2.2 Nuclear Spectroscopy

2.2.1 ^{9}Be(^{36}S, xn yp zα)X reaction studied through gamma-charged particle coincidences

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The studies on nuclear structure of the fusion-evaporation products of the reaction ^{9}Be(^{36}S, xn yp zα)X, initiated in 1990 [1], have been continued with gamma-charged particle and gamma-gamma coincidence measurements.

A high efficiency system for charged particle detection and identification has been built to permit high rate of gamma-charged particle coincidence events, when this system is associated with germanium detectors. Eleven telescopes, each formed by two PIN-diodes, were positioned at forward angles, permiting the detection and identification of charged particles with Z=1 and 2 evaporated from the compound nuclei. The 610 μg/cm^2 berillium target was evaporated on a 36 mg/cm^2 gold backing that was thick enough to stop both fusion products and projectiles, but could allow the crossing of light particles. Seven PIN-diodes, provided with gold absorbers to avoid the high count rate of Coulomb scattered projectiles, were positioned at backward angles. Due to the kinematics of the reaction, only protons could reach these PIN-diodes at backward angles. All the charged particle detectors were built to form a compact system in a spherical chamber of aluminium.

The gamma-particle coincidence measurements have been performed by associating five Compton-supressed HPGe detectors to this system. Also the gamma-gamma coincidence measurements have been carried out using the same arrangement.

The results previously obtained through gamma-recoil nuclei coincidence measurements [1] performed with the Munich Recoil Spectrometer, have been confirmed and better statistics have been achieved. New gamma transitions belonging to ^{42}Ca, ^{43}Ca, ^{42}K and ^{43}K have been observed. The gamma-gamma coincidence results will permit us to build the level scheme for these nuclides with new information. Our results agree with the recently published results about ^{43}K [2] obtained with a similar experiment. The gamma-particle-particle coincidence events confirmed gamma transitions belonging to ^{40}Cl reported by Kozub et al. [3] and will possibly reveal the first evidence of a gamma transition belonging to ^{43}Ar.

[1] M. Moralles, K. Balog, R. Haimerl, P. Jänker, H. Leitz, U. Lenz, K.E.G. Löbner, S.J. Skorka, H.-G. Thies, T. Winkelmann, Jahresbericht 1990, p. 20

[2] R.L. Kozub et al., Phys. Rev. **C46** (1992) 1671

[3] R.L. Kozub et al., Phys. Rev. **C37** (1988) 1791

2.2.2 Fast γ-ray emission from the nonequilibrated 30 MeV ^{3}He+^{25}Mg system

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The γ-emission of highly excited nuclear systems is dominated by the statistical γ-decay of the equilibrated compound nucleus. In addition, for systems at bombarding energies above 10 MeV/nucleon nonstatistical contributions to the γ-yield are observed in the energy region above the giant dipole resonance. While these appear to be understood in terms of bremsstrahlung from nucleon-nucleon collisions [1], some asymmetric systems have been reported [2] to show a large yield of preequilibrium γ-rays in excess of the bremsstrahlung systematics.

We have measured the hard photon spectrum from ^{3}He+^{25}Mg at 30 MeV. In fig. 1 the experimental result is compared with a statistical model analysis for the compound system ^{28}Si at 50 MeV excitation energy, using the computer code CASCADE. For the giant dipole resonance which shows up around 15-20 MeV standard parameters are used. The spectrum clearly exceeds the theoretical curve at high energies. Since we have also measured the angular distribution we can derive the integrated cross section for the purely precompound yield above 30 MeV (table 1). The corresponding emission probability exceeds the bremsstrahlung systematics by an order of magnitude which calls for a more unconventional explanation.

Table 1: Coulomb-corrected bombarding energy per nucleon, angle integrated cross section for γ-ray emission at E_γ >30 MeV and corresponding emission probability per ^{3}He+^{25}Mg collision.

System	$(E\text{-}V_C)/A$ [MeV/u]	$\sigma_\gamma[\mu b]$ (E_γ >30 MeV)	P_γ
^{3}He+^{25}Mg	8.0	12.3±3.7	9.1×10^{-6}

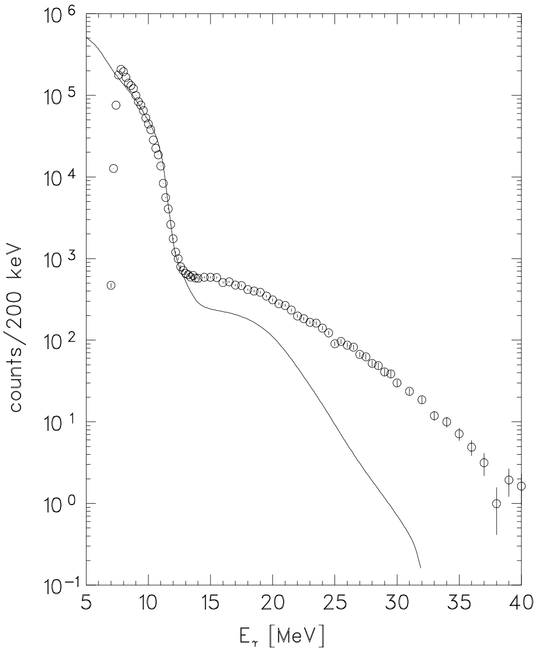

Fig. 1: High energy photon spectrum from the reaction ^{3}He+^{25}Mg at E_{Lab}=30 MeV, θ_γ=90° (open circles) in comparison with a statistical model calculation (solid line). The detector lineshape has been folded into the theoretical curve.

[1] V. Metag, Annalen der Physik 48 (1991) 121
[2] K. A. Snover, Ann. Rev. Nucl. Part. Sci. 36 (1986) 545

2.2.3 Delayed gamma-ray measurements on ^{68}As

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Our measurements of reaction-channel selective gamma-spectra with the RF-recoil-separator of 189 MeV ^{58}Ni on ^{12}C gave us data on ^{68}As-level lifetimes, which do not agree with the published values [1]. The half-lives were derived from the intensities of the gamma peaks of the two germanium-detectors [2]. As the measured half-lives lie well within the region accessible to delayed coinicidence gamma spectroscopy, we did a delayed coinicidence experiment to check our method of half-life measurement with the recoil-spectrometer.

A pulsed beam of ^{12}C with an energy of 39 MeV and 51 MeV irradiated a 500 μg/cm^2 ^{58}Ni target on a thick tantalum-backing. The beam-energy corresponds to a ^{58}Ni beam of 189 MeV and 250 MeV of the recoil-spectrometer-measurements with inverse kinematics. The beam-pulses were 1 ns wide with a repetition rate of 5 MHz. Two Compton-suppressed germanium-detectors of 30 % relative efficiency were placed at 125 degrees from the beam axis. The gamma-energies and the time relative to the beam-pulse were recorded. The gamma-energies vs. time were accumulated into a matrix. At the gamma-lines of ^{68}As (known from the recoil-spectrometer-measurement) time-slices of the matrix were cut to be analysed by the program "lifem".

Results:

The 854 keV gamma-line which depopulates the isomer at 2159 keV shows a half-life of 37 ns in agreement with the known value from delayed-gamma technique [1]. In the recoil-spectrometer data this half-life was not observed, which may be due to the low statistics of this gamma-line and the fact that the method of deriving half-lives from these data looses sensitivity with higher gamma-energies.

The 339 keV gamma-line, which follows the 854 keV line in the level-scheme, shows a half-life component in the delayed coincidence and the recoil-spectrometer measurements.

The recoil-spectrometer data show that the 214 keV gamma- line is "completely" delayed. Also the delayed-gamma-technique data show a half-life, which cannot be explained from the half- lives of the feeding gamma-lines. This demonstrates that there is a second isomer of similar half-life in ^{68}As at 214 keV.

[1] Nuclear Data Sheets **55,1** (1988) 18

[2] H.-G. Thies, K. Balog, L. Corradi, P. Jänker, H. Leitz, U. Lenz, K.E.G. Löbner, M. Moralles, K. Rudolph, S.J. Skorka, Th. Winkelmann, Jahresbericht 1990, p. 21

2.2.4 Spectroscopy of ^{87}Y via ^{90}Zr$(\vec{p},\alpha)^{87}$Y Reaction

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The study of the ^{90}Zr$(\vec{p},\alpha)^{87}$Y reaction was performed not only to improve the experimental information on the ^{87}Y levels, but also to obtain accurate measurements of angular distributions and asymmetries for comparison with those measured at the same incident energy for the ^{91}Zr$(\vec{p},\alpha)^{88}$Y reaction [1].

This comparison allows one to identify the configuration of the ^{88}Y states with energy $\geq$ 2.16 MeV, that are homologous to the low energy states of the ^{87}Y nucleus. The concept of homology of states is a useful spectroscopic tool for nuclear states observed at relatively high excitation energies [2].

In table I all the observed levels of ^{87}Y up to an excitation energy of 2.998 MeV are listed, together with those observed in a previous (p,α) experiment [3] and the corresponding adopted ones [4].

Angular distributions and analyzing powers for transitions to 36 levels of ^{87}Y were obtained.

The DWBA calculations for these levels have been made in a finite range approximation with the TWOFNR code [5], in the framework of a semimicroscopic pickup theory, using a proton-triton interaction potential of gaussian form with range parameter of 1.45 fm. In table II the optical model parameters for the incident protons [6] and emitted α-particles [7], and the geometrical parameters for the triton bound state are shown.

In figs 1 and 2 angular distributions and asymmetries for transitions to the highest excitation energy levels of ^{87}Y are compared with the results of DWBA analysis. From this analysis some new attributions of spin and parity values result. Calculations with double-folded-α-nucleus potentials are also in progress [8].

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[2] E. Gadioli, P. Guazzoni, M. Jaskola, L. Zetta, G. Colombo, G. Graw, R. Hertenberger, D. Hofer, H. Kader, P. Schiemenz, R. Neu, G. Staudt, Phys. Rev. **C** in press
[3] R.J. Peterson and H. Rudolph, Nucl. Phys. **A241** (1975) 253
[4] H. Sievers - Nuclear Data Sheets **62** (1991) 327
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TABLE II

	V_r	r_r	a_r	W_v	r_w	a_w	W_d	r_d	a_d	V_{so}	r_{so}	a_{so}	r_c
p	50.5	1.251	0.678				14.33	1.242	0.483	8.33	1.251	0.678	1.251
α	230.5	1.260	0.700	23.5	1.260	0.700							1.3
t		1.45	0.4										

TABLE I

Present work		(p,α) reaction [3]		Adopted levels [4]	
E_x	J^π	E_x	J^π	E_x	J^π
0	$\frac{1}{2}-$	0	$\frac{1}{2}-$	0	$\frac{1}{2}-$
0.379	$\frac{9}{2}+$	0.38	$\frac{9}{2}+$	0.381	$\frac{9}{2}+$
0.793	$\frac{5}{2}-$	0.79	$\frac{5}{2}-$	0.794	$\frac{5}{2}-$
0.981	$\frac{3}{2}-$	0.99	$\frac{3}{2}-$	0.981	$\frac{3}{2}-$
1.151	$\frac{5}{2}+$	1.15	$(\frac{3}{2}-)$	1.153	$(\frac{5}{2})^+$
1.182	$\frac{3}{2}-$			1.178	$(\frac{3}{2})^-$
1.201	$\frac{5}{2}-$	1.20	$(\frac{5}{2}-)$	1.202	$(\frac{5}{2})^-$
		1.37			
1.401	$(\frac{13}{2}+)$			1.404	$(\frac{13}{2}+)$
		1.58			
1.607	$(\frac{5}{2})^+,(\frac{3}{2})^-$			1.609	$\frac{3}{2}-,\frac{5}{2}-$
1.629	$\frac{5}{2}+$			1.623	$(\frac{5}{2},\frac{7}{2})$
1.704	$\frac{3}{2}-$			1.704	$(\frac{5}{2}-)$
1.757	$\frac{5}{2}+$			1.757	$(\frac{5}{2}+,\frac{7}{2}-)$
		1.79	$\frac{5}{2}-$		
1.802	$\frac{5}{2}-$			1.801	$(\frac{1}{2}-,\frac{3}{2},\frac{5}{2}-)$
1.846	$\frac{1}{2}-$	1.85	$\frac{3}{2}-$	1.851	$\frac{1}{2}-$
1.979	$\frac{7}{2}-$			1.988	$(\frac{7}{2},\frac{9}{2})^-$
2.006	$\frac{11}{2}+$			2.008	$(\frac{7}{2})$
2.113	$\frac{5}{2}+$			2.111	
		2.13	$(\frac{7}{2}-)$		
2.153	$\frac{9}{2}-$			2.159	
2.184	$\frac{7}{2}-$			2.185	
2.209	$\frac{3}{2}-$			2.207	$(\frac{15}{2}+,\frac{17}{2}+)$
				2.210	$\frac{1}{2}$
				2.242	$(\frac{7}{2},\frac{9}{2}-)$
2.249	$\frac{9}{2}-$			2.244	
				2.274	$(\frac{9}{2}+)$
2.276	$(\frac{7}{2}+ + \frac{9}{2}-)$			2.278	$(\frac{7}{2}-)$
2.302	$\frac{11}{2}-$	2.30	$(\frac{9}{2}+)$		
				2.354	
2.365	$(\frac{15}{2}- + \frac{7}{2}+)$			2.367	$(\frac{15}{2}-)$
2.408	$\frac{3}{2}-$			2.409	$(\frac{3}{2})^+$
2.449	$\frac{9}{2}-$			2.446	$(\frac{5}{2})^+$
2.531	$\frac{11}{2}-$			2.532	
2.562	$(\frac{11}{2}+ + \frac{3}{2}-)$	2.57	$(\frac{15}{2}-)$	2.564	$(\frac{9}{2})^+$
				2.572	$(\frac{3}{2}-)$
2.599	$\frac{9}{2}-$			2.595	
		2.63	$(\frac{13}{2}-)$		
2.661	$\frac{9}{2}+$				
2.682	$\frac{11}{2}-$			2.676	$(\frac{17}{2})^-$
2.747	$\frac{3}{2}+$				
2.801	$(\frac{11}{2}+ + \frac{3}{2}-)$				
				2.827	$(\frac{21}{2})^+$
				2.828	$(\frac{3}{2}-,\frac{5}{2}-)$
2.831	$\frac{9}{2}-$				
2.903	$\frac{3}{2}-$			2.901	$\frac{3}{2}-,\frac{5}{2}-$
		2.96	$\frac{5}{2}+$		
2.998	$(\frac{5}{2}++\frac{11}{2}-)$			2.995	$(\frac{5}{2})^+$

