}$	21%
2.42	$[1g_{7/2}\times 0_4^+]_{7/2^+}$	6%
	$[1g_{7/2}\times 2_5^+]_{7/2^+}$	79%
	$[1g_{7/2}\times[2_1^+\times 2_6^+]_0]_{7/2^+}$	9%

quasiparticle $\pi 1g_{7/2}$ configuration to its wave function of about 0.1%, equals 20 μb. Nevertheless, if the amount of destructive admixture of the quasiparticle $\pi 1g_{7/2}$ configuration reaches about 0.8% the cross section becomes negligibly small, as happens with the excitation cross sections of the $[1g_{7/2}\times 2_1^+]_{7/2^+}$ state. In both cases the contribution of the quasiparticle $\pi 1g_{7/2}$ configuration does not exceed 1%. Such high degree of accuracy is beyond the capability of any model calculation. This means that the theoretical predictions of the (*p,t*) cross sections of the 7/2$^+$ states below 1.5 MeV are not very precise because the results are extremely sensitive to small admixtures of the quasiparticle $\pi 1g_{7/2}$ configuration. For the states of other multipolarities, the transition amplitudes between the $1g_{7/2}$(^{123}Sb) ground state and one-quasiparticle configurations of ^{121}Sb are negligibly small. Thus we have no problems of accuracy.

In Fig. 10(c) the results of the calculation of the ^{123}Sb$(p,t)^{121}$Sb reaction cross sections, as a function of excitation energy of ^{121}Sb, are compared to the experimental data shown in Fig. 10(a). In Fig. 10(b) we present the results of the simplified calculations in which the unpaired quasiparticle is considered as a pure spectator. In this case all multiplets $[\alpha_j^+ Q_\lambda^+]_J$ with $|j-\lambda|\leqslant J\leqslant(j+\lambda)$ are degenerate in energy and only the states with the maximum possible value of *J* are presented in Fig. 10(b) because of their largest excitation probability.

A comparison of Fig. 10(b) to Fig. 10(a) indicates that the spectator approach also reproduces the general features of the experimentally observed distribution of the (*p,t*) cross section to low-lying levels in ^{121}Sb. The spectrum is dominated by a very strong transition to the 7/2$^+$ state at 40 keV which is homologous to the $0^+_{\mathrm{g.s.}}$ populated in ^{122}Sn$(p,t)^{120}$Sn reaction and has been discussed above. There is a strongly excited multiplet $[1g_{7/2}\times 2_1^+]_{J^+}$ at about 1 MeV and a large group of states between 1.9 and 2.6 MeV which are excited more weakly. But, as already mentioned

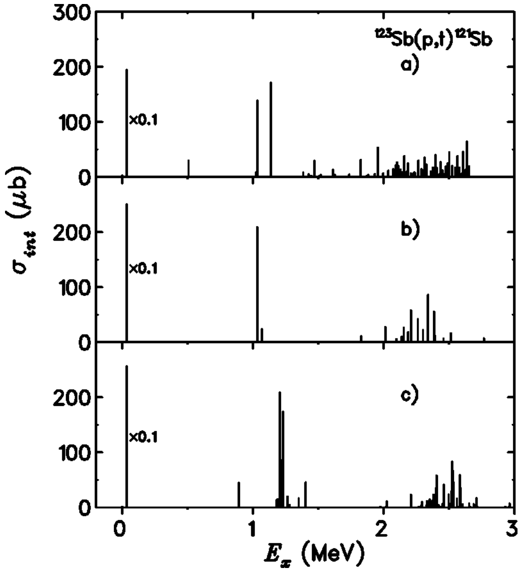

FIG. 10. (a) Experimental and (b), (c) calculated integrated cross sections of the ^{123}Sb$(p,t)^{121}$Sb reaction from 5° to 65° as a function of excitation energy in ^{121}Sb. Calculations are performed (b) assuming that the unpaired quasiparticle is a pure spectator and (c) with wave function of Eq. (1).

above, this approach is not able to describe the splitting of multiplets.

