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1. INTRODUCTION

Large scale investigations have been reported showing the (p,t) reaction to be a very useful spectroscopic tool over a wide range of nuclei [1,2]. It should be said, however, that experimental data have been accumulated demonstrating that the simple DWBA calculation fails to account for the angular distributions and the absolute magnitudes of the cross sections [3-7]. In view of this, during the past few years considerable effort has been devoted to revising the applicability of this spectroscopie tool [4-7]. Thus the first thing to do is to clarify the mechanism of the transfer reaction in question and with this knowledge any reasonable spectroscopic information /spectroscopic factors/ could be hoped to be evaluated from reaction analysis.

We have investigated the two-neutron transfer reaction on even-even Sm isotopes which are known to have a strong collective nature. Some of their states, namely the low-lying collective states, have been found [3] to have rather flat angular distributions not characteristic of any particular l-transfer and are left without any satisfactory explanation. Concerning the reaction mechanism, difficulties can arise particularly for cases where the final nuclear states even at low excitation have a parentage that is based rather on an excited state of the parent nucleus. than on its ground state; the coupling between the elastic and other reaction channels in the case of collective states, the inelastic channels being the most important ones, is sufficiently strong. The transition can then proceed through two-step processes involving inelastic scattering and (2n)-transfer. In this case the one-channel optical model used in constructing the scattering state wave functions for the DWBA calculation breaks down and the coupled channels Born approximation /CCBA/ including inelastic scattering has to be used.

A study of the cross sections for the partial reactions may then suggest which states are likely candidates for access by the two-step process. In general, both the single- and the two-step processes feed a state, they contribute coherently to the (p,t) cross section and the interference between them will affect both the cross section magnitude and the shape of angular distribution.

The aim of this work was to explore the role of multi-step processes in (p,t) reactions on Sm isotopes. We selected some particular states in ^{146,148,152}Sm nuclei to see whether their excitations could be satisfactorily accounted for by multi-step sequential processes involving inelastic excitations followed and/or preceded by a two-neutron transfer with these channels properly coupled together.

2. CCBA ANALYSIS OF THE ^{148,150,154}Sm(p,t) REACTIONS AT E_p=25 MeV

We assumed that the (p,t) reaction is predominantly direct at the present bombarding energy. The coupled channels calculations were performed using the coupled channels Born approximation code CHUCK [8]. According to the assumed excited-core picture the target nucleus (A+2) is described as

$$|A+2\rangle \longrightarrow |A \otimes (2n)\rangle$$

where the core A having a collectivity may or may not be excited. In the case of vibrational nuclei $^{146,148,150}Sm$ there are excited states of two quasiparticle configurations the lowest of which is the collective $2_1^+(3_1^-)$ one-phonon /quadrupole or octopole/ state. The next $4^+(6^-, 5^-)$ two-phonon states are four quasi-particle states and therefore cannot be connected with the ground-state by a two-particle process. In one-step two-nucleon transfer transition these states would have to be populated via their two quasiparticle components only. It means that the main parent of the two-phonon states is, in any case, the collective 2_1^+ state and the two-nucleon transfer reaction connecting them to this state is enhanced in the same sense as the transition from the ground state to the one-phonon state is enhanced. The low lying 2^+, 4^+ levels in rotational nuclei $^{152,154}Sm$ have a similar two- and four quasiparticle character and the enhancement and/or hindrance of two-nucleon transfer has the same physical ground. The two-neutron transfer formfactors are calculated in zero-range approximation and using the method suggested by Bayman and Kallio [9] /TNFF/.

In this calculations the neutrons were assumed to be bound in real Woods-Saxon wells having a radius parameter of 1.25 fm, diffuseness = 0.65 fm and a depth constrained to fit the half of binding energy of the transferred two-neutrons. It is to be noted, a nonzero spin-orbit term was used in the bound-state calculation only in a test run of the code, because omitting it there was no significant effect on the results.

