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Short note

New states and γ-transitions in ^{209}Bi observed in the (^{3}He, d$^*\gamma\gamma$)-subcoulomb-reaction

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Abstract. Single-particle states as well as collective states in the natural Bismuth isotope ^{209}Bi were investigated using two EUROBALL CLUSTER detectors at the Cologne FN-tandem accelerator. The states were populated by the subcoulomb proton stripping reaction ^{208}Pb(^{3}He,d$^*\gamma\gamma$)^{209}Bi at 20.5 MeV beam-energy. Forty-eight γ-transitions and 33 levels were observed for the first time. Gamma-transitions up to an energy of 6.0 MeV were detected. The energy of the observed states were determined to an accuracy of about 0.3 keV.

PACS. 21.10.Pc Single-particle levels and strength function – 23.20.Lv Gamma transitions and level energies – 25.55.-e 3H-, 3He-, and 4He-induced reactions

For tests of the shell-structure of nuclei, the region around the doubly-magic nucleus ^{208}Pb is very interesting. In particular, ^{209}Bi can be used to study single-particle proton states as well as particle-core coupling. The multiplet-structure produced by the ^{208}Pb core excitations coupled to the $\pi 1h_{9/2}$ particle ground state has been well investigated [1,2]. The multiplets produced by the core-excitations and higher single-particle excitations have not been observed completely so far. New developments in γ-ray spectroscopy made it possible to investigate new states.

The experiment was carried out at the Cologne FN-tandem accelerator. The spectrometer designed for this experiment consisted of two unshielded EUROBALL CLUSTER [7] detectors positioned at angles of 90 degrees with respect to the beam-axis and at distances of only 8 centimeters to the target (see fig. 1). The solid angle covered was 25%, and a total photopeak-efficiency of about 7% at 1332 keV could be achieved. The geometry of this spectrometer was optimized to detect low-multiplicity events of high-energy transitions. In addition, the granularity of the CLUSTER detector gives the opportunity to do an analysis of sum-up-events [8]. The energy and efficiency calibration was divided into two parts. The lower part of the energy scale was covered using a ^{226}Ra source, for the higher part up to 7 MeV high-energy γ-transitions following the β-decay of ^{24}Mg were used as described in [9].

Fig. 1. The spectrometer used for the ^{208}Pb(^{3}He,d$^*\gamma\gamma$)^{209}Bi-experiment. One can see the germanium front-ends of the two CLUSTER detectors at a distance of 8 cm from the target which resides in a small chamber.

The energy calibration was accurate about 0.2–0.3 keV in a scale of 0 to 4 MeV and 0.3–0.5 keV from 4 to 7 MeV. Due to the different decay-multiplicities of the calibration-sources and the experiment, a systematic error of the efficiency calibration of approximately 20% had to be taken into account.

The coincidence data was acquired by the improved Cologne FERA-Analyzing System [10] at a coincidence rate of approximately 2×10^4 events per second. We collected 3×10^9 $\gamma\gamma$-coincidence events including addback-

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Table 1. Energy E as well as spin and parity J_i^π of the new states excited through ^{208}Pb(^{3}He, d$^*\gamma$)^{209}Bi. The energy E_γ and the relative intensity I_γ of the depopulating γ-ray transitions are given in the third and fourth column. Furthermore, the energy, spin and parity of the final state of each transition is given if it is known from the literature [3,4]. New levels and transitions have been marked with an asterisk (*).