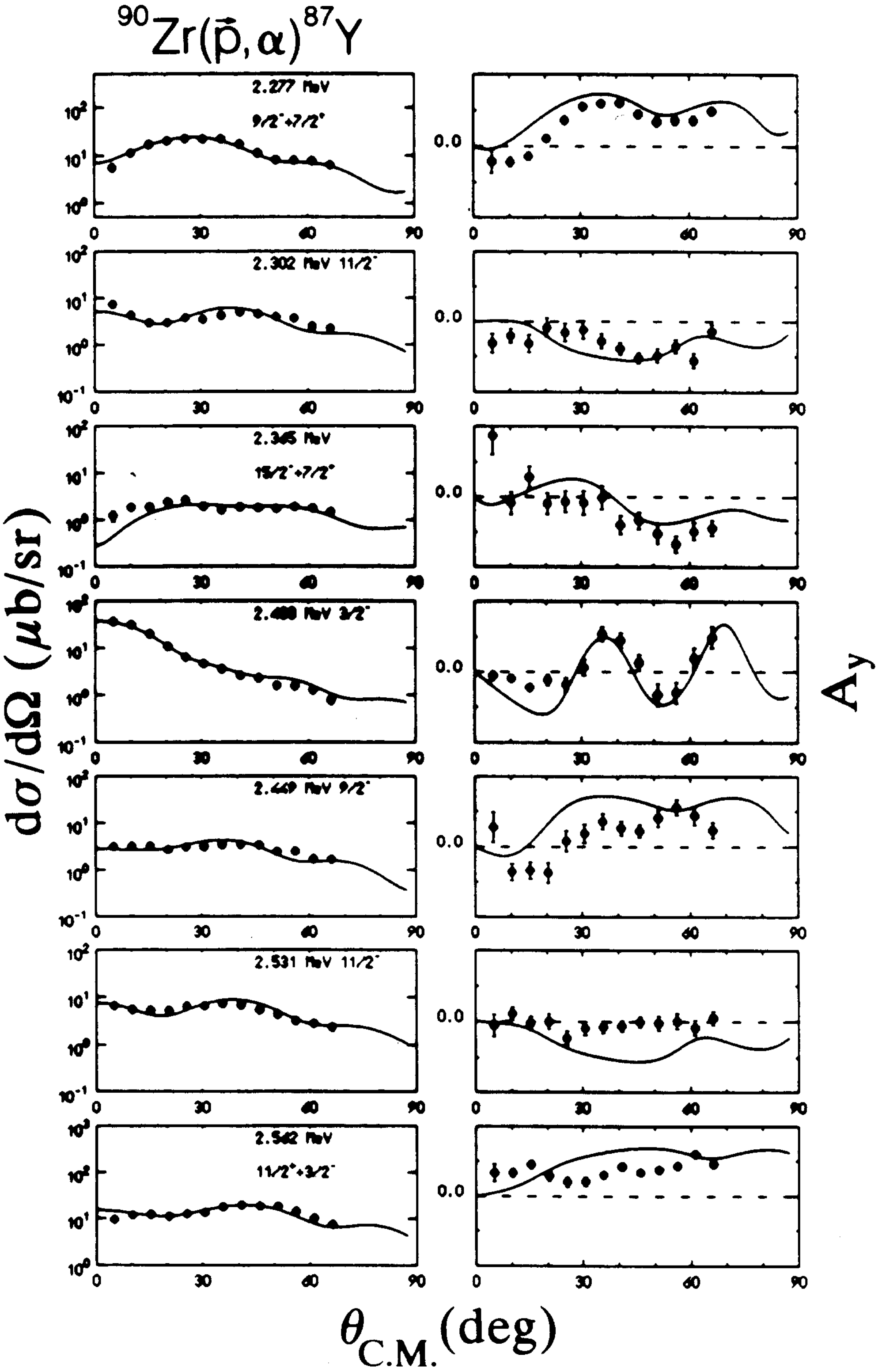

Fig. 1: Comparison of experimental angular Distributions with DWBA predictions

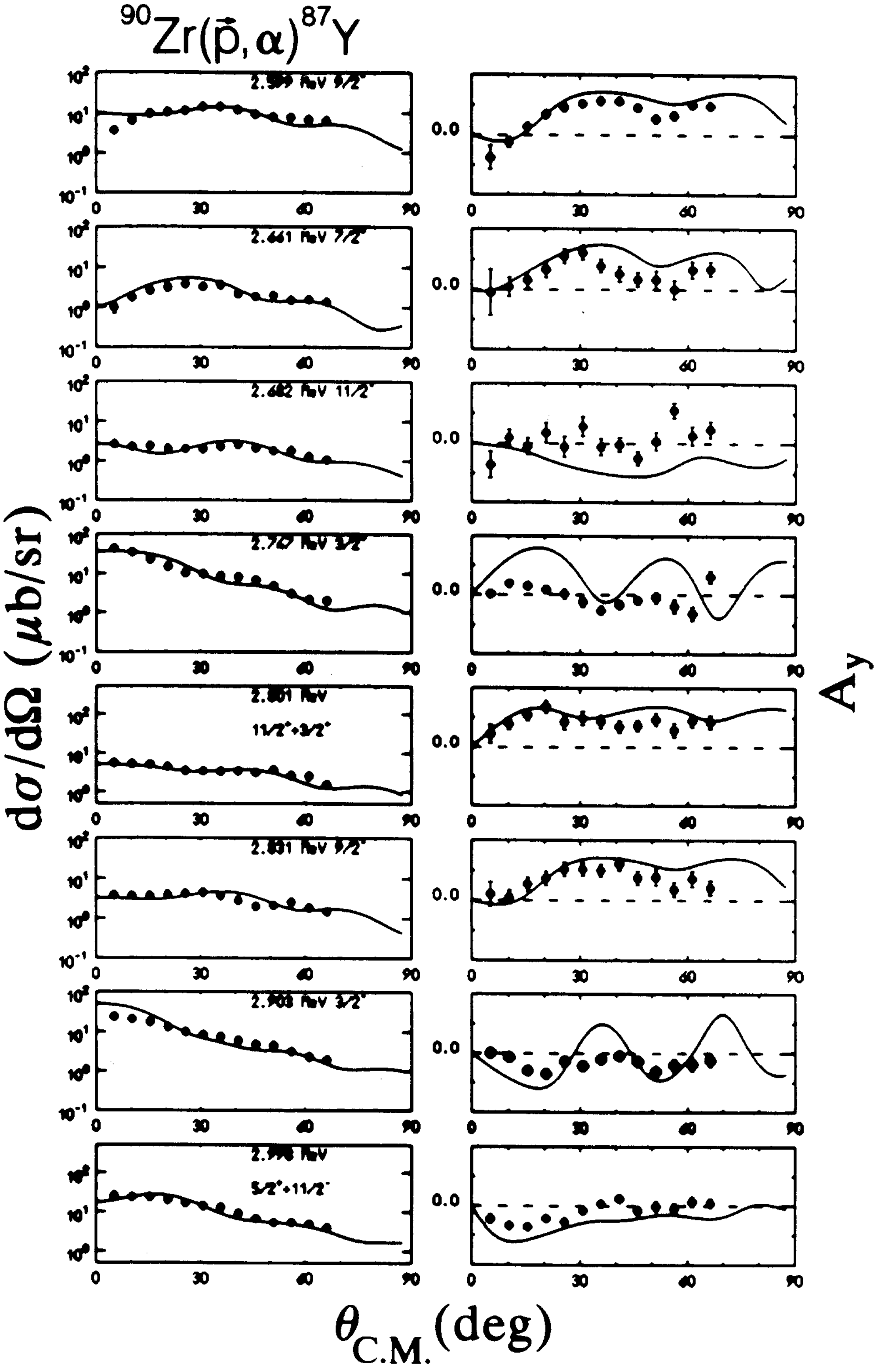

Fig. 2: Comparison of experimental angular Distributions with DWBA predictions

2.2.5 Proton and alpha radioactivity in the vicinity of ^{100}Sn

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During the last year we completed our investigation of the decay properties of the nuclei at and beyond the proton drip–line in the neighbourhood of ^{100}Sn.

Presently the only feasible method to obtain information on the structure of nuclei near the proton drip line is the detailed investigation of their particle decay modes. Ground state proton emission is of particular interest because of its simplicity, no cluster preformation has to be taken into account. It yields direct information on the involved nuclear masses and on single–particle orbitals.

The decay constant λ can be calculated semiclassically by the WKB approximation using a suitable optical model potential. Variations of the proton energy and angular momentum have the strongest influence on the halflife. The energy dependence is mainly determined by the penetrability factor through the long range Coulomb potential. From comparison with measured halflives and from shell model systematics the orbital of the emitted proton may be deduced. The remaining deviation of the observed halflife from the calculated value has to be attributed to microscopic nuclear structure effects.

The energy available for proton emission, Q_p, is strongly influenced by shell effects, particularly in the neighbourhood of doubly magic nuclei. Some mass formulae predict a pronounced odd–even staggering of the proton separation energy S_p as a function of the number of neutrons in the isotopic chains due to the neutron–proton residual interaction [9]. These predictions can be tested by the determination of the proton decay energies of ^{108}I and ^{112}Cs.

The compound nuclei at the proton drip line ^{116}Ba and ^{112}Xe were produced by fusion reactions of ^{58}Ni beams (250 MeV, 275 MeV) with ^{58}Ni and ^{54}Fe targets, respectiveley. The evaporation residues were separated from the beam with the electrostatic separator ESEL [1]. Because of the large acceptance of this system (solid angle 9 msr) the evaporation residues were observed with an efficiency of 10% up to 17% at a 50% background level, even if α particles were evaporated by the compound nucleus.

The residues were implanted in an array of 100 PIN diodes of 1×1cm^2 area and 220 μm thickness, arranged in a 10×10 matrix [2]. With the implantation technique the particle decays of the evaporation residues could be observed in a large solid angle of 80 to 100% of 4π, since the implantation depth of the 0.5 MeV/u evaporation residues is of the same order of magnitude as the range of 1 MeV protons or 4 MeV α particles in the detector material. Futhermore the background from the much longer lived β^+ activities could be drastically reduced by correlating the decay event with the preceding fusion product. In addition to this residue correlation the data could be analysed for possible mother–daughter correlations, so that particle unstable nuclei could be assigned by analysing their decay chains. This technique allowed the observation of particle decays with production cross sections below 1 μb at the borderline of nuclear stability. For example in the reaction of 275 MeV ^{58}Ni beam with ^{58}Ni target the proton emission of ^{109}I was observed with a cross section of ($7\pm2\,\mu$b) even for the unfavourable (αp2n) evaporation in this case.

Analysing the data for α–α and p–α correlations, most of the known activities could be unambiguously identified. Since the measured decay energies are not affected by unknown dead layers, we obtained more precise values for most of the known α emitters in this mass region. The decay energies, given in Table 1, differ by up to 30 keV from the values reported by Schardt et al. [3]. The energies were calibrated with five different alpha lines in the energy range between 5.2 MeV and 8.8 MeV and 624 keV conversion electrons from external sources [2].

nucleus	$E_{p,\alpha}$ [keV]
^{109}I	812 ± 2
^{113}Cs	974 ± 4
^{107}Te	3861 ± 5
^{108}Te	3317 ± 4
^{109}Te	3107 ± 4
^{110}I	3456 ± 5
^{111}I	3174 ± 10
^{110}Xe	3745 ± 15
^{111}Xe	3589 ± 10
^{111}Xe	3500 ± 15
^{112}Xe	3190 ± 15

Table 1: Measured proton and α decay energies

The contribution of the recoiling daughter nucleus, which is very small due to the large pulse height defect of 70-80%, was subtracted from the measured signal, using the modified empirical formula given in [4].
In Figure 1 a spectrum of decay events produced in the reaction (250 MeV) ^{58}Ni + ^{58}Ni , correlated with a preceding evaporation residue within a time window from 40 μs to 240 μs is shown, exhibiting the two proton lines of ^{109}I and ^{113}Cs in the same spectrum. The measured decay energy of ^{109}I (E_p = 812±2 keV) is in very good agreement with the value given by S. Hofmann [5]. The observed proton energy of ^{113}Cs (E_p = 974±4 keV) is 15 keV higher than the value of S. Hofmann [5].
From the intensity of the proton lines as a function of the time difference to the preceding evaporation residue the halflives of ^{109}I and ^{113}Cs were determined to be ($107 \pm 6 \mu s$) and ($22 \pm 8 \mu s$), respectively, which is within the errors in agreement with an earlier measurement of A. Gillitzer et al. [6], using a catcher technique and an ionization chamber.

The two alpha emitters ^{111}Xe and ^{107}Te were also identified by the correlation of their decays. These nuclei are of special interest, since they are the daughter nuclei of a possible proton decay of ^{112}Cs and ^{108}I. To get an unambiguous signature for new proton emitters, produced with small cross sections, subsequent α decay of the populated daughter nuclei was required in the data analysis.
In both reactions, (250 MeV) ^{58}Ni+^{54}Fe and (275 MeV) ^{58}Ni+^{58}Ni, no evidence for the ^{108}I p–decay in correlation with the short lived α emitter ^{107}Te ($T_{1/2} = 3.7$ ms) was found. The sensitivity was limited to halflives below 150 ms, to avoid random correlations to fusion products implanted into the detector array. At a cross section limit of 200 nb we do not observe a new proton line in the energy range of 500 keV< E_p <1.0 MeV correlated with the ^{107}Te α–decay. From the systematics of known evaporation cross sections ($\sigma_{p2n} \approx 50\,\mu$b) a cross section of $\sigma_{p3n} \geq 1\,\mu$b for the production of ^{108}I is expected.

Taking into account the known energy dependence of the halflife for proton decay, it can be ruled out that ^{108}I decays dominantly by proton emission, which would be the dominant decay mode for a proton in this energy range of 500 keV< E_p <1.0 MeV. This conclusion is in agreement with the observation of Page et al. [7], that ^{108}I decays by α emission. The observation of α emission excludes the possibility of a proton emission with a Q value above 1 MeV, which would instead be the predominant decay branch with a halflife below 1 μs.

In the reaction ^{58}Ni + ^{58}Ni with beam energies of 250 MeV and 275 MeV we searched for the proton decay of ^{112}Cs. The detection of ^{112}Cs proton decay is more complicated, because of the longer halflife of the ^{111}Xe daughter nucleus of $T_{1/2} = 890$ ms, requiring a wider time window for the correlation, and the smaller branching ratio for α decay of $b_\alpha = 0.25$, decreasing the sensitivity by a factor of four. For longer time intervals after the implanted residue the β^+ particles appear in random correlations with the alphas from ^{111}Xe. This results in a cross section limit for ^{112}Cs proton decay, which depends on its energy and its halflife. In all energy spectra with different time intervals after the implanted residue no evidence for a new proton line was observed [2].