In the realistic calculations performed with the wave function (1) [Fig. 10(c)], the multiplets split because of the interaction with other [qp×1ph] configurations in which the unpaired quasiparticle moves to another proton level of the average field. It is possible to establish a one-to-one correspondence between the calculated states that carry the main fraction of the $[1g_{7/2}\times 2_1^+]_{J^+}$ multiplet, and the experimentally observed levels. In the calculations the 11/2$^+$ and 9/2$^+$ components come out in reverse order and the 3/2$^+$ component has an excitation energy about 300 keV higher than the experimental one. We have already discussed above why the 7/2$^+$ component of this multiplet has a very weak cross section and it is not clear why the 5/2$^+$ component is not observed either in the present experiment or in other experiments. At higher excitation energies, the fragmentation of the (*p,t*) cross section and the absence of the (*p,t*) strength above 2.7 MeV are reasonably well reproduced by these calculations.

Some general comparisons between the data and the results of calculations can be made taking into account that in the (*p,t*) reaction with even (odd) values of *L* transfer, positive (negative) parity states are excited from the 7/2$^+$ ground state of ^{123}Sb. For a better comparison with the experimental data, the states J_ν^π from the QPM calculations are presented in Figs. 11 and 12 according to the *L* transfer by which they are excited in the (*p,t*) reaction. Their J^π values are not indicated to avoid overloading the figures. To assign *L* transfer for each state their wave functions have been analyzed. A definite *L*-value means that the $[1g_{7/2}\times Q_{Li}^+]_J$ configurations are dominant in their wave functions. As is the case for the

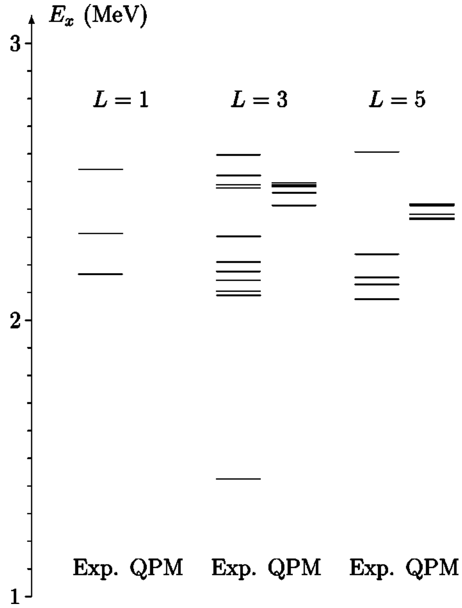

FIG. 11. Negative parity states in ^{121}Sb identified in the present experiment by odd L-transfer values (left) compared with the QPM calculations (right).

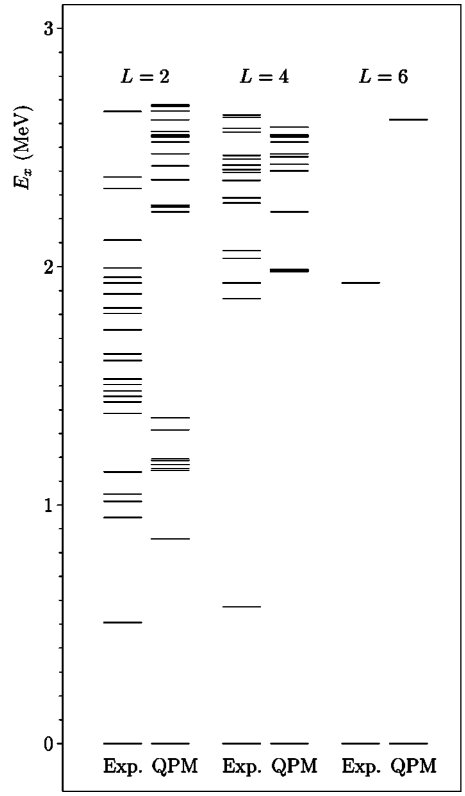

FIG. 12. The same as in Fig. 11 but for positive parity states.

analysis of the angular distributions, calculations predict very weak mixing of different L transfer for practically all excited states.

The experimental spectrum is dominated by states with positive parity. This is not surprising because, above the closed $Z=50$ shell, the first available proton single-particle levels are the $2d_{5/2}$ and $1g_{7/2}$ levels with positive parity, and the $1h_{11/2}$ level with negative parity, the last with an energy about 1 MeV higher. Moreover, the lowest 3^- and 5^- excitations of the ^{120}Sn core, which may change the parity, are more than 1 MeV above the 2_1^+ and 4_1^+ states. Thus, the lowest level with negative parity, and the only one below 2 MeV, has excitation energy of 1.426 MeV. The calculations also predict only one negative parity state below 2 MeV with $J^\pi=11/2^-$. The wave function of this state has the main quasiparticle component $\pi 1g_{7/2}$, with a contribution of 75%.

