Zeitschrift für Physik A Manuscript-Nr.
(will be inserted by hand later)

Coulomb Excitation of the $K^{\pi}=16^{+}$ Rotational Band in ^{178}Hf

E. Lubkiewicz[1], H.J. Wollersheim[2], R. Kulessa[1], Ch. Briançon[3], W. Brüchle[2], O. Constantinescu[3], M. Dębowski[1,2], E. Ditzel[2], H. Folger[2], J. Gerl[2], F. Hannachi[3], T. Happ[2], M. Hussonnois[3], E. Jäger[2], S. Karamian[5], M. Kaspar[4], Th. Kröll[4], Yu.Ts. Oganessian[5], I. Peter[4], H. Schaffner[2], S. Schremmer[4], R. Schubert[2], N. Trautmann[6], K. Vetter[4], and G. Zauner[6]

[1] Physics Institute, Jagellonian University, Reymonta 4, 30-059 Cracow, Poland
[2] Gesellschaft für Schwerionenforschung, D-64220 Darmstadt, Germany
[3] CSNSM-Orsay, IN2P3-CNRS, 91405 Orsay Campus, France
[4] Johann-Wolfgang-Goethe University, D-60325 Frankfurt/Main, Germany
[5] Joint Institute for Nuclear Research, Dubna, 101000 Moscow, Russia
[6] University Mainz, D-55099 Mainz, Germany

April 30, 1996

Abstract. A heavy-ion multiple Coulomb excitation experiment on a very exotic target containing microweight quantities of ^{178}Hf in the $K^{\pi}=16^{+}$ isomeric state has been performed at 4.77 MeV/u ^{208}Pb beam energy. The first excited $I^{\pi}=17^{+}$ state has been observed at an excitation energy of 357.4 ± 0.3 keV with respect to the isomeric state. The intrinsic electric quadrupole moment of $Q_0 = 8.2 \pm 1.1$ b has been derived from the experimental data within the rigid rotor model.

PACS: 21.10.-k, 23.20.-g, 29.25.-t

1. Introduction

During the last decade a large effort was given to the construction of radioactive beam facilities and a large attention had been put into the development of new experimental programs connected with in-beam nuclear structure studies with radioactive exotic beams.
On the other hand a very rich area of similar experimental investigations can be covered with existing facilities if one manages to produce targets containing sufficient quantities of long-lived exotic radioactive nuclei. However, the range of appropriate nuclei is rather limited as compared to the possibilities offered by radioactive beam facilities.

A particularly promising new field of research would be open if one could utilize high-spin isomers as a target. A large number of isomeric excited states are observed in the region of rare earth elements and beyond. Among all known isomers, the $K^{\pi}=16^{+}$ isomeric state in ^{178}Hf is one of the best candidates for this kind of investigations due to its long lifetime ($T_{1/2}$=31 y), relatively low excitation energy of 2.45 MeV and a very high spin [1, 2, 3, 4, 5]. The structure of the state can be understood as a superposition of two 2-quasiparticle configurations $\{(\pi\frac{9}{2}[514]+\pi\frac{7}{2}[404])_{8^-}+(\nu\frac{7}{2}[514]+\nu\frac{9}{2}[624])_{8^-}\}_{16^+}$. The history of the discovery and production of this $K^{\pi}=16^{+}$ isomeric state is a very interesting adventure by itself, ranging from many year irradiation in thermal neutron flux [1, 2] through extraction from Ta accelerator slits [3, 5] up to the ^{176}Yb(α,2n) reaction [4]. The efficiency of the production described by the ratio of produced ^{178m2}Hf over ^{178}Hf nuclei ranges from 10^{-9} up to $5 \cdot 10^{-2}$ for different reactions used in the past.