In order to extract cross section limits as a function of the decay energy, the partial halflives were calculated by scaling the measured halflife of ^{113}Cs, using a WKB calculation to determine the energy dependence for a proton angular momentum of L=2. For high proton decay energies the sensitivity is limited by the exponentially decreasing halflife, and a possible decay with a halflife below 5 μs would have occurred before it could be detected. At low energies the β^+ background increases for the necessarily longer time intervals between the residue and the decay event.

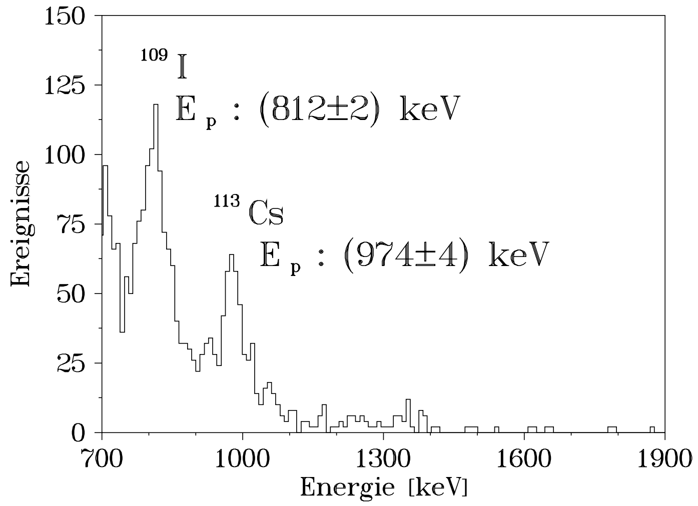

Fig. 1: Energy spectrum of decay events in the reaction 250 MeV ^{58}Ni+^{58}Ni correlated with an evaporation residue within a time window from 40 μs to 240 μs.

Since a cross section in excess of 1 μb is expected for the p3n channel leading to ^{112}Cs, proton decay energies between 800 keV and 1 MeV are excluded. With the systematics of α decay Q values for caesium isotopes and the upper limit of 500 keV for the proton decay Q value of ^{108}I, proton decay energies of ^{112}Cs of more than 1 MeV are ruled out, and the Q$_p$ value must be lower than 800keV.

This observation of a significant odd–even staggering of the proton decay Q values with respect to the neutron number, particularly for light iodine and caesium isotopes, can also be deduced from semiempirical mass systematics [9].

Beside the direct measurement unknown nuclear masses can be extrapolated by experimental mass relations [8]. These extrapolations are uncertain by about 0.4 MeV for the involved nuclei very far from stability. Similar to the Wapstra systematics [8] we used a linear extrapolation of the Q$_\alpha$ and 2p–separation energies in an isotopic chain separately for odd and even neutron numbers. With these relations the groundstate masses and proton separation energies for the odd–Z nuclei ^{104}Sb, ^{105}Sb, ^{108}I and ^{112}Cs are predicted with an error of about 350 keV.

In table 2 the extrapolated and the measured limits for proton groundstate emission of the nuclei ^{108}I and ^{112}Cs are compared.

nucleus	exp. limit from this work [1]	from systematics
^{104}Sb		$Q_p = 475(360)$ keV
^{108}I	$E_p < 500$ keV	$Q_p = 530(300)$ keV
^{112}Cs	$E_p < 800$ keV	$Q_p = 830(360)$ keV

Table 2: Comparison of the proton decay energies from the observed experimental limits and from mass extrapolations

Figure 2 shows the proton decay Q–values of the first three odd–Z isotopic chains above tin, separately for odd and even neutron numbers.

The smooth behaviour of the proton binding energies within the odd–odd and the odd–even isotopic chains justifies an extrapolation for the lightest isotopes (^{104,105}Sb, ^{108}I, ^{112}Cs). Compairing the trends of the chains for the odd and even neutron numbers, it can be concluded, that the last proton in the even nuclei ^{108}I and ^{112}Cs are about 200 keV more bound than in their neighbours ^{109}I ($Q_p = 0.81$ MeV) and ^{113}Cs ($Q_p = 0.98$ MeV).

These extrapolations and the nonobservation of proton radioactivity of ^{108}I and ^{112}Cs confirms the strong role of a proton–neutron pairing contribution [9] for the extremely neutron deficient nuclei with comparable numbers of neutrons and protons, which may thus occupy the same orbitals.

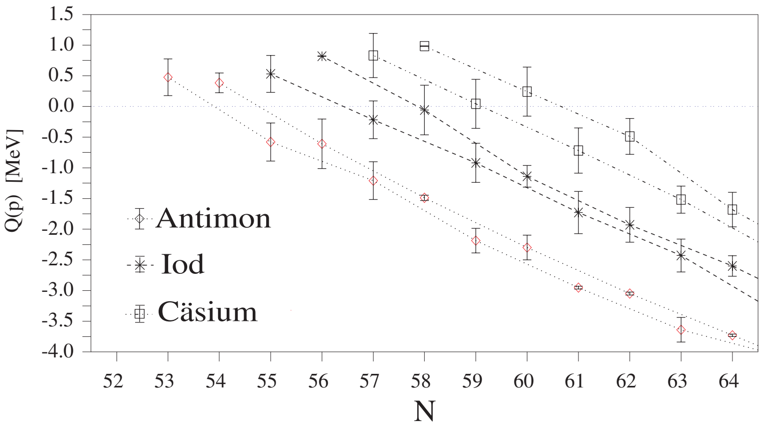

Fig. 2: Q_p values in the antimony, iodine and caesium isotopic chain

The proton separation energies as a function of the neutron number taken from the Wapstra mass table [8] and from our own systematics. The dependency of the decay energy on the neutron number is separately shown for odd and even neutron numbers. All three odd–Z elements show a similar dependency of the decay energies on the neutron number within the odd–odd and odd–even isotopic chains.

The developed technique has proven to be sensitive for the detection of particle unstable nuclei produced with small cross sections, if the correlation with the decay of the daughter nuclei can be used. However the method has reached its limit for the search for new proton emitters between antimony and caesium. In order to extend the study of proton emitters to heavier nuclei in the rare earth region ($Z \geq 57$), the use of unstable beams will be inevitable.

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[6] A. Gillitzer, T. Faestermann, K. Hartel, P. Kienle, E. Nolte, Z.Phys.A 326 (1987) 107
[7] R.D. Page et al., Z.Phys.A 338 (1991) 295
[8] A.H. Wapstra, G. Audi and R. Hoekstra, Atomic Data and Nucl.Data Tables 39 (1988) 281
[9] A.S. Jensen, P.G. Hansen and B. Jonson, Nucl. Phys. A431 (1984) 393.

2.2.6 Study of ^{121}Sb with the ^{123}Sb(p,t)^{121}Sb reaction

U. Atzrott [a], Gh. Cata-Danil [b], G. Graw, P. Guazzoni [c], R. Hertenberger, D. Hofer, M. Jaskola [d], R. Neu [a], P. Schiemenz, G. Staudt [a], B. Valnion, E. Müller-Zanotti, L. Zetta [c]

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[d] Soltan Institute of Nuclear Studies, Swierk, Poland

Much of the existing data on two neutron transfer reactions, such as (p,t), are concentrated on studies with even target nuclei. One reason for this is the semplification introduced by the selection rules governing this type of reactions. Starting from a 0^+ initial state, in the final nucleus only natural-parity states will be populated in a one-step transfer process. In addition, each final state will be populated with a unique L-transfer value which can be deduced from the shape of the angular distribution. Thus the determination of the L-value gives directly both the spin and parity of the observed level. The situation for non zero spin target is usually more complex. Generally more than one L-transfer contributes to the excitation of a given final state.

A method to simplify the situation results from the study of (p,t) reaction in two adjacent nuclei examining the weak coupling relationships between states of these two nuclei [1]. We have observed such relationships studying the homology correspondence for states in ^{205}Tl and ^{206}Pb, reached via the $^{208}\mathrm{Pb}(\vec{p},\alpha)^{205}$Tl and $^{209}\mathrm{Bi}(\vec{p},\alpha)^{206}$Pb respectively [2, 3]. Now we have studied the ^{122}Sn(p,t)^{120}Sn also presented in this Annual Report, as well as the ^{123}Sb(p,t)^{121}Sb reaction, never measured before. The experiment on ^{123}Sb was done at 25 MeV incident energy with the Munich MP Tandem, the Q3D spectrograph and the light ion focal plane detector with periodic read out,from 5^o up to 65^o in step of 5^o. The ^{123}Sb target was 100 $\frac{\mu g}{cm^2}$ thick on carbon backing of $7\frac{\mu g}{cm^2}$. The enrichment of ^{123} Sb was of 98%. The beam current used ranged from $\sim$ 500 nA up to $\sim$ 800 nA.

In fig. 1 the spectra collected at 10^o for two different magnetic setting of the spectrometer, are presented up to an excitation energy of 2.5 MeV. In fig. 2 we present some very preliminary but interesting results for 3 levels of ^{121} Sb. The points represent the experimental cross section values for the ^{123}Sb(p,t)^{121}Sb, while the full line represents the experimental cross section for the parent state reached in the ^{122}Sn(p,t)^{120}Sn reaction. So following the experimental evidence, it seems that the ^{121}Sb $\frac{7}{2}^+$ level at 0.037 MeV could be homologous of the 0^+ ground state of ^{120}Sn and using the notation $|J> = |(J_C, j)J>$ could be described as $|(0^+, g_{\frac{7}{2}})\frac{7}{2}^+>$. In the same way the ^{121}Sb levels, $\frac{9}{2}^+$ at 1.036 MeV and $\frac{11}{2}^+$ at 1.139 MeV could be homologous of the ^{120}Sn 2^+ level at 1.171 MeV and could be described as: 1.036 Mev $\frac{9}{2}^+$ $|(2^+, g_{\frac{7}{2}})\frac{9}{2}^+>$ and 1.139 MeV $\frac{11}{2}^+$ $|(2^+, g_{\frac{7}{2}})\frac{11}{2}^+>$.

The n-values that appear in the drawns represent the spin factor values n = $\frac{(2J+1)}{(2J_C+1)(2j+1)}$, that relate the cross section of the parent state of ^{120}Sn to that of the homologous state of ^{121}Sb.

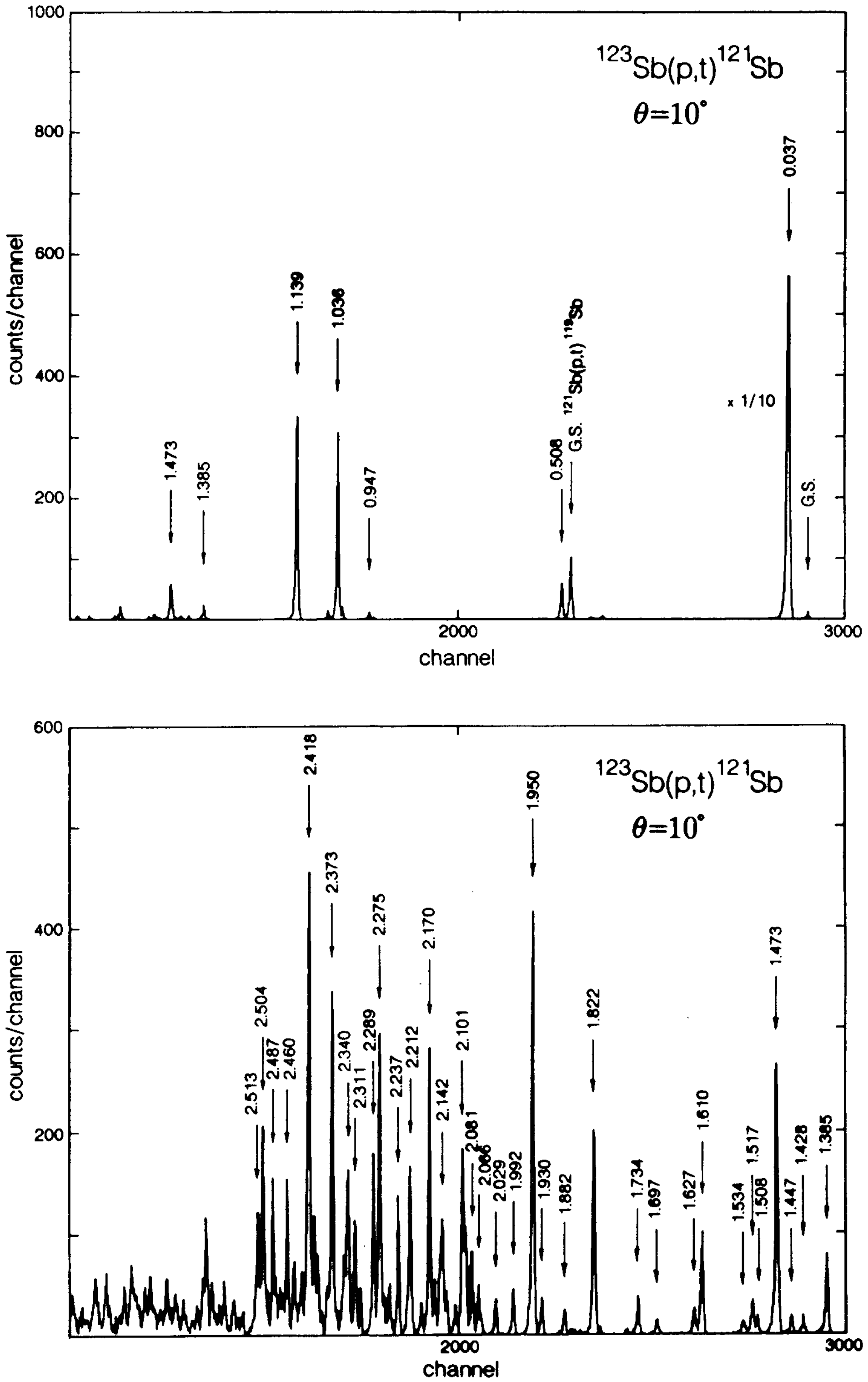

Fig. 1: The ^{123}Sn(p,t)^{121}Sn reaction triton spectra measured at 10° for two different magnetic setting.

