Investigation of 0^+ strength in ^{150}Sm using the (p,t) reaction

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Abstract.   The aim of this investigation is to reveal the structure of ^{150}Sm by measuring for the first time a rather complete set of energy levels of this nucleus up to 4 MeV and determine the total angular momentum of the states. The study was carried out at the 14 MV Tandem Accelerator of the Munich universities by measuring complete angular distributions for states up to 4 MeV excited in the direct two-neutron transfer reaction ^{152}Sm(p,t)^{150}Sm at an incident energy of 22 MeV. Emphasis was put on determining the 0^+ excited states, which are some of the most important excitations in the rare-earth region. Up to now only three 0^+ levels are known in ^{150}Sm, and investigating the distribution of energy and intensity of these excited states also at higher excitation energy might reveal the main contributions in the wave functions of this nucleus.

1. Introduction

The presence of negative-parity states in the low-lying structure of even-even atomic nuclei has been observed in the early days of nuclear physics [1]. These characteristics have been associated with the presence of octupole degrees of freedom, some of the lowest collective modes observed. The octupole deformation has been revealed experimentally only recently in the case of actinides [2]. Since the vibrational spectra are usually interpreted in terms of phonons, these observations led to a search of double-octupole phonon states, similar to the well-known two-phonon states in the case of quadrupole states. The presence of an increased number of 0^+ states in several nuclei has been interpreted with the Interacting Boson Model (IBM) using *spdf* bosons as having mainly *2pf* bosons in their structure [3],[4],[5],[6]. At the same time, the calculations with the Quasiparticle Phonon Model (QPM) show in most of the cases a completely different picture: the octupole phonons are predicted to play a relatively modest role especially at lower excitation energies, indicating that the structure of the lowest excited 0^+ states is described as originating from pairing vibrations [3],[4],[6],[7]. However, the QPM somehow fails to describe

the B(E1)/B(E2) ratio connecting positive and negative parity states in these nuclei, as shown in Refs [6],[7],[8] for the case of ^{232}U. This debate can only be solved if the appropriate states and their decays are measured with great accuracy throughout the nuclear chart. One of the best place to search for such examples is the region of N=88 (^{144}Ba-^{146}Ce-^{148}Nd-^{150}Sm-^{152}Gd-^{154}Dy), which is one of the so-called *octupole-driving numbers* where octupole correlations are estimated to be strong.

2. Experiment details and results

The data analyzed in this paper were obtained by using a (p,t) transfer reaction at an incident energy of the proton of 22 MeV. Protons were accelerated by the Tandem accelerator installed in the Maier-Leibnitz-Laboratory for Nuclear and Particle Physics of LMU Munich and TU Munich. The obtained tritons were analyzed using the Q3D magnetic spectrometer [9] and detected with a system [10] consisting of several detectors, two proportional counters and a plastic scintillator for residual energy measurement.
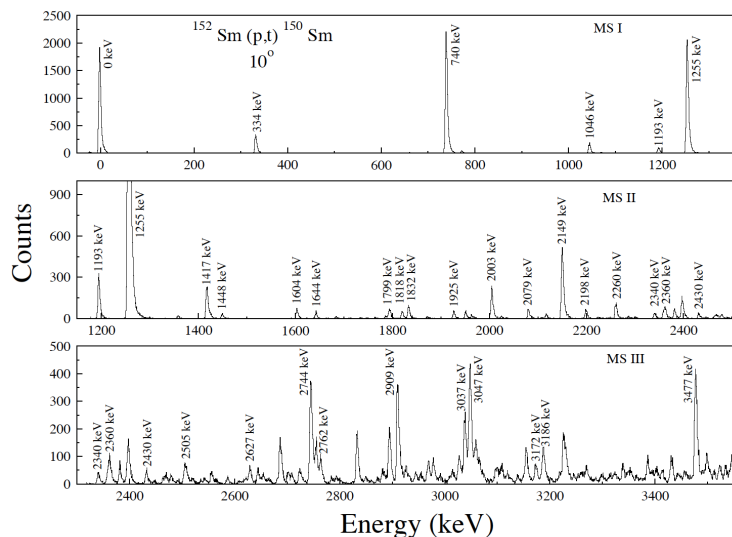

**Figure 1.** Tritons spectra obtained for the three magnetic settings at 10°.

In this experiment the measurements were made using a target with a thickness of 49 μg/cm^2, deposited on a thin carbon foil. The beam current intensity was about 1.7 μA, and the experimental cross sections were obtained by normalizing the resulting peak area to the thickness of target, the solid angle and to the beam charge which was obtained by integrating the current from the Faraday cup. The very good energy resolution, of about 5-10 keV, determined mainly by the thickness of the target, allowed us to observe most of the populated states up to about 4 MeV at the three magnetic settings which include an overlap in energy.