Microweight quantities sufficient for target preparation to be used for nuclear structure studies were produced in a Dubna-Orsay-GSI collaboration. Extending previous studies of Khoo and Løvhøiden [4], the ^{176}Yb(α,2n) reaction was studied in Dubna (E_{α} = 26.5 – 35.5 MeV) and in Alma - Ata (E_{α} = 37 – 43 MeV). According to results of the irradiation carried out at the Dubna U-200 cyclotron, the cross section for the isomer production (with E_{α}=30-34MeV, target thickness 80 mg/cm^2) is ~9mb[6]. After chemical separation of the reaction products targets for nuclear structure studies were prepared by electrospraying the Hf solution on thin carbon foils (40μg/cm^2). A target spot of 5 mm in diameter was formed. For safety reasons each target was covered with an additional thin carbon foil (20μg/cm^2). A comprehensive description of the target production as well as the various scientific studies in which these targets are used can be found in the literature [6, 7, 8, 9].

Basic spectroscopic properties of the ^{178m2}Hf isomeric state were theoretically predicted [10, 11] and successfully confirmed by first experiments performed with isomeric targets [12, 13]. A collinear laser spectroscopy experiment at the PARIS separator in Orsay [12] delivered the value of the spectroscopic quadrupole moment (Q_s=6.00(7) b), the magnetic moment ($\mu_I = 8.16(4)\ \mu_N$) and the change in nuclear mean-square charge radius between the isomeric and the ground state ($\delta < r^2 > =$ -0.059(9) fm^2). The first two attempts devoted to the search of excited states were performed at the Munich tandem accelerator with a deuteron beam [13] and in the presently described experiment. In the inelastic scattering on ^{178m2}Hf targets a new excited state at the energy of 356.5±0.4 keV was observed together with a weak evidence for a second one at 737±2 keV in the particle spectra measured with the Q3D spectrograph. The first excited state can be assigned to the isomeric rotational band ($I^{\pi}=17^{+}$) and the second one would be a very good candidate for the next $I^{\pi}=18^{+}$ state.

In the present experiment we have decided to use the Coulomb excitation with heavy ions. The multiple Coulomb excitation with heavy ions is one of the best ways to study excited rotational and vibrational nuclear states. Such experiments do not only deliver energies of excited states but also electromagnetic multipole moments. Furthermore, the Coulomb excitation does not destroy the target which has to be recognized as a very important feature in case of such rare targets as ^{178m2}Hf. After a careful examination of the Coulomb excitation, fusion and direct reaction cross sections with a broad range of projectiles, the ^{208}Pb beam was chosen due to its high Coulomb excitation cross section, low γ-background from projectile excitations and negligible reaction cross sections on carbon and oxygen which are the major constituents of the isomeric targets.

2. Experiment and data analysis

The experiment was performed at the UNILAC linear accelerator of Gesellschaft für Schwerionenforschung in Darmstadt. Two targets containing ~0.6% of ^{178m2}Hf nuclei in the $K^{\pi}=16^{+}$ state (1.6 and $1.2 \cdot 10^{14}$ atoms) with respect to other present Hf isotopes were bombarded with ^{208}Pb ions at 4.77 MeV/u beam energy and ~3nA current. Due to the extremely low content of ^{178m2}Hf in the target material detailed studies of a huge background originating from other constituents of the target were very important. Thus, separate runs in the same experimental conditions were carried out with ^{176,177,178,179}Hf, ^{12}C and ^{nat}Pt stable targets.

The experimental set-up used for the detection of particle – particle – γ coincidences was developed at GSI for Coulomb excitation experiments [14]. It consisted of eight high-efficiency Ge detectors positioned at 25^o and 155^o with respect to the beam direction and five position sensitive parallel-plate avalanche counters for particle detection which covered almost 80% of the relevant solid angle. For measurements in the forward direction a sectioned annular detector was used covering the laboratory angle range of $20^o \leq \theta_{LAB} \leq 45^o$. Its azimuthal angle ($\phi$) sensitivity was based on a division of its anode foil into 20 radial sections of 18^o each. The polar angle could be derived with $\sim 1^o$ accuracy from the time difference of the anode and cathode signals. Additional four particle rectangular shaped detectors were placed around the target and covered the polar angle range of $53^o \leq \theta_{LAB} \leq 90^o$.