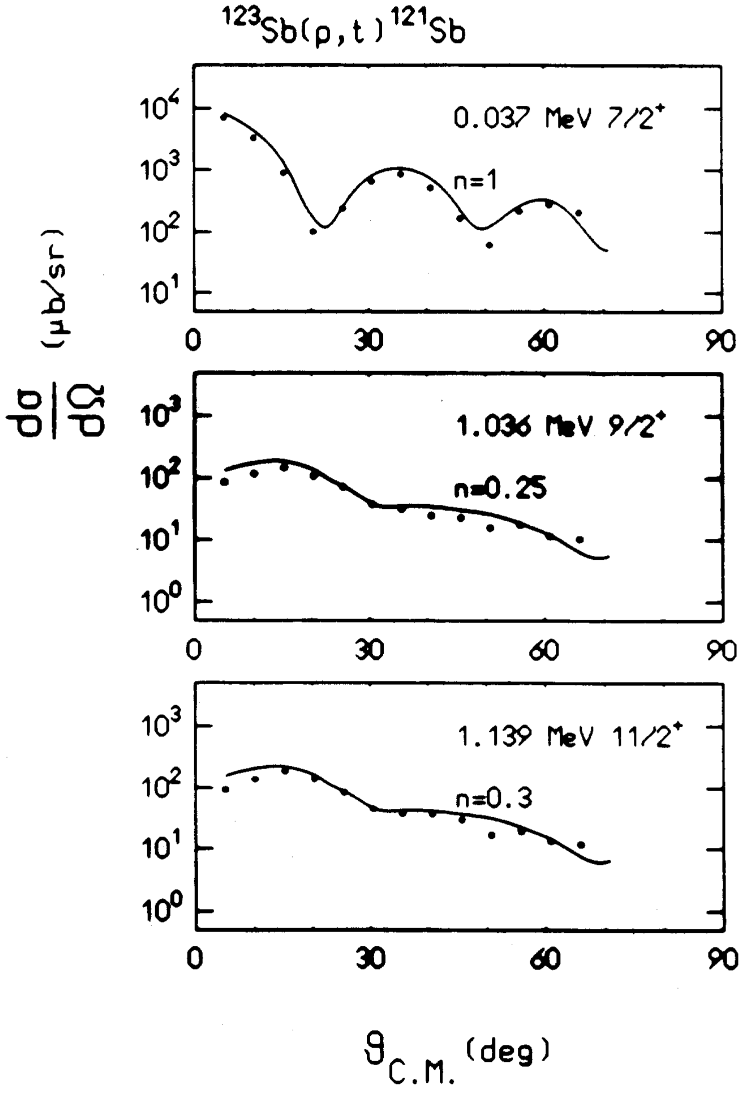

Fig. 2: The ^{122}Sn(p,t)^{120}Sn reaction triton spectra measured at 10° for two different magnetic setting.

[1] K.A. Erb and T.S. Bathia, Phys. Rev. **C7** (1973) 2500

[2] E. Gadioli, P. Guazzoni, S. Mattioli, L. Zetta, G. Graw, R. Hertenberger, D. Hofer, H. Kader, P. Schiemenz, R. Neu, H. Abele and G. Staudt, Phys. Rev. **C43** (1991) 2572

[3] E. Gadioli, P. Guazzoni, M. Jaskola, L. Zetta, G. Colombo, G. Graw, R. Hertenberger, D. Hofer, H. Kader, P.S chiemenz, R. Neu, G. Staudt, Phys. Rev. **C** in press

2.2.7 Study of the ^{122}Sn(p,t)^{120}Sn reaction

U. Atzrott [a], Gh. Cata-Danil [b], G.Graw, P. Guazzoni [c], R. Hertenberger, D. Hofer, M. Jaskola [d], R. Neu [a], P. Schiemenz, G. Staudt [a], B. Valnion, E. Müller-Zanotti, L. Zetta [c]
[a] Physikalisches Institut der Universität Tübingen
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The reaction ^{122}Sn(p,t)^{120}Sn was studied at 25 MeV incident energy, using the Munich MP Tandem accelerator, the Q3D spectrograph and the light ion focal plane detector with periodic read out. Angular distributions were measured from 5^o up to 75^o with $5\ ^o$ step, using a 134 $\frac{\mu g}{cm^2}$ ^{122}Sn target on carbon backing of 19 $\frac{\mu g}{cm^2}$ enriched at 96%. The beam current used was $\sim$ 500 nA.

It is the aim of this investigation to identify two-neutron hole states in ^{120}Sn. The knowledge of these states is desirable in view of measuring the (p, α) reaction on the same target. In this reaction an excitation of states can be expected whose configurations result from the coupling of a one-proton-hole to the two-neutron-hole states deduced in the (p,t) reaction. Furthermore, the knowledge of these two-hole and the one-hole states which are excited by the (p,t) and (p, α) reactions on ^{122}Sn, respectively, is necessary for the interpretation of the multiplets of homologous states excited by the (p,t) and (p, α) reactions on ^{123}Sb. The concept of homology of nuclear states [1] is discussed elsewhere in this Annual Report.

The t-spectra obtained were analyzed with the computer code Autofit. Fig. 1 shows a spectrum obtained at 10^o for two magnetic settings, up to an excitation energy of 3 MeV. About 50 levels have been observed. In fig. jbRef2 experimental angular distributions for 20 transitions are reported together with theoretical curves obtained in the framework of a semimicroscopic pick-up theory. The calculations have been done using the code TWOFNR [2]. The optical model parameters used are listed in table I [3].

TABLE I

	V_r	r_r	a_r	W_v	r_w	a_w	W_d	r_d	a_d	V_{so}	r_{so}	a_{so}	r_c
p	50.0	1.25	0.65				10.0	1.30	0.60	3.0	1.25	0.70	1.25
t	176	1.14	0.72	18.0	1.61	0.82				8.0	1.10	0.80	1.30
B.S.		1.3	0.5										

[1] E. Gadioli, P. Guazzoni, M. Jaskola, L. Zetta, G. Colombo, G. Graw, R. Hertenberger, D. Hofer, H. Kader, P. Schiemenz, R. Neu, G. Staudt, Phys. Rev. **C** in press
[2] M. Igarashi - TWOFNR Code, 1977, unpublished
[3] D.G. Fleming, H. Blann, H.W. Fulbright and J.A. Robbins, Nucl. Phys. **A157** (1970) 1

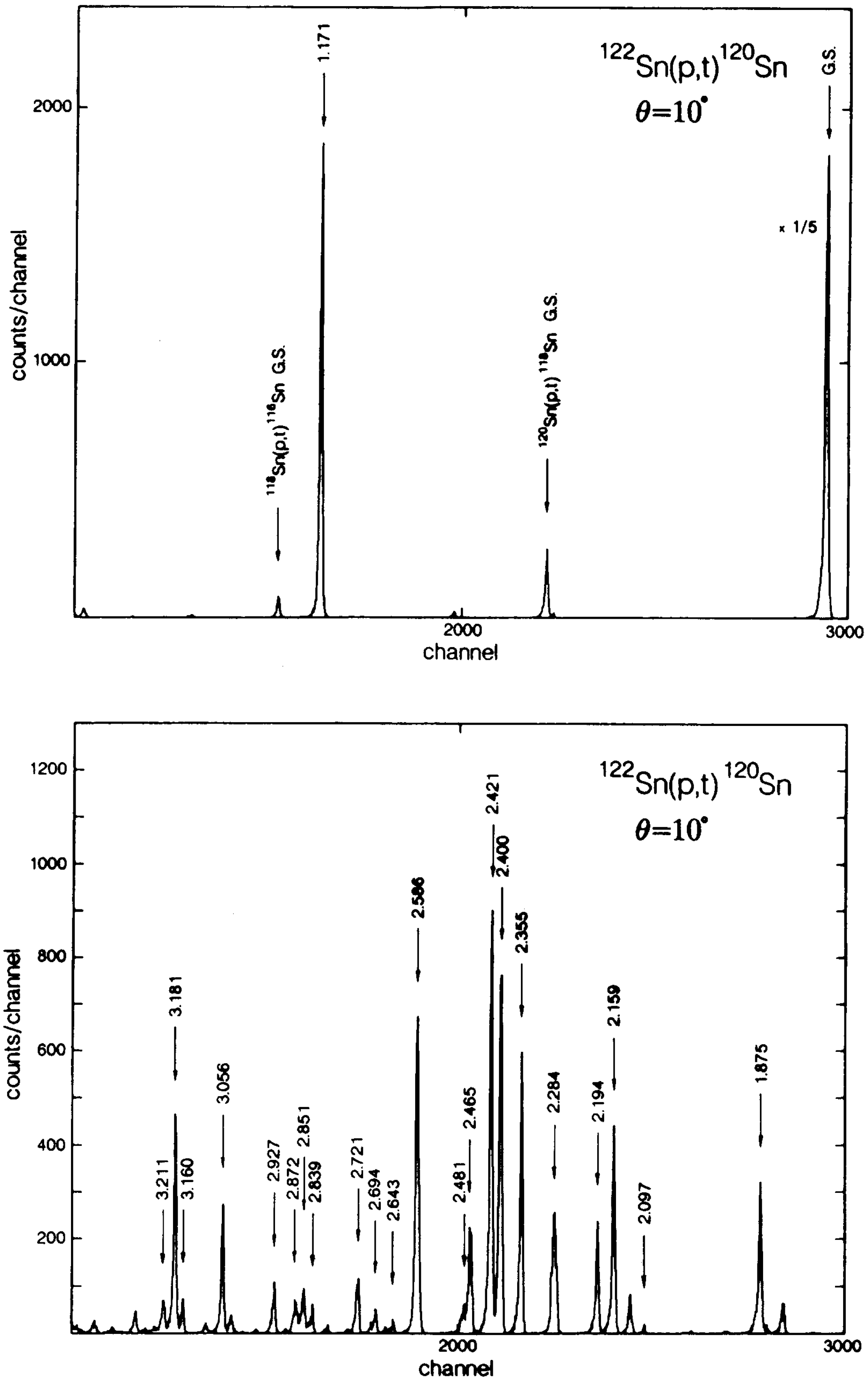

Fig. 1: The ^{122}Sn(p,t)^{120}Sn reaction triton spectra measured at 10^o for two different magnetic setting.

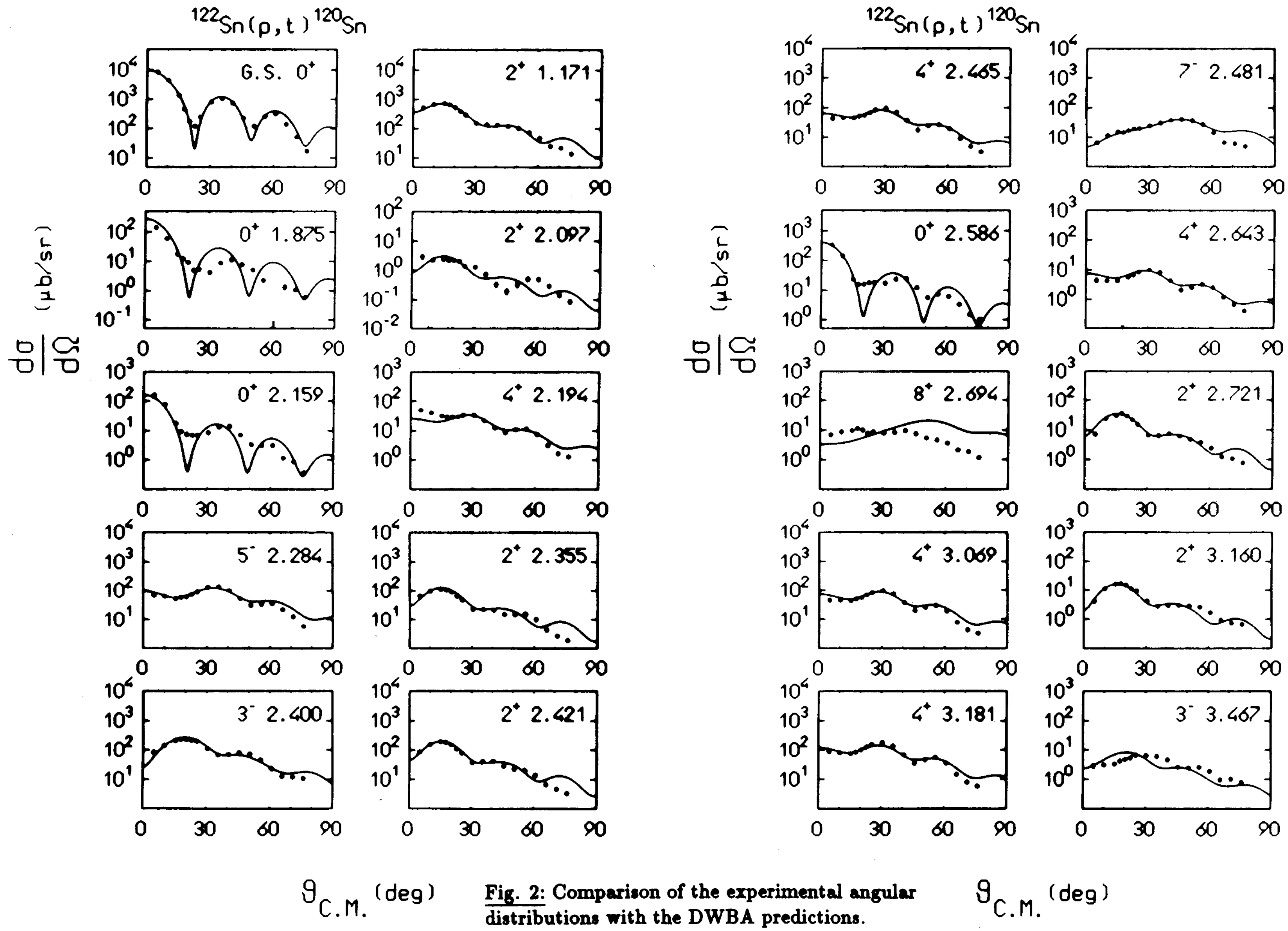

Fig. 2: Comparison of the experimental angular distributions with the DWBA predictions.

2.2.8 Level structure of ^{124}Te measured with the (n,γ) reaction

R. Georgii, T. von Egidy, M. K. Balodis [a], V. A. Khitrov [b], P. T. Prokofjev [a], A. M. Sukhovoj [b], A. V. Voinov [b]

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Recently the even-even Te (Z=52) nuclei became the subject of several studies [1–5]. It would be interesting to find correlations with the Cd (Z=48) isotopes and their special features, especially the intruder states. They are also an ideal testing ground for the dynamical symmetries of the IBM model. But so far, even for the low lying states no complete understanding of the nuclear structure could be achieved.

Especially for the isotope ^{124}Te the situation is very complicated. At lower excitation energies it seems to be an ideal collective nucleus. The energy ratio of $E(4_1^+)/E(2_1^+) \approx 2$ supports the spherical vibrator (SU(5) limit of IBM), but at higher excitation energies there is the problem of large anharmonicities. The γ–soft rotor (O(6) – limit of IBM) describes the level sequence for the 2–phonon triplet very well, but faces the problem, that the above energy ratio is well below the ideal O(6) value of 2.5. Consequently both model limits fail to some extent [5]. Additionally there is the problem, that there are much more 2^+ levels observed than predicted. They seem to be not collective, as indicated by the two limits.