The very small reaction amplitude for the transition $1g_{7/2}(^{123}\mathrm{Sb})\rightarrow 1h_{11/2}(^{121}\mathrm{Sb})$, as discussed above, accounts for the small excitation cross section of the level at 1.426 MeV (see Table I). The comparison between experimental results and theoretical predictions allows a tentative assignment $J^\pi=11/2^-$ to this level. This is in agreement with the strong $L=5$ transition observed in the $^{120}\mathrm{Sn}(^3\mathrm{He},d)^{121}\mathrm{Sb}$ reaction [13,26] yielding $J^\pi=9/2^-,11/2^-$.

A group of negative parity levels is observed between 2.1 and 2.6 MeV. For negative parity, the calculation gives a number of states concentrated at the right excitation energy, although with a higher density. The angular distributions of cross sections for the three levels at 2.165, 2.312, and 2.545 MeV are well reproduced by an $L=1$ transfer. The wave functions of these states should have a large contribution from $[1g_{7/2}\times 1^-]_{J^-}$ configurations, if they were populated by a one-step excitation process. Furthermore, the lowest 1^- state in ^{120}Sn with two-phonon nature $[2_1^+\times 3_1^-]_{1^-}$ is located at about 3.5 MeV. No 1^- levels below 3 MeV have been observed, either in the $^{122}\mathrm{Sn}(p,t)^{120}\mathrm{Sn}$ reaction [38] or in the nuclear resonance fluorescence experiments [54], the most selective experiments for the excitation of the 1^{-1} states in even-even nuclei. Therefore, none of the $(5/2-9/2)^-$ states below 3 MeV in the present calculations has a structure allowing its excitation by an $L=1$ transfer. The relatively large (p,t) cross sections for these levels, especially for the one at 2.312 MeV, is even more puzzling. The excitation of the levels by $L=3$ and $L=5$ takes place because of the $[1g_{7/2}\times 3_1^-(5_{1,2}^-)]_{J^-}$ transition amplitudes. The other one-phonon states with $J^\pi=3^-$ and $J^\pi=5^-$ in the ^{120}Sn core have energies higher than 3 MeV and their contribution to states in ^{121}Sb below 3 MeV is very small. The number of levels excited by $L=3$ is larger than expected from the $(2J+1)$ rule of a possible multiplet splitting. The theoretical interpretation is very simple. Each member of the multiplet $[1g_{7/2}\times 3_1^-]_{J^-}$, interacting with other $[\mathrm{qp}\times 1\mathrm{ph}]_{J^-}$ configurations of the same spin and parity, admixes and gives a part of its transition amplitude to the last configurations which have their own negligibly small value of the excitation amplitude.

In the present experiment no $L=7$ transitions have been observed. However, in ^{120}Sn a level with $J^\pi=7^-$ has been found at 2.480 MeV in the $^{122}\mathrm{Sn}(p,t)^{120}\mathrm{Sn}$ reaction [38]. In the calculations the multiplet of the $[1g_{7/2}\times 7_1^-]_{J^-}$ states with J ranging from 7/2 to 21/2 is located at about 2.35 MeV and is weakly fragmented, except for the $7/2^-$ component. Since the 7^- level at 2.480 MeV in ^{120}Sn has an integrated cross section of 115 μb, it is not clear why the members of this multiplet, at least those with the largest *J*, have not been observed in the ^{123}Sb$(p,t)^{121}$Sb reaction.

The situation of the positive parity states in ^{121}Sb below 3 MeV is much more complex compared to the negative parity states, due to their higher density. In addition, the number of the positive parity [qp×1ph] configurations which carry nonzero value of the transition amplitude from the $7/2^+$ ground state in ^{123}Sb is much larger. On the contrary, only one 3^-, two 5^-, and one 7^- excited states below 3 MeV have been observed in the ^{122}Sn$(p,t)^{120}$Sn reaction [38]. It has to be noted that only these excitations of the core ^{120}Sn coupled to the $7/2^+$ quasiparticle configuration have a nonvanishing value of the reaction amplitude. The number of the positive parity states in ^{120}Sn observed in the (p,t) reaction is much larger. Establishing a correspondence between them and the one-phonon states in the ^{120}Sn calculations, four 0^+, six 2^+, five 4^+, and one 6^+ states (see Fig. 8) have been assumed to carry the transition amplitude. A few other positive parity state excitations of the core with the smallest values of the (p,t) cross section have been neglected.