Both, the recoiling target and projectile nuclei were detected in coincidence. They could be distinguished on the basis of kinematic correlations between their scattering angles. The high precision of the particle position measurement and the possibility of particle identification allowed for a precise Doppler correction of the measured γ-ray energies. In all stages of the final analysis only peripheral collisions were taken into account for which ^{208}Pb nuclei were recorded in the forward annular detector while the scattered target constituents were observed in one of the rectangular detectors ($\theta_{CM} = 45.4^o$ – 69.2^o). The time information from Ge-detectors allowed for a differentiation of prompt from delayed γ-rays (with respect to the high-frequency of the accelerator). Delayed events contained mostly lines coming from the decay of the $K^{\pi}=16^{+}$ state and were used for a continuous monitoring of the energy calibration of Ge detectors during the whole experiment and finally gave a precise energy adjustment of all detectors.

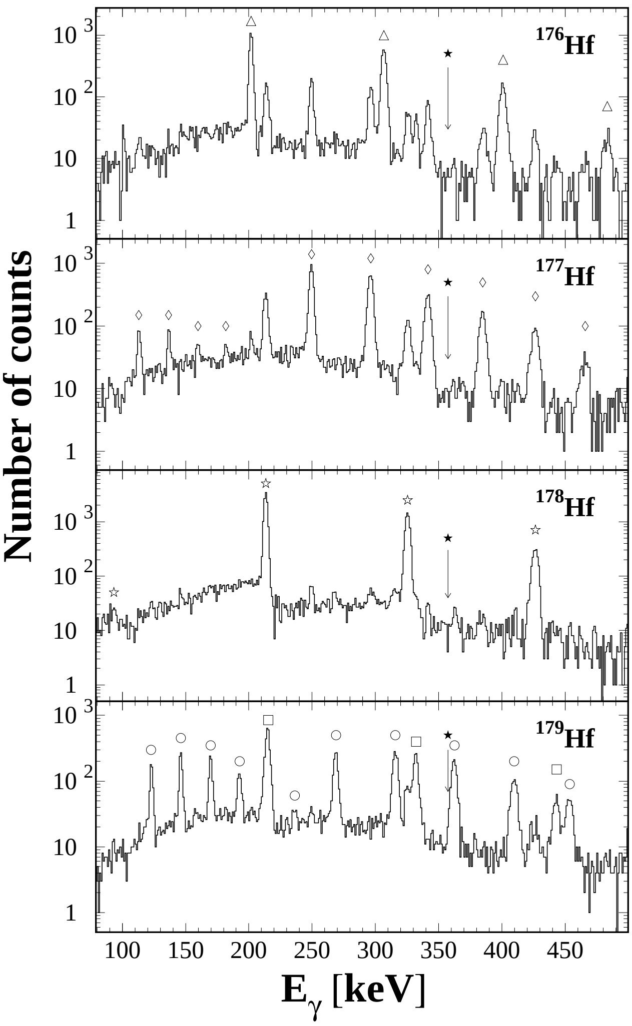

Fig. 1. The γ-ray spectra obtained for the ^{176}Hf ($\triangle$), ^{177}Hf ($\diamond$), ^{178}Hf (open star) and ^{179}Hf ($\circ$) stable targets. Lines corresponding to the main isotopes are marked by symbols. In the ^{179}Hf spectrum also lines belonging to ^{180}Hf ($\square$) are marked. The full star denotes the energy where the new γ-transition was found.