Therefore we measured during the last years transfer reactions and photo excitation in ^{124}Te [4]. The ^{123}Te(n,γ)^{124}Te reaction, together with $\gamma - \gamma$ coincidences was measured in Riga and in Dubna in order to complete the level scheme. In Dubna the special method of sum coincidences was applied. γ – cascades to the ground state and the first 2^+ level were analyzed. This was done with Ge(Li) detectors, which could detect a gamma cascade as long as the intensity of the primary feeding was larger than about 0.5 % of the whole intensity of all decays to either the groundstate or the first excited level. From these experiments and the photo excitation data a level scheme up to 4.5 MeV was constructed (Fig. 1), which should be complete up to 3.5 MeV.

This data clearly verify the observation of Bushnell et al. [6], who found a strange deexcitation of a level at 3.1 MeV. It is strongly fed by the capture state, but there is <u>no</u> transition from there to the ground state or to any other low lying level, as well as <u>no</u> evidence in the photo excitation experiment. On the other hand there is a weak transtion to the 2988 keV level and an extremly strong decay to the 2747 keV level.

This observation as well as the low lying structure are now under theoretical studies. Preliminary results, using the quasi particle phonon model indicate the 3.1 MeV level to be a 3-phonon state, with a mixture of quadrupole and octopole phonons. It would decay to the 2.747 MeV 2-phonon state, but not to the ground state. Another possibilty is that this level is an intruder state. At lower excitation energies, there was no evidence found for intruder states [2,5], but at energies above 2.5 MeV they are not excluded. A third possibilty is the exsistence of a mixed symmetry state which was already proposed for the 2091 keV level [2].

[1] C.S. Lee et al. , Nucl. Phys. **A 528** (1991) 381
[2] C.S. Lee et al. , Nucl. Phys. **A 530** (1991) 58
[3] R.F. Casten et al. , Phys. Rev. **C 44** (1991) 523
[4] R. Georgii et al. , Jahresbericht 1990, p. 37 and 1991, p. 44
[5] W.-T. Chou et al. , Phys. Rev. **C 46** (1992) 2283
[6] D.L. Bushnell et al. , Phys. Rev. **179** (1969) 1113

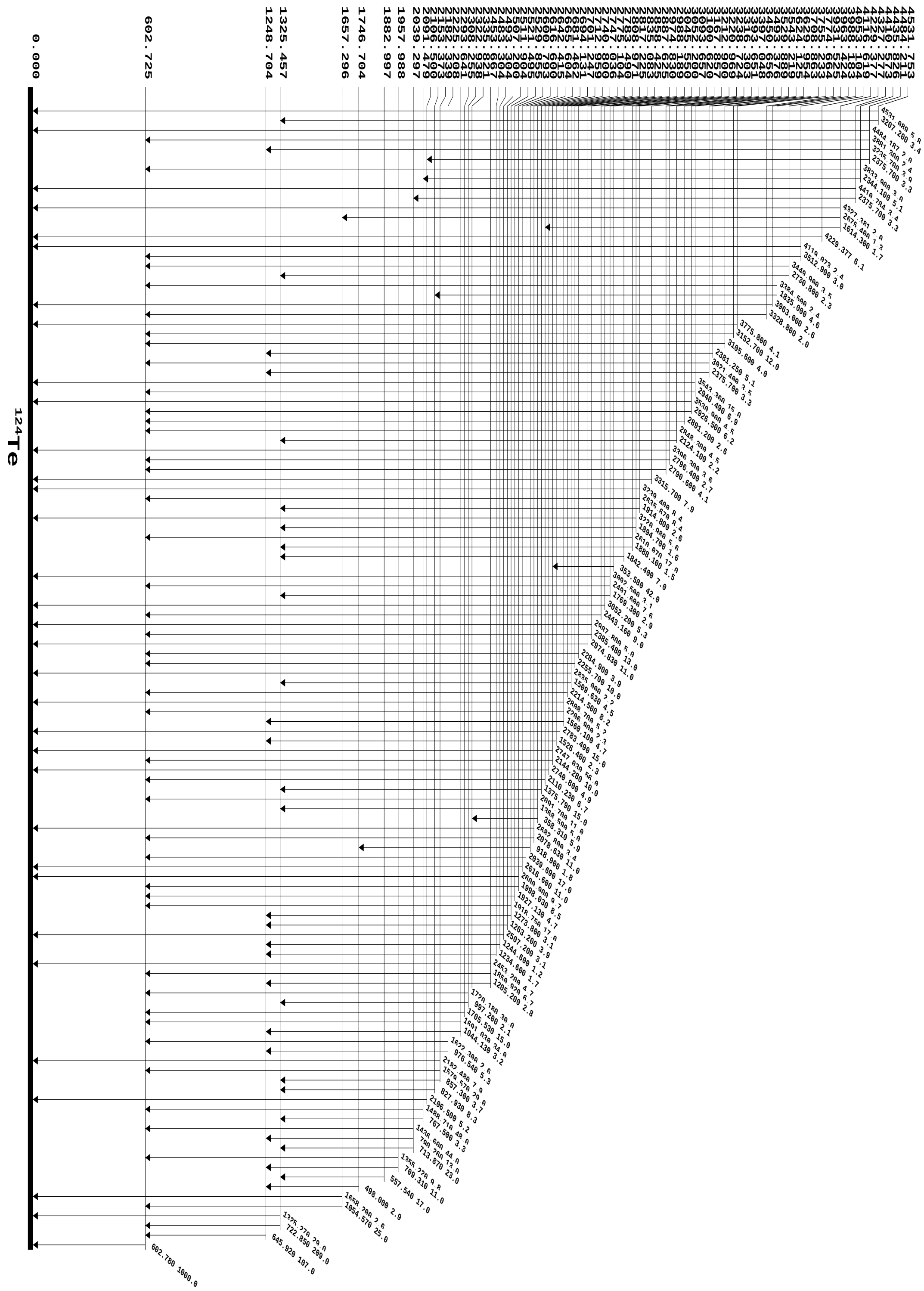

Fig. 1: Level scheme of ^{124}Te from ^{123}Te(n,γ)^{124}Te and ^{124}Te(γ,γ')^{124}Te experiments

2.2.9 Spectroscopy of ^{170}Tm via the ^{169}Tm(d,p) reaction

W. Schauer, S. Schründer, T. von Egidy, R. Georgii, G. Graw, R. Hertenberger, D. Hofer, R.W. Hoff[a], J. Klora, H. Lindner, W. Oelmaier, J. Ott, B. Valnion, E. Müller-Zanotti
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The reaction ^{169}Tm(d,p)^{170}Tm has been studied using a 20 MeV deuteron beam produced by the Munich MP tandem accelerator. The energy resolution was $\approx$ 2 keV using a $\approx 40\mu g/cm^2$ thick ^{169}Tm target. Spectra at $\Theta_{\rm lab} = 20^0$,$\Theta_{\rm lab} = 30^0$ and $\Theta_{\rm lab} = 40^0$ were measured up to 2 MeV excitation energy. Several years ago at the ILL, Grenoble, the reaction ^{169}Tm(n,γ)^{170}Tm was investigated and the ^{169}Tm(d,p)^{170}Tm reaction was measured at 11.93 MeV with the Q3D at the tandem accelerator [1]. Average resonance capture (ARC) data were measured by Casten and Gill and evaluated by R. W. Hoff [2]. All this information was used for the interpretation of our data. A total of over 100 levels were found. The states were compared with the results of DWBA calculations performed using the computer code DWUCK4. A spectrum is shown in Fig. 1.

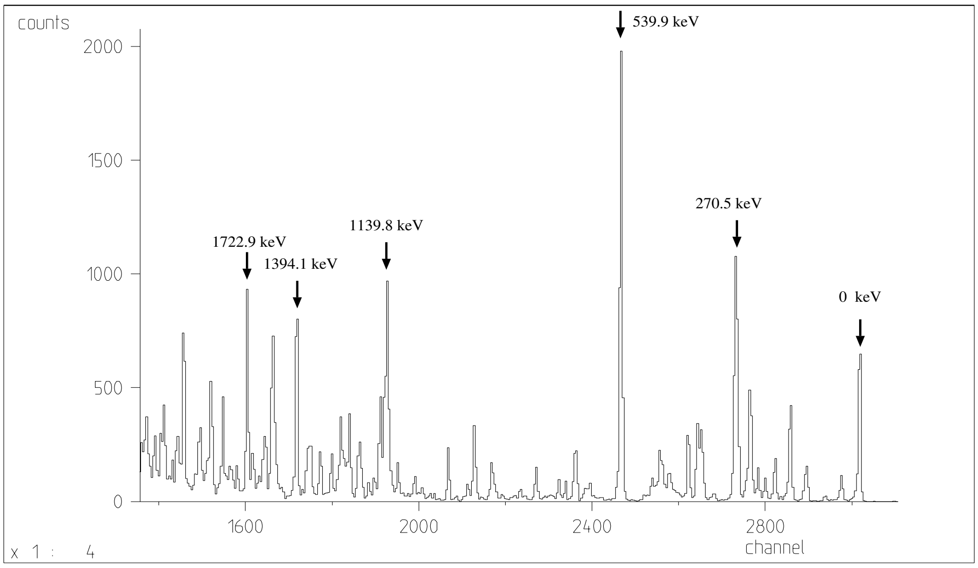

Fig. 1: Spectrum of ^{169}Tm(d,p)^{170}Tm at 30^0 and 20 MeV

[1] S. Schründer, Diploma thesis,TU München 1991
[2] R. W. Hoff, private communication

2.2.10 The level scheme of ^{171}Tm examined by multiple neutron capture and the (^{3}He,d) transfer reaction

M. Weber, H.G. Börner [a], T. von Egidy, W. Schauer, R. Georgii, S. Faber, G. Graw, D. Hofer, R. Kokowski, E. Müller-Zanotti, J. Ott, W. Oelmaier, B. Valnion
[a] Institut Laue-Langevin, F-38042 Grenoble, France

The high neutron flux available at the high flux reactor in Grenoble makes it possible to observe multiple neutron capture in (n,γ) experiments and examine nuclear structure of nuclei that can not be reached by ordinary (n,γ) reactions. In this work, this facility was used to investigate the energy levels in ^{171}Tm.

Previous energy values in the level scheme of ^{171}Tm have been obtained by measurement of the β-decay of ^{171}Er and by transfer reactions like ^{170}Er(^{3}He,d)^{171}Tm and ^{170}Er(^{7}Li,2n$\alpha\gamma$)^{171}Tm. Only four levels have been observed in (n,γ) reactions [1]. Recent data from ^{169}Tm(n,γ) measurements with the high resolution crystal spectrometers GAMS 2/3 and GAMS 1 at the ILL contain (n,γ) lines from both single and double neutron capture. From the intensity variation with time it was possible to separate lines originating from single or double capture and thus to distinguish lines in ^{170}Tm from lines in ^{171}Tm. Previous assignments of ^{170}Tm transitions in the work of S. Schründer were also taken into account [2]. Using the selected (n,γ) lines of ^{171}Tm, it was possible to determine more precise values for the energy levels in ^{171}Tm. Due to the unique resolving power of the GAMS 2/3 spectrometers the energy errors were improved at least by one or two orders of magnitude.

An additional measurement of the ^{170}Er(^{3}He,d)^{171}Tm transfer reaction was carried out with the Q3D spectrograph at the Munich Tandem accelerator. The Ritz combination method was used to compare (n,γ) and transfer reaction data. Three new energy levels above 1 MeV were identified (1785,378(18) keV, 1848,63(4) keV and 1858,88(3) keV.

Using the new level energies, the rotational parameters A in the various rotational bands and various level spacings and the decoupling parameters a in the K = 1/2 bands were calculated (Fig. 1). They show considerable accordance with theoretical values [3].

[1] V.S. Shirley, Nuclear Data Sheets 66 (1992) 69
[2] S. Schründer, Diplomarbeit TUM 1991
[3] B.E. Chi, Nucl. Phys. **83** (1966) 97

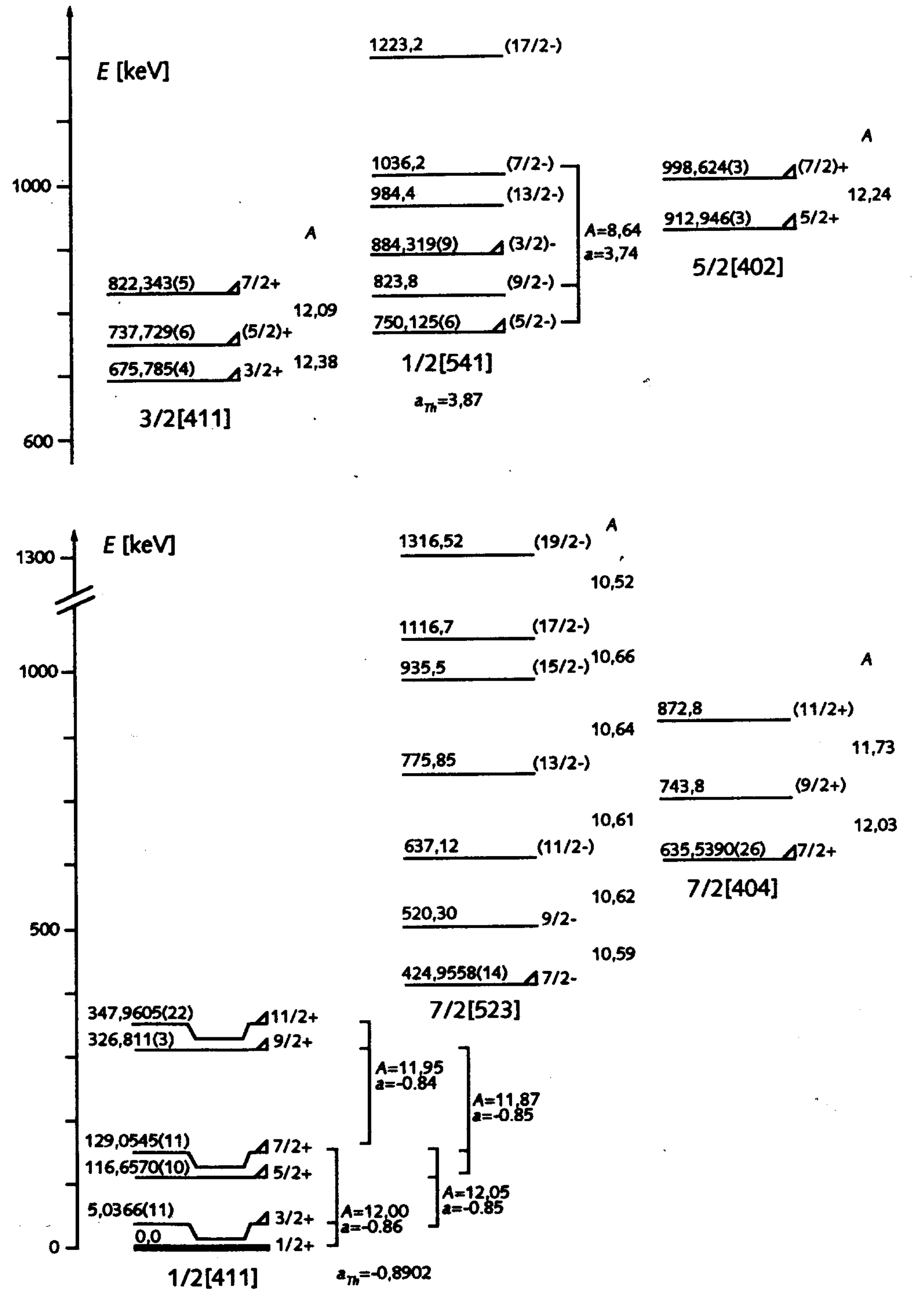

Fig. 1: Rotational bands in ^{171}Tm and level energies from double neutron capture measurements. Level energies obtained from these measurements are marked with a small triangle - other level energies were taken from [1]. Calculated values for the rotational parameter A and the decoupling parameter a (for K = 1/2) are given on the right side of the bands.