E_{level}	J_i^π	E_γ	I_γ	E_{final}	J_f^π
3159.3 1	$3/2^{(+)}$	242.7 1	55 20	2917.6 1	$(1/2^+)$
		314.2 2	100 10	2845.1 1	$1/2^+$
		392.5 2	40 10	2766.6 1	$3/2^+$
		716.5 2 *	90 20	2442.9 1	$1/2^+$
3197.4 2	$1/2, 3/2, 5/2^+$	352.3 1	70 20	2845.1 1	$1/2^+$
		431.2 2 *	50 15	2766.6 1	$3/2^{(+)}$
		705.1 2 *	100 10	2492.8 1	$3/2^+$
3269.6 2	$1/2, 3/2, 5/2^+$	424.5 1	100 10	2845.1 1	$1/2^+$
		826.5 2 *	30 10	2442.9 1	$1/2^+$
3449.1 2 *		2552.8 2 *	100	896.3 1	$7/2^-$
3590.5 2 *		745.3 2 *	100	2845.1 1	$1/2^+$
3633.8 2	$1/2^-$	436.3 2 *	2 1	3197.4 1	$1/2, 3/2, 5/2^+$
		514.37 2 *	100 30	3119.5 1	$3/2^-$
		677.8 2 *	20 6	2955.9 1	$3/2^+$
		788.8 2 *	3 1	2845.1 1	$1/2^+$
		867.2 2 *	20 6	2766.6 1	$3/2^+$
		1140.8 2 *	6 2	2492.8 1	$3/2^+$
		1191.0 2 *	4 1	2442.9 1	$1/2^+$
3759.0 5 *		2862.7 5 *	100	896.3 1	$7/2^-$
3772.5 2 *		2876.3 2 *	100	896.3 1	$7/2^-$
3782.6 2 *		2886.3 3 *	100	896.3 1	$7/2^-$
3801.4 2 *[a]		2905.1 2 *		896.3 1	$7/2^-$
		3801.0 5 *		0	$9/2^-$
3808.2 2 *		2199.7 2 *	100	1608.6 1	$13/2^+$
3816.7 3 *[b]		2920.4 2 *	100	896.3 1	$7/2^-$
3913.2 2 *		1420.4 2 *	100	2492.8 1	$3/2^+$
4091.4 4 *		1648.5 4 *	100	2442.9 1	$1/2^+$
4096.6 2 * [c]		977.1 2 *	100	3119.5 1	$3/2^-$
4236.8 3 *		3340.6 3 *	100	896.3 1	$7/2^-$
4415.4 2 *		1295.9 2 *	100 30	3119.5 1	$3/2^-$
		1922.4 2 *	3 1	2492.8 1	$3/2^+$
4426.7 3 *		3530.4 3 *	100	896.3 1	$7/2^-$
4438.9 2 *		3542.6 3 *		896.3 1	$7/2^-$
		4439.1 3 *		0	$9/2^-$
4478.2 3 *		3581.9 3 *	100	896.3 1	$7/2^-$
4516.5 3 *[d]		3620.2 3 *	100	896.3 1	$7/2^-$
4588.1 3		3692.1 3 *		896.3 1	$7/2^-$
		4587.8 6		0	$9/2^-$
4739.6 2 *		3843.3 2 *	100	896.3 1	$7/2^-$
4786.3 3 *		3890.0 2 *	100	896.3 1	$7/2^-$
4904.2 3 *		4007.9 3 *	100	896.3 1	$7/2^-$
5054.0 4 *		4157.7 4 *	100	896.3 1	$7/2^-$
5152.2 3 *		4255.9 3 *	100	896.3 1	$7/2^-$
5190.7 4 *		4294.4 4 *	100	896.3 1	$7/2^-$
5291.4 4 *		2525.6 5 *	100	2766.6 1	$3/2^{(+)}$
5292.5 3 *		2095.1 3 *	100	3197.4 1	$1/2, 3/2, 5/2^+$
5369.7 4 *		2926.9 4 *	100	2442.9 1	$1/2^+$
5563.3 6 *		3070.5 6 *	100	2492.8 1	$3/2^+$
5668.3 3 *		4772.0 3 *	100	896.3 1	$7/2^-$
5788.7 4 *		4892.4 4 *	100	896.3 1	$7/2^-$
6301.0 4 *		5404.7 4 *	100	896.3 1	$7/2^-$
6381.9 6 *		5485.6 6 *	100	896.3 1	$7/2^-$
6712.1 4 *		5815.8 4 *	100	896.3 1	$7/2^-$
6900.4 7 *		6004.1 7 *	100	896.3 1	$7/2^-$

[a] This level could be the 3800.8 keV level ($7/2^+$ or $9/2^+$) reported in [3].
[b] [3] reports a different level at 3817.9 keV with gamma decays not seen in this experiment.
[c] [3] reports a different level at 4096.1 keV. The 2488.2 keV γ-decay of this level was not seen in this experiment.
[d] The 4515.2-level (especially its depopulating 2906.6 keV transition) reported in [3] could not be observed in this experiment. Therefore the 4516.5 keV level must be new.