A test calculation was carried out also, using cluster transfer form factors for single-step transitions with values of transferred angular momentum to reveal differences, if it is any, between the two form factor calculation methods for two-neutron transfer reaction. The bound-state wave functions in these cases were the usual Woods-Saxon wave functions in which the transferred (2n)-particle is bound to the core in a single-particle type cluster state. The depth of the potential well was adjusted to give the known (2n) separation energy. The potential parameters were the same as for the single neutron used in TNFF calculation. The radial quantum numbers N and L were fixed by the Talmi-Moshinsky transformation from the single nucleon to cluster coordinates /Table 1/, assuming the same possible configurations of the transferred nucleons as in case of TNFF calculations.

The results are displayed in Fig. 1. The TNFF and cluster transfer calculations are in reasonable agreement with each other.

For the inelastic processes conventional macroscopic collective form factors were used. The optical potentials and the deformation parameters for the proton inelastic scattering were derived from our coupled channels analysis of elastic and inelastic proton scattering on the even-even Sm isotopes [10]. For triton parameters we used those of Mulligan et al. [11] based on an analysis of triton scattering on ^{138,140,142}Ce nuclei at E_t=15 MeV and extrapolated in energy and N-Z according to a reasonable guess. The deformation parameters for triton inelastic scattering are extracted from the macroscopic deformation lengths $(\beta_\lambda r_0^p = \text{const.})$ evaluated from proton scattering analysis. Two-way coupling treatments were made for inelastic scattering processes.

The possible intermediate channels of importance for multi-step processes are schematically shown in Fig. 2 for the (p,t) reactions in the case of the various Sm nuclei. The spectroscopic data used for calculation are also shown. For transfer transitions between states with spins I_i and I_f, where I_i, $I_f \neq 0$ the contributions to the transfer strengths from the other possible transfer processes with $\ell_{tr} > |I_f - I_i|$ are found to be negligable.

The complete calculations for the ^{148}Sm(p,t)^{146}Sm, ^{150}Sm(p,t)^{148}Sm and ^{154}Sm(p,t)^{152}Sm reactions at 25 MeV are presented in Figs. 3, 4 and 5 respectively. The two-neutron spectroscopic amplitudes /relative to ground state ones/ as free parameters were varied to achieve good agreement with the experimental cross section. The two features that determine the strength of the coupling between a pair of states are the fraction of the parentage of the state in the heavier nucleus that is based on the other nucleus, and the degree to which the extra pair of neutrons is correlated in the way it exists in the triton.

The relative spectroscopic amplitudes evaluated from CCBA analysis are shown in Table 2. The amplitudes relating two excited states in target and final nuclei are new and can be provided by multi-step process analysis only, in contrast to one step analysis based on the target ground state. As can be seen in Figs. 3-5 good agreement both in shape and size between experimental and calculated differential cross sections is obtained for states excited through a two-step mechanism, and direct excitation is allowed also. The importance of using coupled channels treatment in such cases can hardly be questioned.

3. SUMMARY

We have used a zero-range coupled channels Born approximation to explain the two-neutron transfer reactions $^{148,150,154}Sm$ (p,t) leading to the low-lying excited states of final nuclei. On comparing the theoretical calculations with experimental data we have noticed that there are serious deficiencies in the ability of the single-step calculations to describe adequately the shapes and magnitudes of the angular distribution; we also point out the importance of the higher order processes. For both the vibrational and permanently deformed Sm nuclei, consistent agreement has been found assuming the multi-step reaction mechanism including inelastic excitation of the collective low-lying states in both the target and final nuclei, when the coupling is strong and when there exist several competing routes through collective excitations. The coupled channels analysis has resulted in new spectroscopic information which could not be provided by the usual simple DWBA method.