2.2.11 New transitions in ^{177}Hf studied by Coulomb excitation

A. Gollwitzer, J. de Boer, N.A. Gollwitzer, A. Lösch,
H.J. Maier, F. Rieß, M. Springer, M. Würkner, E.G. Vogt

To facilitate the interpretation of planned Coulomb-exitation experiments of the $K^{\pi} = 16^{+}$ isomer in ^{178}Hf [2], the five most abundant hafnium-isotopes were studied with 125 MeV ^{32}S projectiles. The experimental setup consisted of five Compton-suppressed high-purity germanium-counters in coincidence with 24 PIN-diodes. The gamma-ray energies were corrected for Doppler shift.

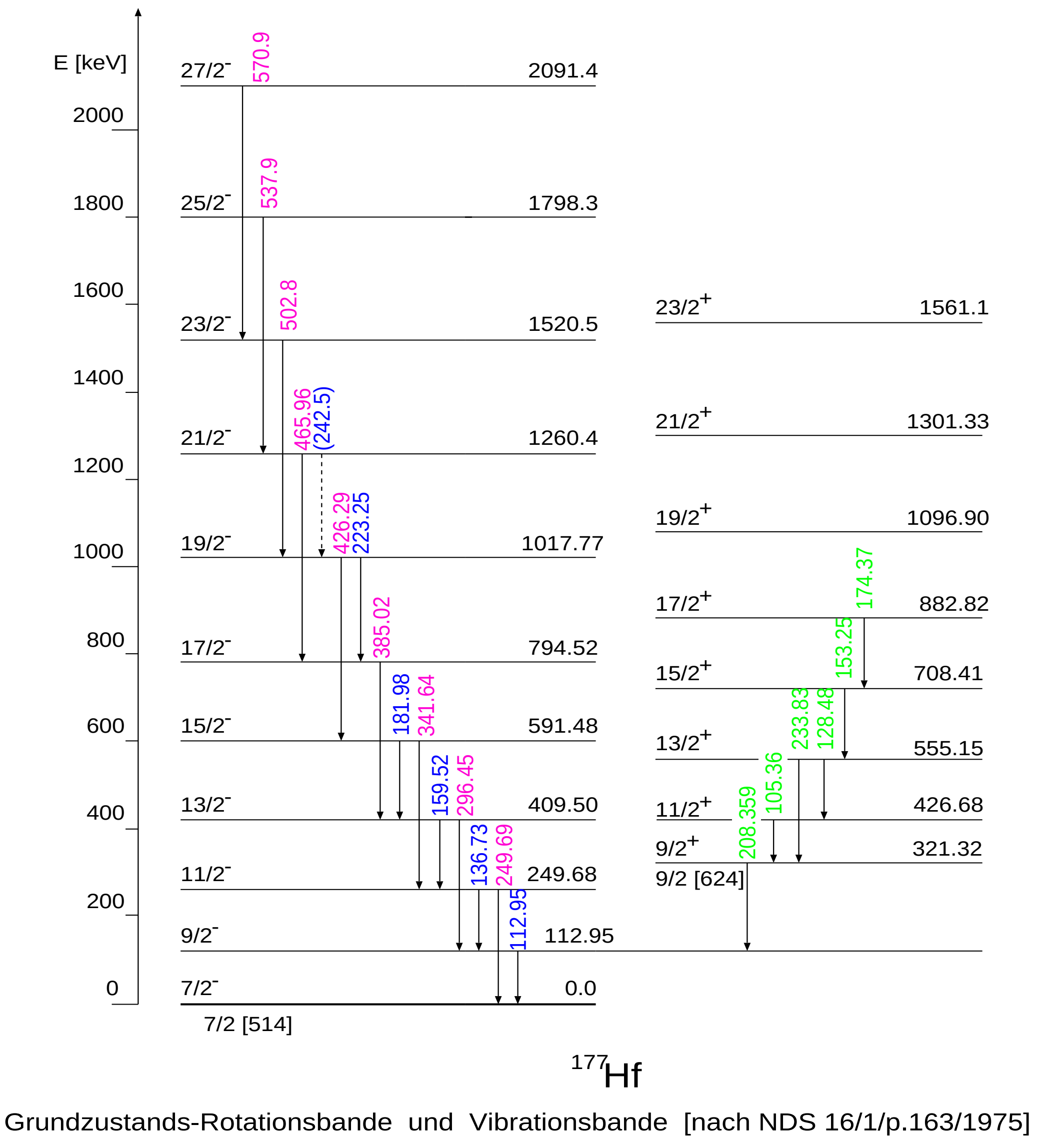

Fig. 1: Ground state rotational band and rotational band based on another one-particle state of ^{177}Hf Coulomb-exited in this work (full level scheme see [1])

In the rotational band we have observed one new transition ($19/2^- \rightarrow 17/2^-$) and we confirmed the uncertain $15/2^- \rightarrow 13/2^-$ cascade transition. Moreover transitions within the γ-vibrational-band and from the γ-vibrational-band to the groundstate-band (Fig. 2) were seen. Because the target was enriched only to 82.8% transitions in other Hf-isotopes were also present. We found that an isotopic admixture as small as 1% (^{179}Hf) could be identified in the spectrum. It might therefore be possible to investigate the $17^+ \rightarrow 16^+$transition in the ^{178m_2}Hf [2] high-spin target using this technique.

The evaluation of the gamma-intensities in terms of collective-model parameters for E2 and M1 matrix elements is in progress.

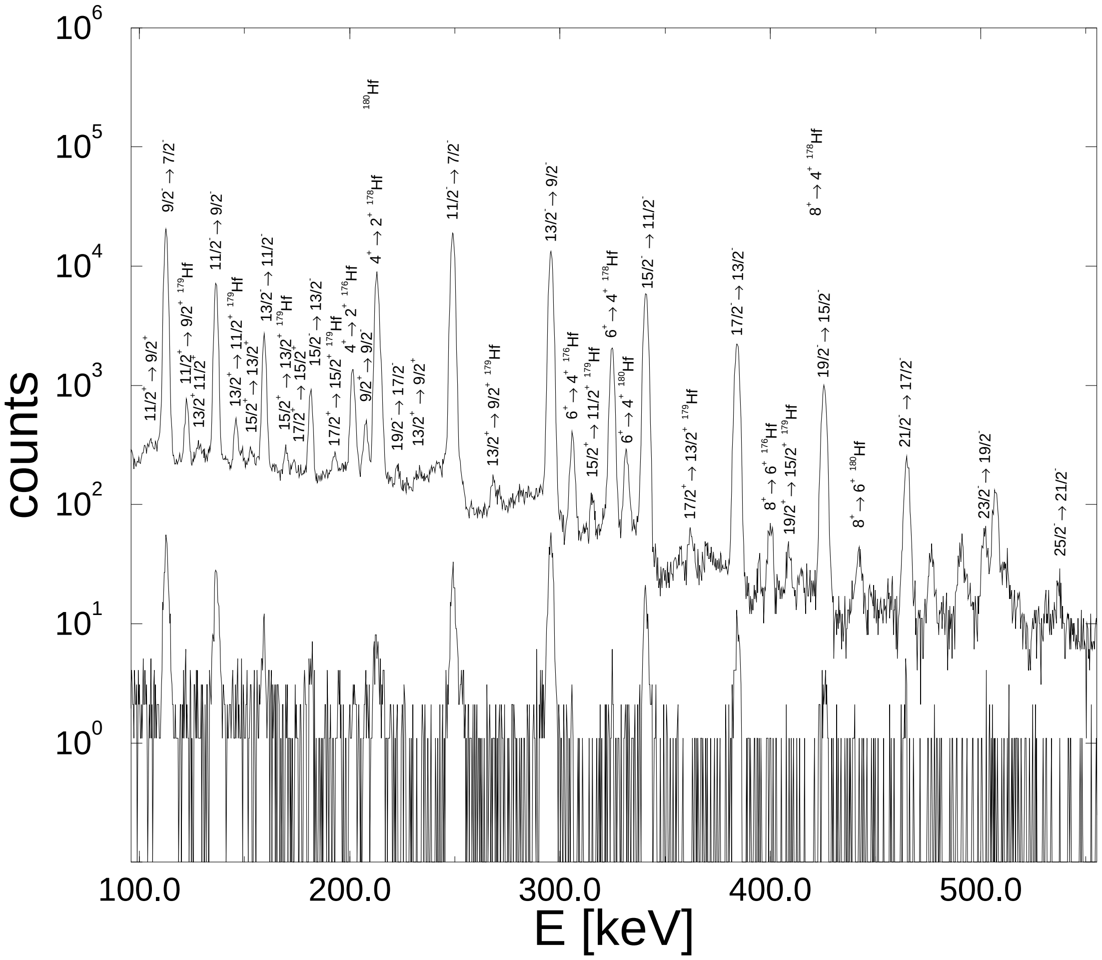

Fig. 2: gamma-ray spectrum in coincidence with ^{32}S backscattered from ^{177}Hf The spectrum in the lower half of the picture are gamma-gamma-particle coincidences obtained by setting gates on the E2-rotational-band.

[1] Nuclear Data Sheets, **16** (1975) 1

[2] Th. Happ et al. Inelastic scattering of deuterons and protons from the isomeric state of ^{178m_2}Hf, Jahresbericht B.L. 1992

2.2.12 Inelastic scattering of deuterons and protons from the isomeric state of ^{178m_2}Hf

Th. Happ [a], J. de Boer, Ch. Briançon [c], O. Constantinescu [b], T. Faestermann, H. Folger [a], S. Fortier [b], J. Gerl [a], G. Graw, A. Gollwitzer, N.A. Gollwitzer, D. Hofer, M. Hussonnois [b], S.A. Karamian [d], R. Kulessa [a], A. Lösch, E. Müller-Zanotti, W. Oelmaier, Yu.Ts. Oganessian [b], F. Rieß, L. Rosier [b], G. Rotbart [b], Z. Szeglowski [b], M. Springer, B. Valnion, E.G. Vogt, H.-J. Wollersheim [a], M. Würkner
[a] GSI, Darmstadt;
[b] JINR, Dubna;
[c] CSNSM, Orsay;
[d] JINR, Dubna

By inelastic-scattering reactions from a ^{178m_2}Hf target, the band built on the 16^+ isomeric state can be populated and the moment of inertia as well as the quadrupole moment of the band may be determined.

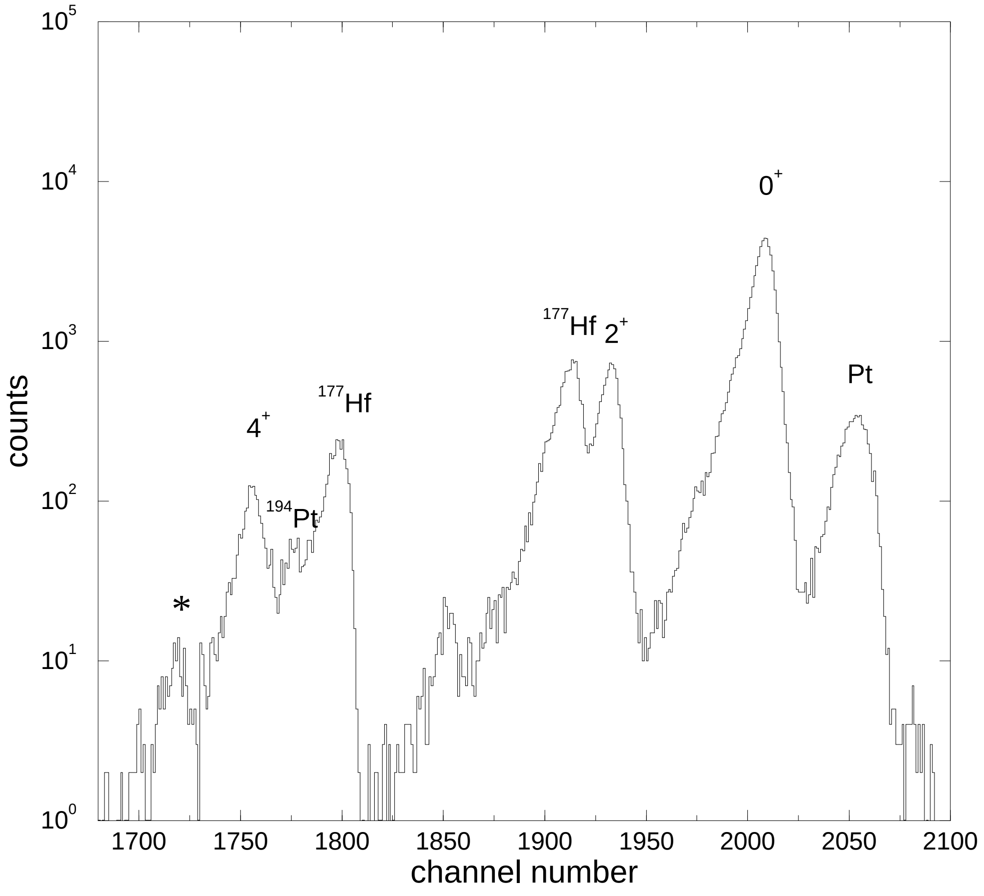

Fig. 1: Spectrum of inelastically scattered deuterons (E_d=22 MeV) from ^{178m}Hf, measured at a laboratory angle of 100°

Only $2 * 10^{14}$ atoms in the isomeric state were produced in Dubna using the ^{176}Yb(α,2n) reaction [2] by bombarding a highly enriched ^{176}Yb-target (99.999%). From the irridiated material a target was prepared after chemical separation of hafnium from the bulk material and by electro-spraying of the Hf-solution onto a thin carbon foil. The following stable Hf-isotopes contaminate the target: $1.8 * 10^{15}$ atoms of ^{176}Hf, $1.8 * 10^{16}$ atoms of ^{177}Hf, $4.8 * 10^{15}$ atoms of ^{178}Hf, and $1.8 * 10^{14}$ atoms of ^{179}Hf.