The spectrum of the positive parity states identified in the present experiment is compared with the QPM predictions in Fig. 12. The comparison between the experiment and calculations for $L=0$ has already been discussed. Most of the positive parity states in ^{121}Sb are excited by $L=2$ or $L=4$. Only one level at 1.932 MeV has an admixture of $L=6$. It does not match well, either in the excitation energy or in the cross section value, with the level in ^{120}Sn at 2.691 MeV($\sigma_{int}=36.8\,\mu$b) which has been assigned as $(2^+ + 6^+)$. As in the case of negative parity states, the fragmentation of the levels excited by $L=2$ and $L=4$ transfers is somewhat underestimated, especially for the $L=2$ transfer in the energy region between 1.4 and 1.9 MeV. By considering excitation energy and reaction cross section arguments, we can infer that the levels in this energy region carry some fragments of the $[1g_{7/2}\times 2_1^+]_{J^+}$ configurations. Above 1.9 MeV the calculated states are much more numerous than the experimental states. It is clear that many levels may be missed because of low cross sections.

IV. SUMMARY

Accurate measurement of the (p,t) reaction differential cross sections for the transitions to the levels of ^{121}Sb nucleus allows us to confirm or determine energies of 66 levels, 33 of which have been seen for the first time, and to determine the angular momentum transfer values for 64 levels. The *L*-transfer values allow us unambiguously to assign parity to these levels and to determine a well-defined range for the *J* values. The experimental reaction data have been analyzed by using conventional Woods-Saxon potentials for the entrance proton and exit triton channel. The DWBA calculations have been performed in the finite range approximation. A dineutron cluster pickup mechanism describes the angular distributions rather well.

In order to achieve a better understanding of the experimental results, the present (p,t) data have been supplemented by microscopic calculations. The calculations carried out for the ^{121}Sb excited states with J^π from $1/2^\pm$ to $19/2^\pm$ up to an excitation energy of 3.5 MeV, give a reasonably good description of the experimental fragmentation of the cross sections and the absence of the (p,t) strength above 2.7 MeV.

Four experimental $7/2^+$ states identified in the energy range between 2.1 and 2.5 MeV are well reproduced by the theoretical calculations, not only in regard to their energies, but also in regard to the integrated cross sections.

Simplified calculations in which the unpaired quasiparticle is considered as a pure spectator are able to reproduce the general features of the (p,t) cross section distribution, but fail to describe the fragmentation.

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[1] K. A. Erb and T. S. Bhatia, Phys. Rev. C **7**, 2500 (1973).
[2] I. C. Oelrich, K. Krien, R. M. Del Vecchio, and R. A. Naumann, Phys. Rev. C **14**, 563 (1976).
[3] E. Gadioli, P. Guazzoni, S. Mattioli, L. Zetta, G. Grew, R. Hertenberger, D. Hofer, H. Kader, P. Schiemenz, R. Neu, H. Abele, and G. Staudt, Phys. Rev. C **43**, 2572 (1991).
[4] E. Gadioli, P. Guazzoni, M. Jaskola, L. Zetta, G. Graw, R. Hertenberger, D. Hofer, H. Kader, P. Schiemenz, R. Neu, and G. Staudt, Phys. Rev. C **47**, 1129 (1993).
[5] P. Guazzoni, M. Jaskola, L. Zetta, G. Graw, R. Hertenberger, D. Hofer, P. Schiemenz, U. Atzrott, R. Neu, and G. Staudt, Phys. Rev. C **49**, 2784 (1994).
[6] P. Guazzoni, M. Jaskola, L. Zetta, J. Gu, A. Vitturi, G. Graw, R. Hertenberger, D. Hofer, P. Schiemenz, B. Valnion, U. Atzrott, G. Staudt, and G. Cata Danil, Z. Phys. A **356**, 381 (1997).
[7] P. Guazzoni, M. Jaskola, L. Zetta, J. Gu, A. Vitturi, G. Graw, R. Hertenberger, P. Schiemenz, B. Valnion, U. Atzrott, and G. Staudt, Eur. Phys. J. A **1**, 365 (1998).
[8] J. N. Gu, A. Vitturi, C. H. Zang, P. Guazzoni, L. Zetta, G. Graw, M. Jaskola, and G. Staudt, Phys. Rev. C **55**, 2395 (1997).
[9] R. E. Snyder and G. B. Beard, Nucl. Phys. **A113**, 581 (1968).
[10] J. M. R. Hutchinson, F. J. Schima, and B. M. Coursey, Phys. Rev. C **18**, 408 (1978).
[11] H. H. Hansen, D. Mouchel, and A. Nylandsten Larsen, Z. Phys. A **305**, 347 (1982).
[12] R. A. Meyer, R. G. Lanier, and J. T. Larsen, Phys. Rev. C **12**, 2010 (1975).
[13] P. D. Barnes, C. Ellegaard, B. Herskind, and M. C. Joshi,