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ABSTRACT

The simple assumption of a direct one-step two-neutron transfer often fails to explain the /p,t/ reaction. For this reason, experimental /p,t/ angular distributions previously measured at 25.5 MeV on even Sm isotopes were reanalysed. It was found that the observed transitions to low-lying collective states, with anomalously shaped angular distributions, were consistent with a two-step reaction mechanism including two-neutron transfer and inelastic excitations both in target and in final nucleus.

АННОТАЦИЯ

Были исследованы реакции /p, t/ на четных протонах при энергии бомбардирующих частиц 25,5 Мэв. Наблюдаемые переходы к низко лежащим коллективным состояниям, где угловое распределение - аномальное, не удалось объяснить при предположении одношаговой двухнейтронной передачи. Для анализа реакций /p,t/ был проведен расчет, принимающий во внимание переходы более высокого порядка через промежуточные состояния. Величина непрямых переходов, содержащих инеластическое возбуждение как мишени, так и конечного ядра, имела почти такое значение, как и прямых переходов. Было достигнуто удовлетворительное согласие как по форме, так и по величине углового распределения в полном диапазоне ядер, где в свойствах ядер наблюдается переход от выбрационного до перманентно-деформированного.

KIVONAT

Az egyszerü direkt, egy-lépéses két-neutron transfer modell feltételezésével a /p,t/ reakciókat gyakran nem sikerül leirni. Ezért a 25.5 MeV energián, korábban mért /p,t/ szögeloszlásokat ujra analizáltuk. Azt találtuk, hogy az alacsonyan fekvő kollektiv állapotokhoz vezető átmenetek, amelyek anomalis szögeloszlással rendelkeznek, jól értelmezhetők két-lépéses reakció mechanizmus feltételezésével, amelyben két-neutron transfer és mind a bemenő, mind a kimenő csatornákban inelastikus szórások játszódnak le.

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Table 1.

Cluster transfer quantum numbers and possible configurations of the transferred neutrons for the $^{148}Sm(p,t)^{146}Sm$ reaction.

Transition	quantum numbers N	L	S	ℓ_{tr}	configurations
$0^+ \rightarrow 0^+$	6	0	0	0	$(2f7/2)^2$
$0^+ \rightarrow 2^+$	4	2	0	2	$(2d3/2)^2$
$0^+ \rightarrow 3^-$	4	3	0	3	$(2d5/2)(2f7/2)$
$0^+ \rightarrow 4^+$	3	4	0	4	$(1g7/2)^2$

Table 2

Particle transfer relative spectroscopic amplitudes: $a^{j}_{j_1 j_2} = A^{j}_{j_1 j_2} / A_{g.s.}$. The notation $(2j_1, 2j_2)j$ is 2 X angular momentum in orbitals coupled to angular momentum j.

parent st. / final st.		$a^{j}_{j_1 j_2}$ $(2j_1, 2j_2)j$ 0^+_1		2^+_1		3^-_1		4^+_1	
^{146}Sm	0^+	(7,7)0	1.						
	2^+	(3,3)2	.87	(7,7)0	.6				
	4^+	(7,7)4	-1.2					(3.3)2	.68
^{148}Sm	0^+	(7,7)0	1.						
	2^+	(3,3)2	.95	(7,7)0	1.23				
	3^-	(5,7)3	.82			(7,7)0	-0.5		
^{152}Sm	0^+	(7,7)0	1.						
	2^+	(3,3)2	.94	(7,7)0	.61				
	4^+			(3,3)2	.71			(7,7)0	0.67