Experiments were performed by bombarding the thin target with 22 and 26 MeV protons and 22 MeV deuterons from the Munich Tandem-Accelerator. The projectiles scattered through angles of 100° and 135° were detected in a Q3D magnetic spectrograph equipped with a 1.8 m long gas-filled multiparameter focal-plane detector [1]. Limited by target inhomogeneities, a resolution of 10 keV FWHM could be achieved.

The spectrum of the (d,d') reaction (Fig. 1) contains the lines of the elastic scattering from Hf and from a Pt contamination together with inelastic-scattering lines belonging to the stable isotopes ^{176,177,178}Hf. A line at an excitation energy of 353 keV may be attributed to the ^{178}Hf nucleus in its 16^+ isomeric state (^{178m_2}Hf). This peak was not observed in the reference spectrum taken with the stable-isotope target. There are also indications of a corresponding line in the (p,p') spectrum on ^{178m_2}Hf. The interpretation of our measurements is, however, still uncertain and further experiments are planned.

[1] R. Hertenberger et al., Nucl. Instr. and Meth., **A258** (1987) 201

[2] Yu.Ts. Oganessian et al. J.Phys.G: Nucl.part.Phys.**18** (1992) 393

2.2.13 Coulomb excitation of ^{179}Hf

A. Gollwitzer, J. de Boer, N.A. Gollwitzer, A. Lösch, M. Loewe,
J.Kvasil[a], H.J. Maier, P. Pemler, F. Rieß, M. Springer, M. Würkner, E.G. Vogt
[a] Department of Nuclear Physics, Charles University Prague

In connection with the planned γ-spectroscopy of the $K^\pi = 16^+$ isomer in ^{178}Hf [2] the five most abundant hafnium-isotopes were studied by Coulomb exitation with 125 MeV ^{32}S projectiles. The experimental setup consisted of five Compton-suppressed high-purity germanium-counters in coincidence with 24 PIN-diodes placed at backscattering angles.

Due to recoil velocities of the target nucleus of up to 1% of the speed of light, the γ-energies must be corrected for Doppler shift.

The level scheme obtained from the measured transition energies is given in Fig. 1. The highest rotational state ($23/2^+$) was not previously known. The level energy of the 1350keV $23/2^+$ state and the intensities of its decay transitions (502 and 265 keV) agree well with theoretical calculations based on a quasiparticle-phonon model with the inclusion of Coriolis coupling [3]. Gates were set on the known E2-transitions to establish the assignment of the peak at 502keV to the $23/2^+ \rightarrow 19/2^+$ transition. Unfortunatly the γ-tansition $23/2^+ \rightarrow 21/2^+$ is not resolved from the transition $13/2^+ \rightarrow 9/2^+$, but it can be approximatly disentangled by a γ-ray fit program.

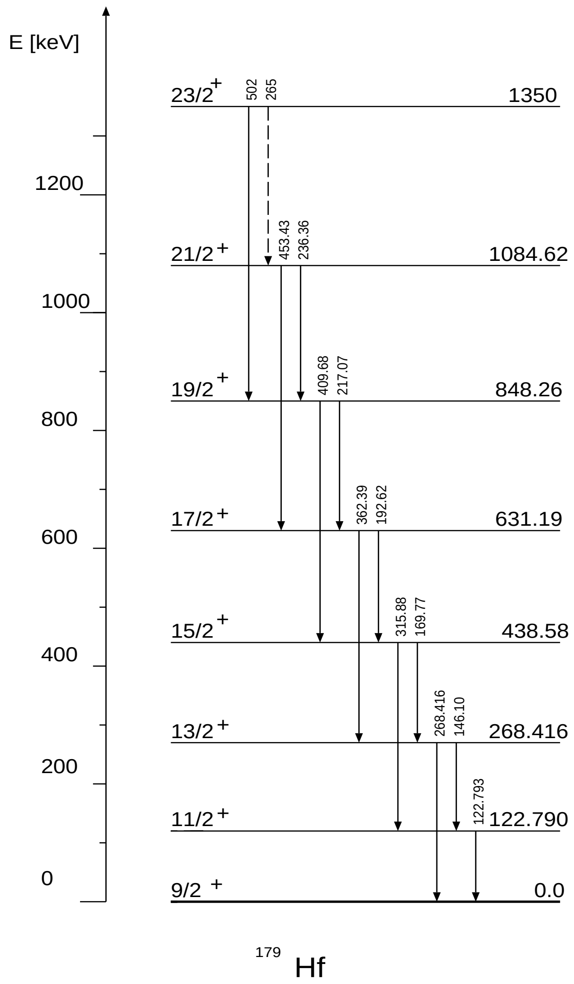

Fig. 1: Members of the ground-state rotational band of ^{179}Hf excited in this work (full level scheme see [1])

[1] Nuclear Data Sheets, **55** (1988) 483

[2] Th. Happ et al., Inelastic scattering of deuterons and protons from the isomeric state of ^{178m_2}Hf, Jahresbericht B.L. 1992

[3] C.F. Liang, P. Paris, J. Kvasil, R.K. Sheline, Phys. Rev. **C44** (1991) 676

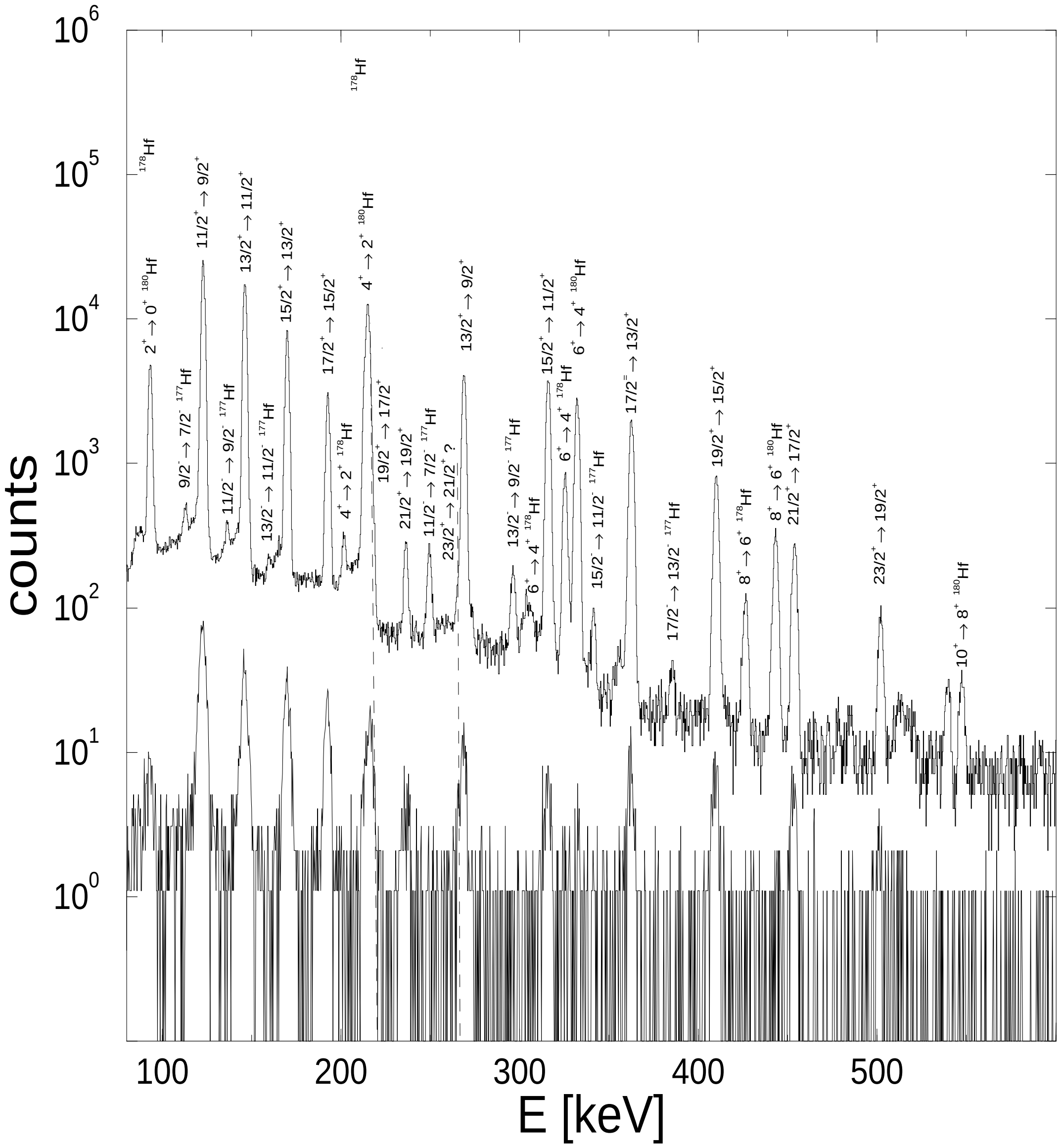

Fig. 2: γ-ray spectrum in coincidence with ^{32}S backscattered from ^{179}Hf
The underlying spectrum is the sum of all spectra of the five gamma counters created by setting gates on the E2-rotational-band.

2.2.14 Spectroscopy of ^{229}Pa and ^{231}Pa

A. Lösch, J. de Boer, N.A. Gollwitzer, G. Graw, C. Günther[a], R. Hertenberger, D. Hofer, J. Kvasil[b], H.J. Maier, E. Müller-Zanotti, F. Rieß, M. Würkner
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The lower part of the level scheme for the nuclei ^{229}Pa and ^{231}Pa – both lying at the border of a region for which octupole deformation is expected – is dominated by a K=1/2 rotational band built on the 1/2[530] Nilsson level. Its $3/2^-$ member lies at 19 keV in ^{229}Pa and forms the ground state in ^{231}Pa. Whereas for ^{229}Pa the level spacing can accurately be reproduced by the rigid rotor formula, Coriolis coupling effects seem to destroy this structure in ^{231}Pa (see Fig. 1) leading to experimental ambiguities in the interpretation of the γ-spectra.

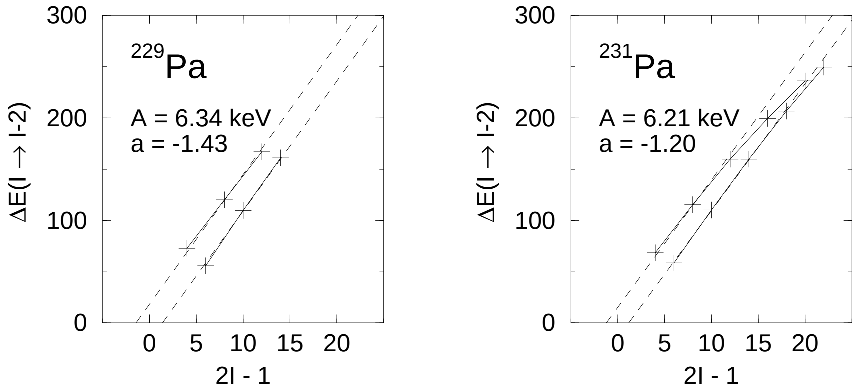

Fig. 1: Transition energies within the 1/2[530] band as a function of (2I-1). The dashed line shows a fit for the first three transitions to the rigid rotor model: $\Delta E(I \rightarrow I\text{-}2) = 2A(\ 2I\text{-}1 + (\text{-}1)^{I+1/2}\ a)$.

Both nuclei were studied using a $\approx$100 μg/cm^2 ^{231}Pa target and analyzing the ejectiles of the reactions ^{231}Pa(p,t)^{229}Pa and ^{231}Pa(p,p')^{231}Pa with our Q3D magnetic spectrograph equipped with a position-sensitive focal plane detector.

^{229}Pa was predicted [1] to be stably octupole-deformed, characterized by a $5/2^{\pm}$ parity doublet at 0 and 0.2 keV, respectively. The 1/2[530] rotational band was claimed to start at 123 keV. Our measurements [4] did not support this assignment.

Angular distributions were measured for 28 levels up to an excitation energy of 950 keV. DWBA calculations reproduce the angular distribution for L=0 transfer and two $I^{\pi}=3/2^{-}$ levels in addition to the $3/2^{-}$ member of the 1/2[530] band were found in the energy region investigated (see Fig. 2). Calculations for L$\neq$0 transfer including multi-path processes are in progress but the fits are not yet satisfying.

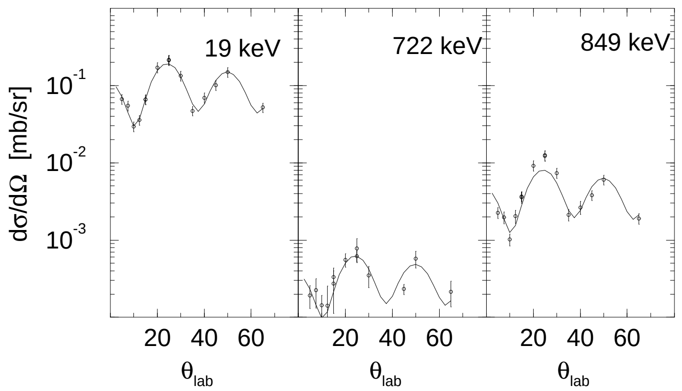

Fig. 2: Angular distribution for the reaction ^{231}Pa(p,t)^{229}Pa. The solid lines show the result of a DWBA calculation for L=0 transfer.

In ^{231}Pa the lowest levels of the 1/2[530] rotational band closely resemble those of ^{229}Pa. Even the higher members of this band with positive signature have almost the same energies as the corresponding levels in ^{229}Pa. The structure of this band together with high conversion coefficients for the M1 transitions of the negative-signature to the positive-signature levels has two effects: 1. Due to the low energy, these transitions are invisible in both conversion-electron and γ-spectroscopy. 2. The high conversion causes a depopulation of the negative signature side of the band leading to a decrease in intensity of all decays between these levels.

Attempts were made to interpret the observed γ-transitions stemming from Coulomb-excitation experiments with ^{32}S in terms of Coriolis coupling calculations [2]. Since a number of different assignments are possible it would be highly desirable to establish the exact level positions.

^{231}Pa was studied using the reaction ^{231}Pa(22 MeV p, p') at $\theta_{lab} = 60°$ and $\theta_{lab} = 90°$. The energy calibration was performed with the reaction ^{232}Th(p,p'). Two main results emerged from this experiment:

1. Non-negligible impurities in the ^{231}Pa target lead to an uncertainty in the interpretation of observed peaks in the spectra. The comparison between the 60° and 90° spectra and calculations of reaction kinematics can give a hint whether a peak stems from an excited state or from an impurity (see Fig. 3).