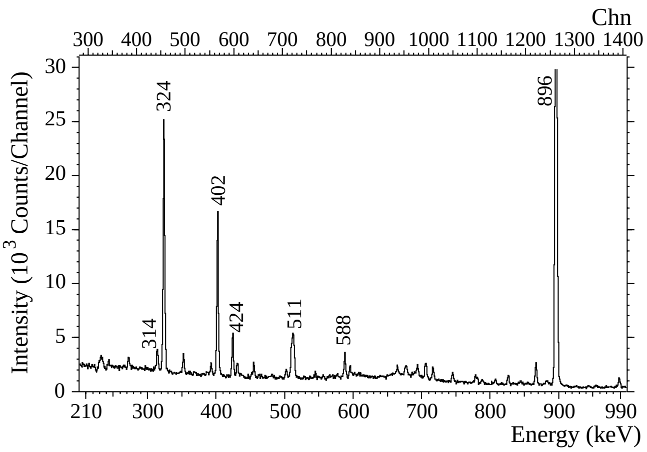

Fig. 2. Coincidence-spectrum gated on the 1546 keV transition. The ground-state transition at 896 keV reaches $7{\times}10^4$ counts/channel.

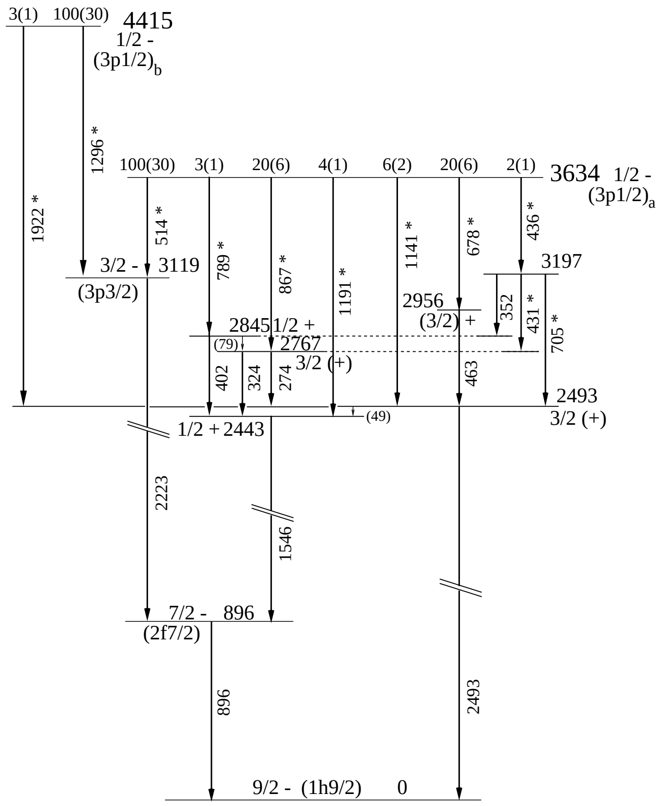

Fig. 3. Part of the levelscheme showing the decay of the two ($\pi 3p_{1/2}$)-single-particle-fragments at 4415 and 3634 keV. The latter one shows a rather complex decay through 7 γ-transitions. The transitions found in this experiments are marked with an asterisk (*).

events during 45 hours of measurement time. The data was sorted offline into a $\gamma\gamma$-coincidence matrix. Here, nearest-neighbour-addback-techniques have been used to take full advantage of the high-energy efficiency of the Cluster detector. A coincidence-spectrum gated with the 1546 keV-transistion to the ($\pi 2f_{7/2}$) is shown in fig. 2. Compared to earlier measurements [1], the statistics are increased by a factor of approximately 300. Apart from the reaction ^{208}Pb(^{3}He,d$^*\gamma\gamma$)^{209}Bi, the channels (^{3}He,2n)^{209}Po and (^{3}He,3n)^{208}Po could be observed with a relative intensity of 54% (2n) and 87% (3n) compared to the intended reaction.