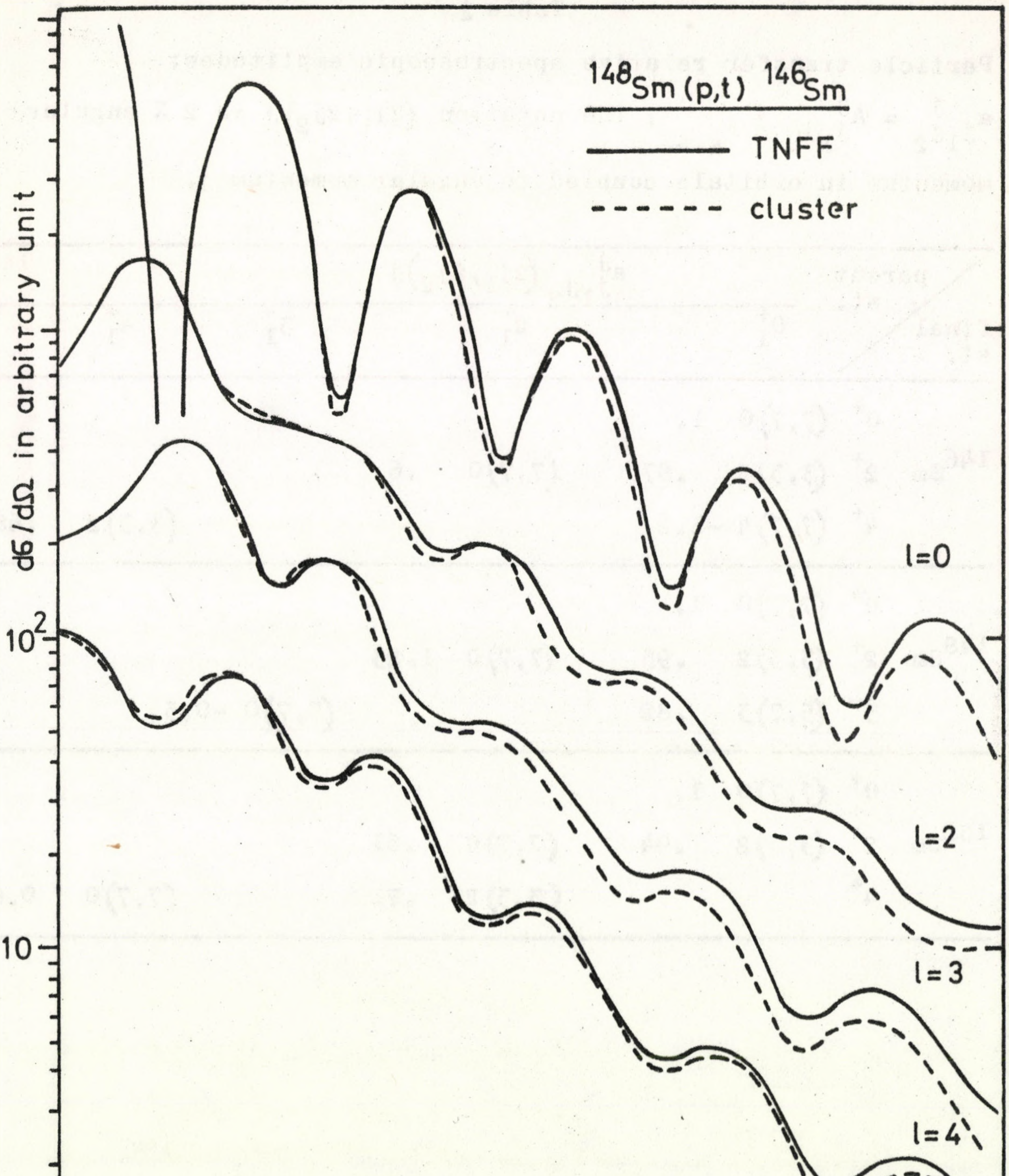

Fig.1. Comparison of the angular distributions of $^{148}Sm(p,t)^{146}Sm$ reaction for different values of l_{tr} arising from TNFF and cluster transfer calculations