2. 16 levels were observed up to an excitation energy of 443 keV. Above this energy a level identification is impossible because of the impurity counts. Table 1 lists the observed states.

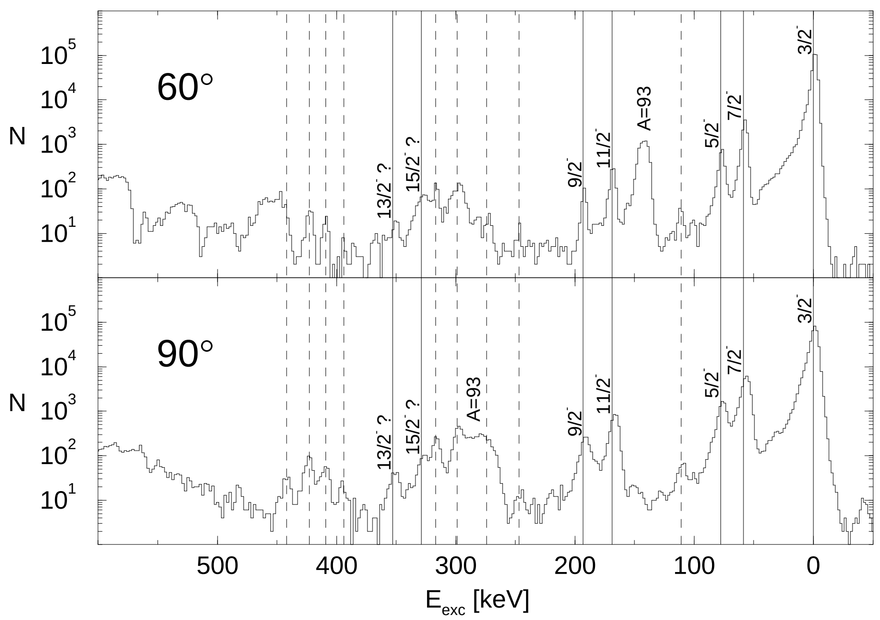

Fig. 3: Proton spectra of the reaction ^{231}Pa(22 MeV p, p') at $\theta_{lab} = 60°$ and $\theta_{lab} = 90°$.

The position of the $15/2^-$ and $13/2^-$ states of the 1/2[530] rotational band could not be determined accurately. For this purpose a target free of heavy impurities would be necessary. A hot lab which could produce this target is under construction. A preliminary approach is the study of ^{231}Pa via the (d,d') reaction at 28 MeV which would shift the heaviest mass seen (A=93) to an excitation energy of about 700 keV.

$E_{(p,p')}$ keV	E_{lit} keV	I^{π}
0	0	$3/2^-$
58	58.570 *3*	$7/2^-$
77	77.685 *17*	$5/2^-$
111	111.653 *12*	$(9/2^+)$
168	169.0	$11/2^-$
193	193	$9/2^-$
247	247.320 *6*	$7/2^+$
273	272 *1*	$5/2^-$
298		
317	317.95 *4*	$(3/2^+)$
327	329.0	$15/2^-$
351	353	$13/2^-$
395	393 *2*	
410		
424		
443	442 *2*	$5/2^+$

Table 1: Excited states in ^{231}Pa. The estimated errors for the excitation energy $E_{(p,p')}$ are 1.5 keV. The column E_{lit} gives the values found in [5, 2, 3] for the known levels.

[1] I. Ahmad, J. Gindler, R. Betts, R. Chasman, and A. Friedman. *Phys. Rev. Lett.*, 49(24):1758, 1982.

[2] J. de Boer, N. Gollwitzer, A. Lösch, H. Maier, H. Müller, M. Rohn, B. Ackermann, T. Bihn, V. Grafen, C. Günther, M. Marten-Tölle, N. Singh, and R. Tölle. *Z. Phys. A*, (344):41–48, 1992.

[3] J. Erskine, G. Kyle, R. Chasman, and A. Friedman. *Phys. Rev.*, C11(2):561, 1975.

[4] V. Grafen, B. Ackermann, H. Baltzer, T. Bihn, C. Günther, J. de Boer, N. Gollwitzer, G. Graw, R. Hertenberger, H. Kader, A. Levon, and A. Lösch. *Phys. Rev.*, C44(5):R1728, 1991.

[5] P. Hornshøj, P. Tidemand-Petersson, R. Kaczarowski, B. Kotlinska, and J. Żylicz. *Nucl. Phys.*, A248:406–428, 1975.

2.2.15 Particle spectroscopy of ^{231}Pa

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The K=1/2$^-$[530] rotational band whose I^{π}=3/2$^-$ member forms the ground state in ^{231}Pa was studied by particle spectroscopy using Coulomb excitation by ^{1}H (11 MeV) and ^{4}He (21 MeV) beams. The target used was 9μg/cm^2 and 76μg/cm^2 ^{231}Pa on a C-backing. At $\Theta_{Lab} = 135^{\mathrm{O}}$ the backscattered particles were analyzed in a Q3D magnetic spectrograph equipped with a position and angle resolving focal-plane detector[1]. The on-line readout was treated by software[2]. An energy calibration was performed using a 100μg/cm^2 ^{232}Th target in the same setup. The resulting spectra are shown in Fig. 1

and Fig. 2. Excitation energies and probabilities were determined with the help of the peak-fitting code GASPAN[3].

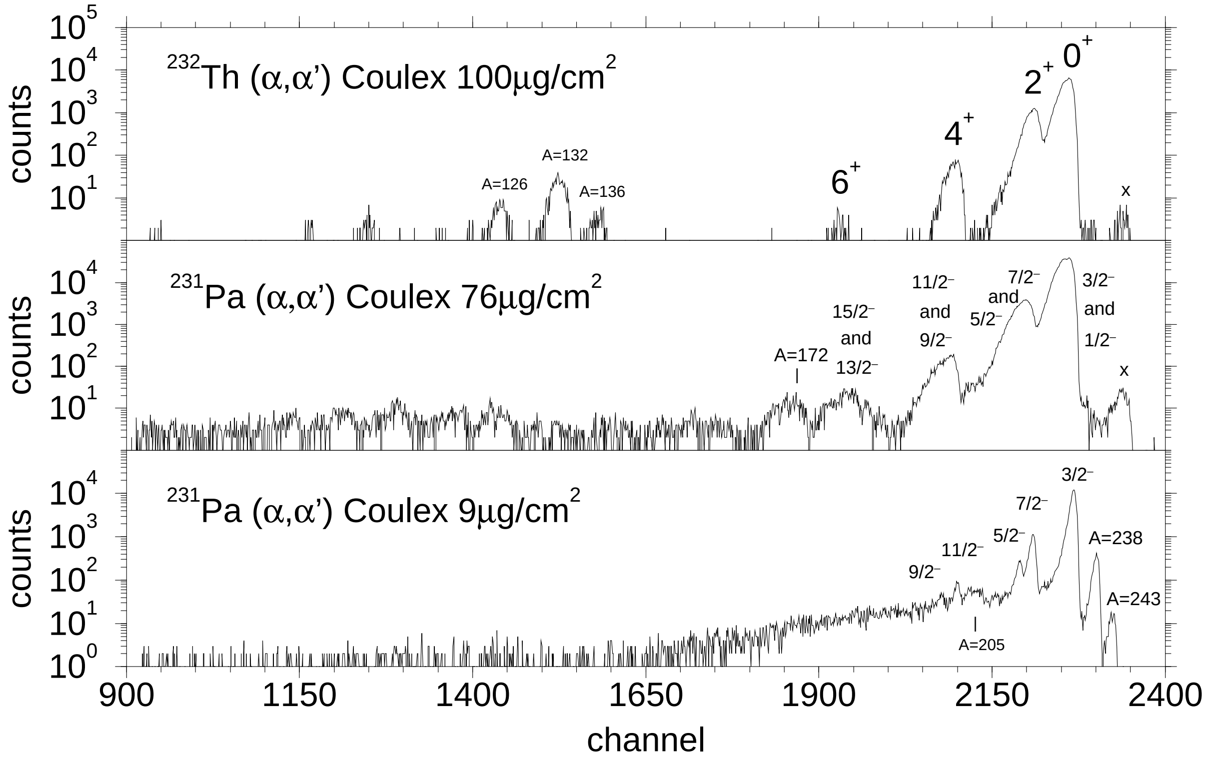

Fig. 1: ^{4}He spectra for E_{Lab}=21MeV at Θ_{Lab}=135$^{\rm o}$. Contaminations are indicated with their mass number A. Peeks labeled 'x' are artifacts due to the detector.

It was possible to observe double-step Coulomb excitation with protons for the first time. Excitation energies[4] of the levels $3/2^-$, $7/2^-$, $5/2^-$, $11/2^-$ and $9/2^-$ were confirmed to within ± 1 keV, detecting no new lines. The rotational model was applied to calculate the E2 and E4 matrix elements from the intrinsic quadrupole and hexadecupole moments, Q_2 and Q_4. Using the semiclassical computer code COULEX[5] the calculated excitation probabilities were fitted to the experimental data by varying the intrinsic moments, and the values

$$Q_2 = (2.9 \pm 0.1)\text{eb} \quad ; \quad Q_4 = (1.9 \pm 0.6)\text{eb}^2.$$

were obtained. They are approximately corrected for deviations between the semiclassical and quantum mechanical calculations. In Fig. 3 the shape of the nucleus ^{231}Pa is shown with the deformation parameters $\beta_2 = (0.22 \pm 0.01)$ and $\beta_4 = (0.07 \pm 0.02)$ corresponding to the measured intrinsic moments Q_2 and Q_4.

[1] E. Zanotti, et al. *NIM A310 (1991)*, 706–707. 1991.
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[3] F. Riess. *Jahresbericht 1991*, page 168.
[4] J. de Boer, et al. *Jahresbericht 1991*, page 68.
[5] F. M. Indenkämpen. *Jahresbericht 1991*, page 169.

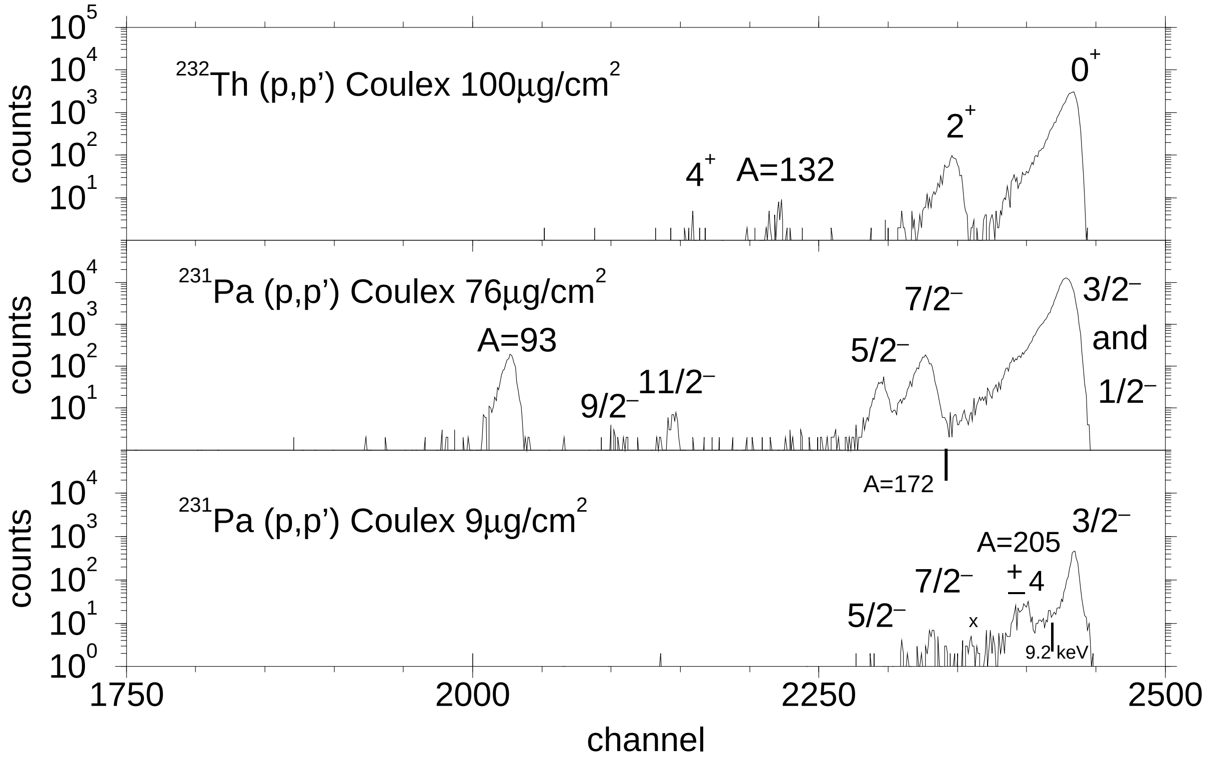

Fig. 2: ^{1}H spectra for E_{Lab}=11MeV at Θ_{Lab}=135^{O}. Determined contaminations are indicated with their mass number A. Peeks labeled 'x' are artifacts due to the detector. The position of the unresolved 9.2keV state is marked.

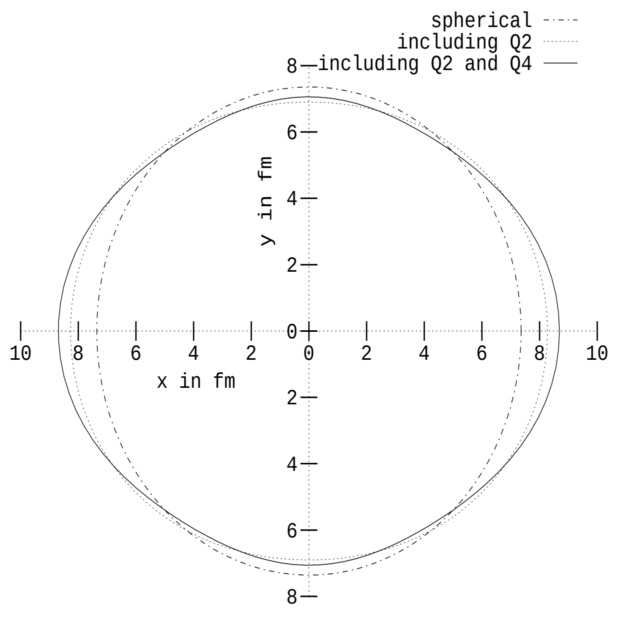

Fig. 3: Shape of ^{231}Pa nucleus; dashed-dotted line: no deformation; dotted line: with β_2 deformation; solid line: with β_2 and β_4