Phys. Lett. **23**, 266 (1966).
[14] D. S. Andreev, P. A. Voronova, K. I. Erokhina, V. S. Zvonov, A. S. Mishin, and A. A. Pasternak, IZV. Akad. Nauk. USSR, Ser. Fiz. **39**, 1631 (1975) [Bull. Acad. Sci. USSR, Phys. Ser. **39**, 5 (1975)].
[15] K. C. Jain, K. P. Singh, G. Singh, S. S. Datta, and I. M. Govil, Phys. Rev. C **40**, 2400 (1989).
[16] P. Richard, C. F. Moore, J. A. Becker, and J. D. Fox, Phys. Rev. **145**, 971 (1966).
[17] L. Veeser and J. Ellis, Nucl. Phys. **A115**, 185 (1968).
[18] R. Arking, R. N. Boyd, J. C. Lombardi, and A. B. Robbins, Nucl. Phys. **A240**, 235 (1975).
[19] W. M. Stewart, N. Baron, and R. F. Leonard, Phys. Rev. **171**, 1316 (1968).
[20] F. R. Metzger and M. Longhoff, Phys. Rev. **132**, 1753 (1963).
[21] E. C. Booth, R. G. Arnold, and W. J. Alston, Phys. Rev. C **7**, 1500 (1973).
[22] G. Endres, H. Langhoff, W. Mückenheim, F. Wolf, P. Rullhusen, F. Smend, and M. Schumacher, Z. Phys. A **302**, 61 (1981).
[23] E. Barnard, N. Coetzee, J. A. M. de Villiers, D. Reitmann, and P. van der Merwe, Nucl. Phys. **A172**, 215 (1971).
[24] H. R. Hooper, P. W. Green, H. E. Siefken, G. C. Neilson, W. J. McDonald, D. M. Sheppard, and W. K. Dawson, Phys. Rev. C **20**, 2041 (1985).
[25] W. P. Piel, Jr., P. Chowdhury, U. Garg, M. A. Quader, P. M. Stwertka, S. Vajda, and D. B. Fossan, Phys. Rev. C **31**, 456 (1985).
[26] T. Ishimatsu, K. Yagi, H. Ohmura, Y. Nakajima, T. Nakagawa, and H. Orihara, Nucl. Phys. **A104**, 481 (1967).
[27] M. Conjeaud, S. Harar, M. Caballero, and N. Cindro, Nucl. Phys. **A215**, 383 (1973).
[28] T. Tamura, H. Iimura, K. Miyanic, and S. Ohya, Nucl. Data Sheets **64**, 323 (1991).
[29] P. D. Barnes, E. R. Flynn, G. J. Igo, and R. Woods, Bull. Am. Phys. Soc. **12**, 19 (1967).
[30] E. U. Baranger, Adv. Nucl. Phys. **4**, 261 (1971).
[31] G. Vanden Berghe and E. Degrieck, Z. Phys. **262**, 25 (1973).
[32] K. Heyde, P. Van Isacker, M. Waroquier, J. L. Wood, and R. A. Meyer, Phys. Rep. **102**, 291 (1983).
[33] V. G. Soloviev, *Theory of Complex Nuclei* (Pergamon, Oxford, 1976).
[34] V. G. Soloviev, Ch. Stoyanov, and A. I. Vdovin, Nucl. Phys. **A342**, 261 (1980).
[35] A. I. Vdovin, V. G. Soloviev, and Ch. Stoyanov, Yad. Fiz. **20**, 1131 (1974) [Sov. J. Nucl. Phys. **20**, 593 (1975)].
[36] Nguyen Dinh Thao, V. G. Soloviev, Ch. Stoyanov, and A. I. Vdovin, J. Phys. G **10**, 517 (1984).
[37] E. Zanotti, M. Bisenberger, R. Hertenberger, H. Kader, and G. Graw, Nucl. Instrum. Methods Phys. Res. A **310**, 706 (1991).