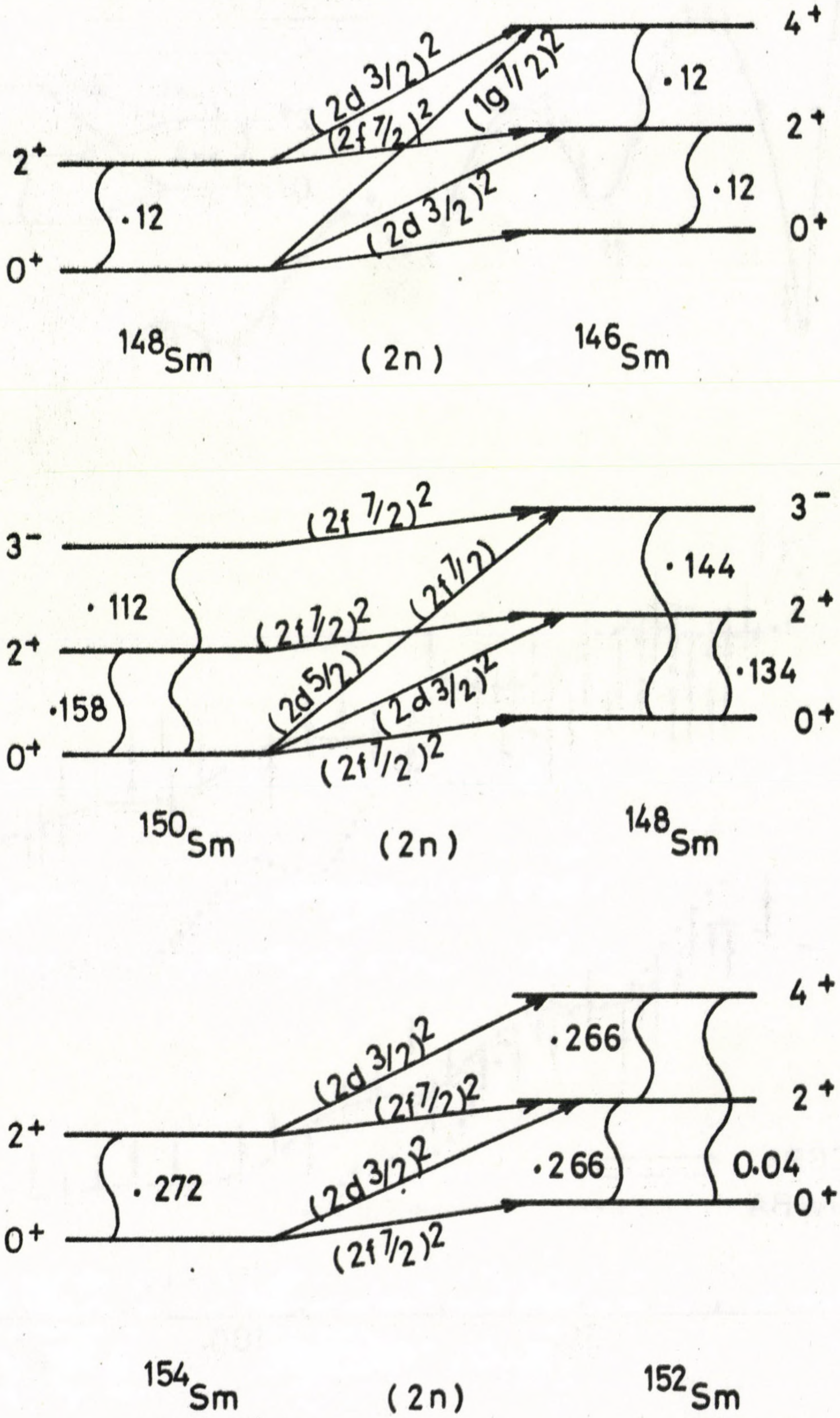

Fig. 2. Coupling schemes used in the CCBA calculations

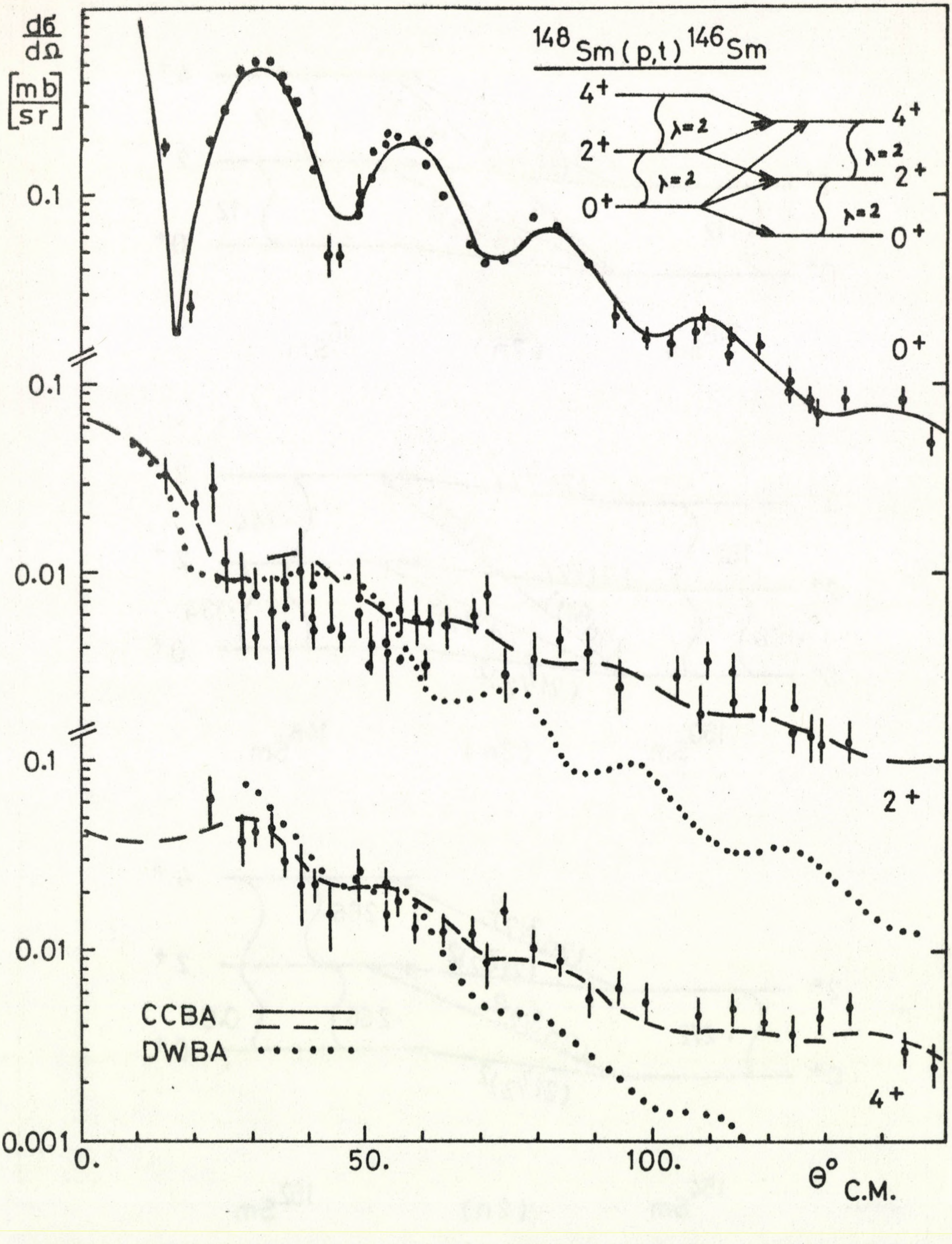

Fig. 3. Angular distributions of $^{148}Sm(p,t)^{146}Sm$ reaction leading to the low lying vibrational collective states