The Doppler correction was determined from the observed γ-ray energy shifts of the known transitions. For the analysis of the experimental Doppler correction the individual ϕ segments were used and the θ region was divided into 6 sub-sections. For each angular range ($\Delta\theta$, $\Delta\phi$) and for each Ge detector the γ spectra were accumulated. The ϕ division was defined by the resolution of the forward particle detector and the θ division was forced by the requirement of sufficient statistics. From the angle dependent γ spectra the Doppler shifted energies corresponding to the $4^{+} \rightarrow 2^{+}$ and $6^{+} \rightarrow 4^{+}$ ground state band transitions in ^{178}Hf were extracted. The determined Doppler shift was fitted with a fourth order θ-dependent polynomial separately for each ϕ segment and Ge detector. Such a method of experimentally determined Doppler correction allowed to account for any asymmetry in the experimental set-up and finally led to the best quality of the γ-spectra. The final γ-spectra were accumulated for each of the measured targets making use of the one common Doppler correction described above. All γ-ray lines observed in the Coulomb excitation on all Hf targets were identified as known ground band transitions in ^{176}Hf [16], ^{177}Hf [17], ^{178}Hf [18], ^{179}Hf [19] and ^{180}Hf [20]. Spectra for ^{176}Hf,^{177}Hf,^{178}Hf and ^{179}Hf stable targets are shown in Fig. 1. The full star denotes the energy where the new γ-transition was found with the isomeric target. The main components of the isomeric target (^{176,177,178}Hf) do not show any peak structure at the marked energy and no substantial background from the ^{12}C was observed. One of the isomeric targets was slightly polluted by ^{194,196}Pt which can be explained by the chemical separation method adopted for the target preparation [9].

For the analysis of the γ-ray intensities the amount of ^{178m2}Hf relative to ^{178}Hf is essential. Therefore, a γ-ray activity measurement and an X-ray fluorescent analysis of the targets was also performed at GSI Darmstadt and Mainz University. On the basis of these measurements a mean amount of $1.5 \cdot 10^{14}$ ^{178m2}Hf atoms was determined for both investigated targets which contained also $2.3 \cdot 10^{16}$ atoms of other Hf isotopes, mainly ^{177}Hf and ^{178}Hf. The relative production rate of ^{177}Hf and ^{178}Hf isotopes was determined for an other target in a (d,d') experiment and amounts to $\frac{^{177}Hf}{^{178}Hf} = 2.5 \pm 0.3$ [13, 15]. Since the Hf material was produced in the ^{176}Yb(α,2n) reaction always at the same α-energy the quoted value can also be used for the present experiment. As one can see from Fig. 2, ^{176}Hf was also present in the investigated targets and the estimated ratio $\frac{^{176}Hf}{^{178}Hf}$ was 0.40 ± 0.08. From the total number of Hf atoms contained in the targets and the isotope ratios given above the amount of ^{178}Hf atoms can be derived which gives the isomer to ground state ratio $\frac{^{178m2}Hf}{^{178}Hf}$=0.024(4).

3. Results and discussion

The spectra of the isomeric targets contain γ-lines which belong mostly to ^{176}Hf, ^{177}Hf and ^{178}Hf with a very small admixture of ^{179}Hf. In order to search for excited states built on the $K^{\pi} = 16^{+}$ isomeric bandhead a new "artificial" spectrum was constructed by summing up the data for ^{176,177,178,179}Hf in such a way that the resulting spectrum had to reflect the intensities of major lines observed with the isomeric target. A comparison of such a spectrum with the one obtained for the ^{178m2}Hf target (the Pt non-polluted one) is shown in Fig. 2. Both spectra are almost identical except for one new transition observed with the isomeric target. The additional peak marked with a star appears at E_{γ}=357.4±0.3 keV. On the basis of theoretical predictions [11] and the previous deuteron scattering experiment [13] it could be assigned to the $17^{+} \rightarrow 16^{+}$ transition in the rotational band built on the four-quasiparticle $K^{\pi}=16^{+}$ isomeric state in the ^{178}Hf.