The first magnetic setting allowed to cover an energy region up to 1.3 MeV and the spectra were measured at laboratory angles of 5°, 10°, 14°, 17°, 20°, 25°, 30°, 35° and 40°. The second magnetic setting covered an energy region up to 2.5 MeV, while the last magnetic setting was extending up to 4 MeV. Spectra were measured at the same angles in each of the three magnetic settings.

In Figure 1 the tritons spectra measured at all magnetic settings at the angle of 10° are presented and the energies of the strongly populated levels in the reaction ^{152}Sm(p,t)^{150}Sm are highlighted. For the interpretation of the spectra obtained at the three magnetic settings, an energy calibration was performed using the ^{154}Gd(p,t)^{152}Gd and ^{172}Yb(p,t)^{170}Yb calibration

Table 1. Energies and cross sections at 5°, 17° and 30° for 0^+ excited states obtained in this study .

Energy (keV)	Cross section (μb/sr)		
	5°	17°	30°
0.0	1083.5(73)	21.4(10)	368.6(36)
740.5	999.4(70)	20.3(9)	320.5(34)
1255.2	899.5(67)	14.0(8)	239.0(29)
1604.9	7.5(3)	0.2(7)	2.1(2)
2079.9	6.3(3)	0.2(7)	1.6(1)
2149.1	54.3(8)	6.5(3)	9.2(3)
2627.6	5.2(2)	1.0(1)	1.3(1)
2744.0	33.9(5)	4.9(2)	10.2(3)
2909.8	31.0(5)	2.7(1)	7.9(2)
3186.8	11.3(3)	2.6(2)	4.2(2)
3477.7	31.8(5)	4.3(2)	11.7(3)
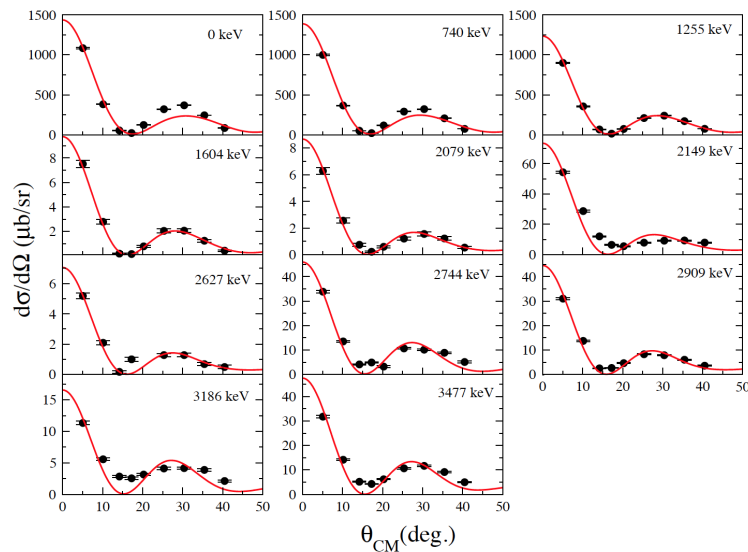
Figure 2. Experimental angular distributions (dots) and DWBA calculations (line) for transferred angular momentum L=0 .

reactions measured in the same magnetic conditions. The program used to analyze the spectra obtained in this experiment is called RadWare [11]. This program is a software package used for interactive graphical analysis and for the study of nuclear structure.