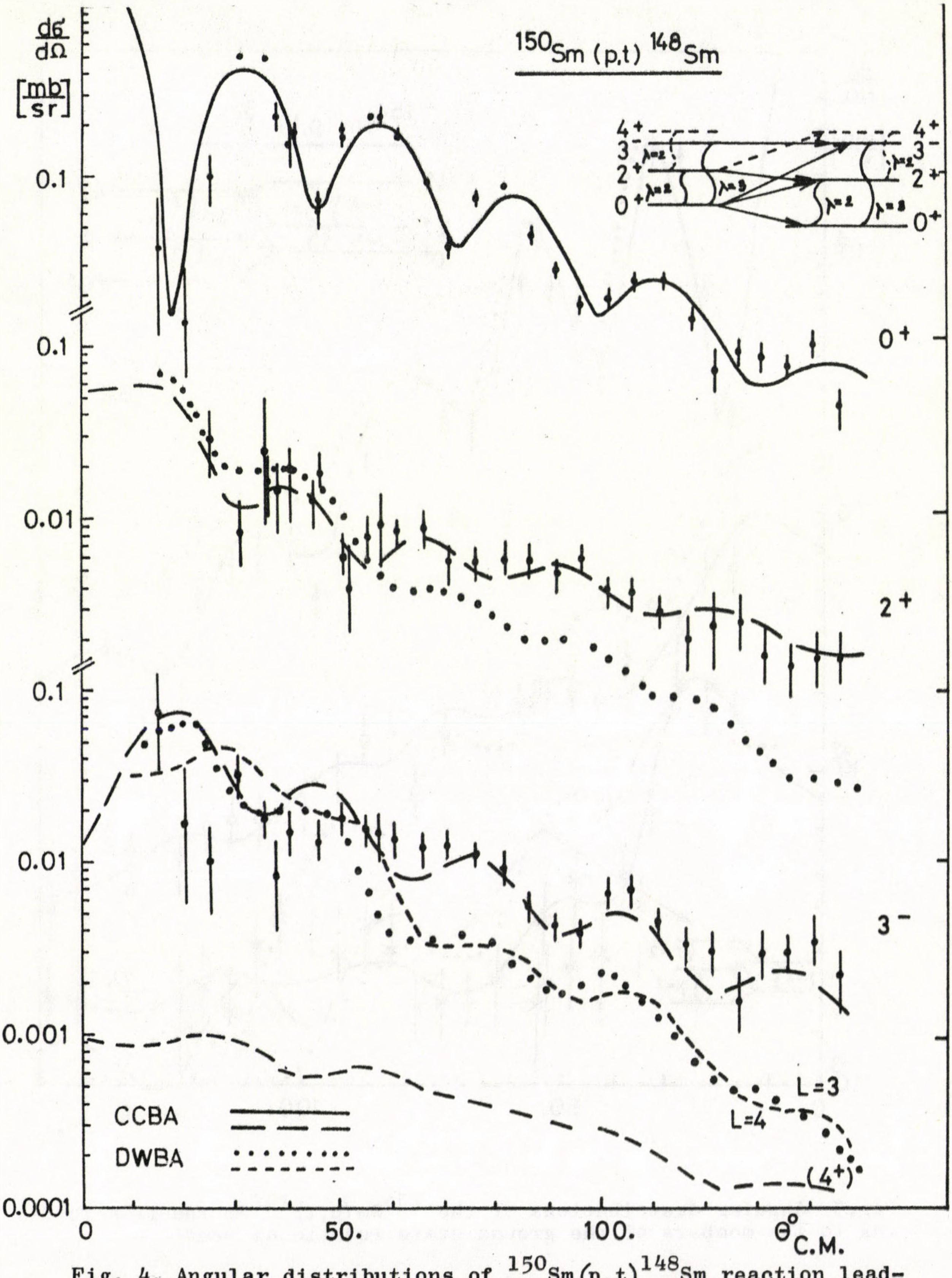

Fig. 4. Angular distributions of $^{150}Sm(p,t)\,^{148}Sm$ reaction leading to the low lying vibrational collective states