[38] P. Guazzoni, M. Jaskola, L. Zetta, A. Covello, A. Gargano, Y. Eisermann, G. Graw, R. Hertenberger, A. Metz, F. Nuoffer, and G. Staudt, Phys. Rev. C **60**, 054603 (1999).
[39] J. R. Comfort, ANL Physics Division, Informal Report PHYS-1970B, 1970.
[40] M. Igarashi, computer code TWOFNR (1977) (unpublished).
[41] F. G. Perey, Phys. Rev. **131**, 745 (1963).
[42] D. G. Fleming, M. Blann, H. W. Fulbright, and J. A. Robbins, Nucl. Phys. **A157**, 1 (1970).
[43] R. L. Varner, W. J. Thompson, T. L. McAbee, E. J. Ludwig, and T. B. Clegg, Phys. Rep. **201**, 57 (1991).
[44] R. A. Hardekopf, R. F. Haglund, Jr., G. G. Ohlsen, W. J. Thompson, and L. R. Veeser, Phys. Rev. C **21**, 906 (1980).
[45] G. Cata-Danil, P. Guazzoni, M. Jaskola, L. Zetta, G. Graw, R. Hertenberger, D. Hofer, P. Schiemenz, B. Valnion, E. Zanotti-Müller, U. Atzrott, F. Hoyler, F. Nuoffer, and G. Staudt, J. Phys. G **22**, 107 (1996).
[46] J. Ball, Phys. Rev. C **6**, 2139 (1972).
[47] P. Guazzoni, L. Zetta, M. Jaskola, J. N. Gu, A. Vitturi, Y. Eisermann, G. Graw, R. Hertenberger, and G. Staudt, Proceedings of the XXVI Mazurian Lakes School of Physics, Krzyze, 1999 [Acta Phys. Pol. B **31,** 417 (2000)].
[48] V. Yu. Ponomarev, V. G. Soloviev, Ch. Stoyanov, and A. I. Vdovin, Nucl. Phys. **A323**, 446 (1979).
[49] R. A. Broglia, O. Hansen, and C. Riedel, Adv. Nucl. Phys. **6**, 287 (1973); D. R. Bes, R. A. Broglia, O. Hansen, and O. Nathan, Phys. Rep., Phys. Lett. **34C**, 1 (1988).
[50] V. Yu. Ponomarev, M. Pignanelli, N. Blasi, A. Bontempi, J. A. Bordewijk, R. De Leo, G. Graw, M. N. Harakeh, D. Hofer, M. A. Hofstee, S. Micheletti, R. Perrino, and S. Y. van der Werf, Nucl. Phys. **A601**, 1 (1996).
[51] A. I. Vdovin, V. V. Voronov, V. G. Soloviev, and Ch. Stoyanov, Fiz. Elem. Chastists At. Yadra **16**, 245 (1985) [Sov. J. Part. Nucl. **16**, 105 (1985)].
[52] S. Gales, Ch. Stoyanov, and A. I. Vdovin, Phys. Rep. **166**, 125 (1988).
[53] J. Bryssinck, L. Govor, V. Yu. Ponomarev, F. Bauwens, O. Beck, D. Belic, P. von Brentano, D. De Frenne, C. Fransen, R.-D. Herzberg, E. Jacobs, U. Kneissl, H. Maser, A. Nord, N. Pietralla, H. H. Pitz, and V. Werner, Phys. Rev. C **62**, 014309 (2000).
[54] J. Bryssinck, L. Govor, D. Belic, F. Bauwens, O. Beck, P. von Brentano, D. De Frenne, T. Eckert, C. Fransen, K. Govaert, R.-D. Herzberg, E. Jacobs, U. Kneissl, H. Maser, A. Nord, N. Pietralla, H. H. Pitz, V. Yu. Ponomarev, and V. Werner, Phys. Rev. C **59**, 1930 (1999).