In order to obtain the value of the transferred angular momentum L, we compared the experimental angular distributions with those obtained from the calculations made using DWBA method [12]. In terms of numerical calculations we used CHUCK3 code [13] and we assumed in a first step that the (p,t) reaction which we investigated took place in a single step process. The optical model parameters used in performing the DWBA calculations were taken from [14].
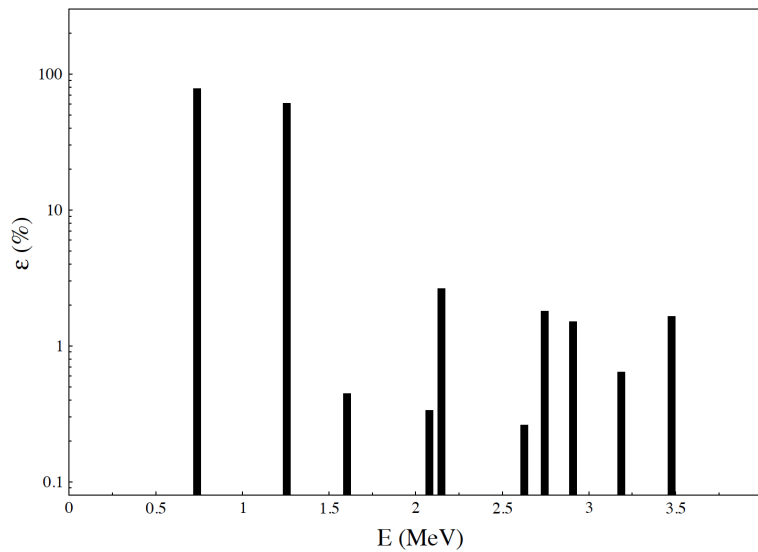
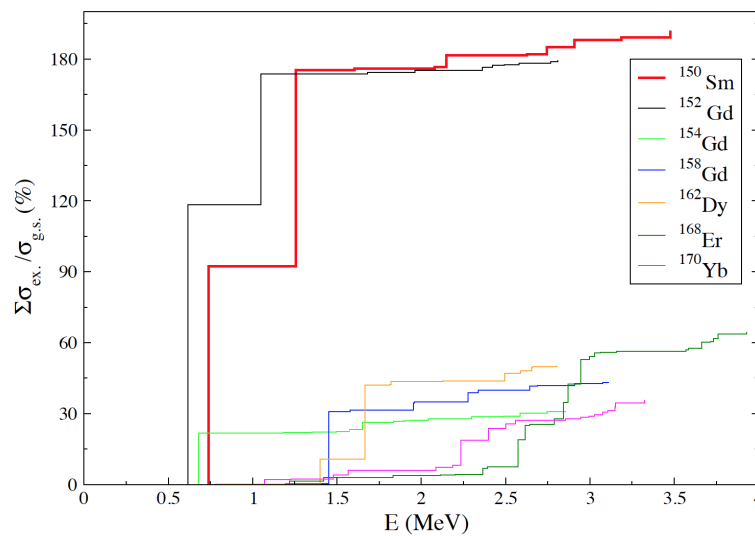**Figure 3.** Transfer strength for 0^+ excited states.

Figure 4. Comparison between cumulative transfer strengths for 0^+ excited states in nuclei from rare-earth region.

In Table 1 the energies and cross sections at $5°$, $17°$ and $30°$ for 0^+ excited states obtained in this investigation are presented. In Figure 2 the experimental angular distributions (black dots) and DWBA calculations (red line) for transferred angular momentum $L = 0$ are displayed. It can be observed that eleven angular distributions were obtained in the center of mass system for the states 0^+ from which eight, namely at the energies 1604 keV, 2079keV, 2149 keV, 2627 keV, 2744 keV, 2909 keV, 3186 keV and 3477 keV, are new, whereas the other three states were confirmed. In Figure 3 and in Figure 4 are presented both the transfer strength and the cumulative transfer strengths for 0^+ excited states in rare-earth nuclei. As can be seen in Figure 3 and in Ref. [15] the transfer strengths to the first two 0^+ excited states for ^{150}Sm, studied here, and ^{152}Gd are very strong in comparison with the transfer strengths to the other excited

states. In Figure 4 is presented a comparison between cumulative transfer strengths for 0^+ excited states in nuclei from rare-earth region and we can observe a difference between the data for ^{150}Sm and ^{152}Gd and the other nuclei. This difference is due to the shape coexistence.

In Figure 3 is presented the transfer strength for the 0^+ states seen in the present experiment. One can observe that the intensity of the first two excited levels is approximately constant, and roughly at the same level as the ground state. This situation is similar with the case of ^{152}Gd [15], where a similar pattern was interpreted as arising from the shape coexistence of spherical and deformed configurations. Such an argument is supported by the experimental data also in ^{150}Sm.

This situation can be seen even better in Figure 4, where we compare the cumulative transfer strength for all the nuclei in the rare-earth region where recent (p,t) experiments have been performed [15], [16], [17]. For several nuclei it was shown that the increased number of 0^+ states observed can be related with the presence of double *pf* states in the IBM. This will be investigated in the near future in the case of ^{150}Sm, while more microscopic calculations would be very helpful to asses the structure of these states.

3. Conclusions

We have presented an investigation of the nucleus ^{150}Sm from the experimental point of view using the (p, t) transfer reaction. We presented the experimental conditions and the results obtained such as the new levels observed after the spectra analysis and the confirmation of the existence of most states previously known based on the comparison between the experimental angular distributions and the calculations made by using Distorted Wave Born Approximation. From the present data eleven angular distributions were obtained for the 0^+ excited states from which eight are new, while the other three states were confirmed.

4. Acknowledgments

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