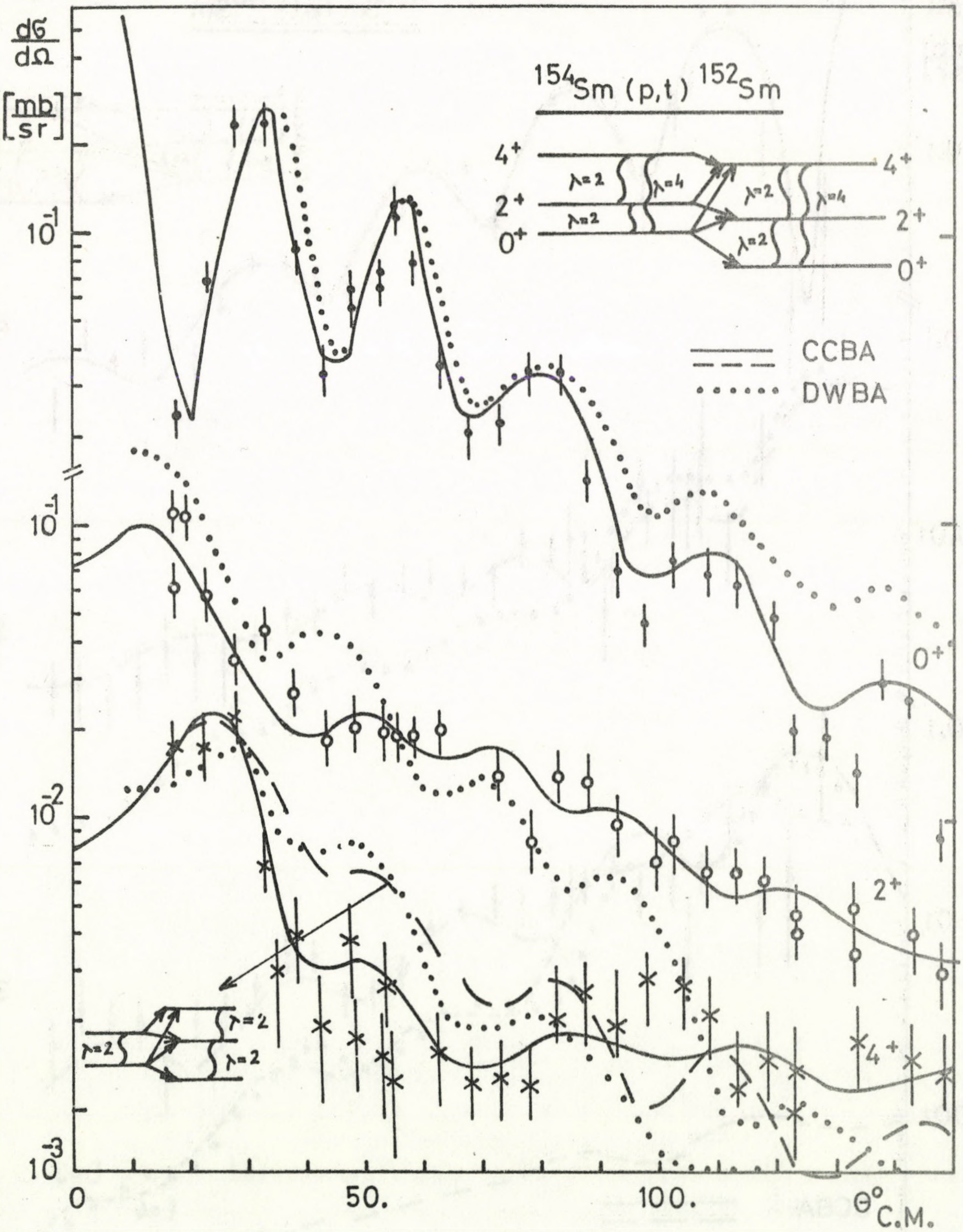

Fig.5. Angular distributions of the $^{154}Sm(p,t)^{152}Sm$ reaction leading to the members of the ground state rotational band

62.703

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