We write d* to include the various exit channels of deuterons with spin 1 and 0 and the (pn)-channel, which we did not distinguish in particular. Thus we have $\{$ d ($S=1$), d ($S=0$), (pn) $\} \subset$ d*. In order to reduce the competing fusion reactions mentioned above, we choose a beam energy of 20.5 MeV. This is close to the Coulomb-barrier of 21.4 MeV so that fusion reactions are suppressed, whereas the stripping of one proton is preferred.

A total of 48 new γ-ray transitions and 33 new levels in ^{209}Bi were found with respect to 190 levels known or at least suggested so far [3]. These new levels and transitions extended the level-scheme up to an energy of 6.9 MeV and can be seen in Table 1. The spins, parities and configurations of the new levels have to be determined by further measurements. For levels not decaying directly to the ground state, it was possible to determine the branching ratios. These branching ratios will be useful for tests of the shell model.

Special interest has to be paid to the single-particle transitions of ^{209}Bi. The single-particle states have been investigated quite well in former particle-spectroscopy experiments [5,6] whereas only few of the γ-ray transitions between them could be found [1]. The ($\pi 3p_{1/2}$)-single-particle state has been identified to be fragmented into a dominant fragment at 3.64 MeV and a weaker one at 4.42 MeV [5]. From these levels, no depopulating γ-ray transitions have been observed so far. In the present experiment the decay of both of the ($\pi 3p_{1/2}$) single-particle-fragments could be observed. In addition, the high-energy resolution of the γ-spectrometer made it possible to determine the exact level energies. The scheme of this decay is shown in fig. 3. The single-particle-fragment $(\pi 3p_{3/2})_b$ at 4415 keV decays via only two γ-transitions: a very strong one to the ($\pi 3p_{3/2}$)-level at 3119 keV and a weak one with only 3% relative intenisty to the $3/2^+$-level at 2493 keV. The decay of the $(\pi 3p_{1/2})_a$-fragment is much more complex: in this experiment, seven γ-transitions depopulating this level at 3634 keV were observed. The configuration of most of the final levels is known and given in Table 2. The strongest γ-decays of both of the ($\pi 3p_{1/2}$)-fragments occur through the M1 spinflip-transition to the ($\pi 3p_{3/2}$)-level at 3119 keV. The branching ratios found in this experiment make it worthwhile to perform further calculations concerning the configuration of the two ($\pi 3p_{1/2}$)-fragments.

Summarizing we have demonstrated the power of the subcoulomb proton-stripping reaction combined with high-efficiency γ-ray detectors Thirty-two new levels and 48 new transitions were found in ^{209}Bi, which is one of the best examined nuclei. Among these transitions are the decays of the two fragments of the ($\pi 3p_{1/2}$) single-particle-fragments.

Table 2. Depopulating γ-transitions and branching ratios out of the 3633 keV level. The configurations of the final levels are given in the last column.

E_γ	I_γ	E_{final}	I_{final}	Configuration according to [3]
436.3*2*	2*1*	3197.4	1/2, 3/2, 5/2 $^+$	
514.4*2*	100*10*	3119.5	$3/2^-$	$\pi\, 3p_{3/2}$
677.8*2*	20*6*	2955.8	$3/2^+$	$(^{208}\text{Pb}\,3-)(\pi\,1h_{9/2}) + (^{210}\text{Po}\,0+)(\pi\,3\text{d}^{-}_{3/2}1)$
788.8*2*	3*1*	2845.1	$1/2^+$	$(^{208}\text{Pb}\,5-)(\pi\,1h_{9/2})$
867.2*2*	20*6*	2766.5	$3/2^+$	$(^{208}\text{Pb}\,5-)(\pi\,1h_{9/2})$
1140.8*2*	6*2*	2492.8	$3/2^+$	$(^{208}\text{Pb}\,3-)(\pi\,1h_{9/2}) + (^{210}\text{Po}\,0+)(\pi\,3\text{d}^{-}_{3/2}1)$
1191.0*2*	4*1*	2442.8	$1/2^+$	$(^{210}\text{Po}\,0+)(\pi\,3s^{-}_{1/2}1)$

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