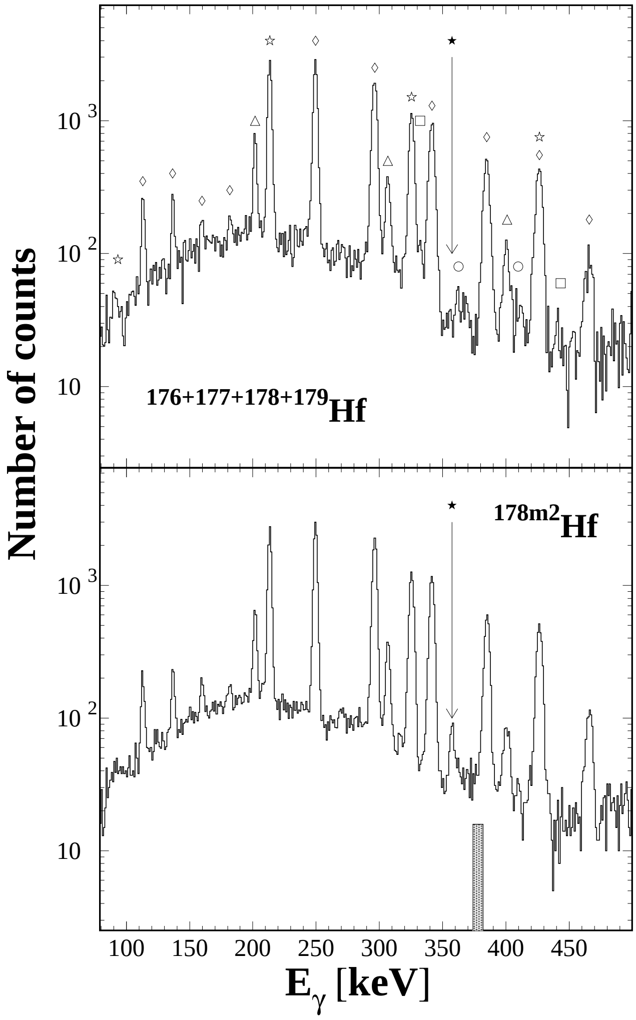

Fig. 2. The "artificial" γ-ray spectrum obtained from measurements with the ^{176}Hf, ^{177}Hf, ^{178}Hf and ^{179}Hf targets (top) and the measured spectrum obtained for the isomeric target (bottom). Lines are marked with the same symbols as in Fig. 1. The $17^{+} \rightarrow 16^{+}$ transition is marked by the full star, while the hatched area corresponds to the expected appearance of the $18^{+} \rightarrow 17^{+}$ transition in the isomeric $K^{\pi} = 16^{+}$ band.

No other new γ-lines were identified in the γ-spectrum presented in Fig. 2 (bottom) as well as in its high energy region. From the $17^{+} \rightarrow 16^{+}$ transition energy, under the assumption of rigid rotation we have calculated the level energies of the higher spin members of the $K^{\pi}=16^{+}$ rotational band. The hatched region marked in Fig. 2 corresponds to the expected γ-ray energy of the $18^{+} \rightarrow 17^{+}$ transition. The calculated excitation probability of the 18^{+} state is by one order of magnitude smaller than the probability to excite the 17^{+} level and therefore the transitions $18^{+} \rightarrow 16^{+}$ and $18^{+} \rightarrow 17^{+}$ could not be observed within the statistics obtained in the present experiment.

For the γ-ray intensities measured as a function of the impact parameter one can usually obtain the electromagnetic multipole moments independent of any nuclear model[21, 22]. However, this model independent analysis could not be adopted to the present experiment since only one state in the excited cascade was observed which was not only directly populated but also fed from the high-spin members of the rotational band. A proper calculation of the excitation and the decay of the Coulomb excited cascade requires a complete set of level energies and matrix elements of electromagnetic multipole operators between states in the cascade. Therefore, a model dependent analysis was performed which included all states up to $I^{\pi} = 28^{+}$ in the rotational band built on the isomer. The level energies were calculated using the energy of the $17^{+} \rightarrow 16^{+}$ transition as explained above.

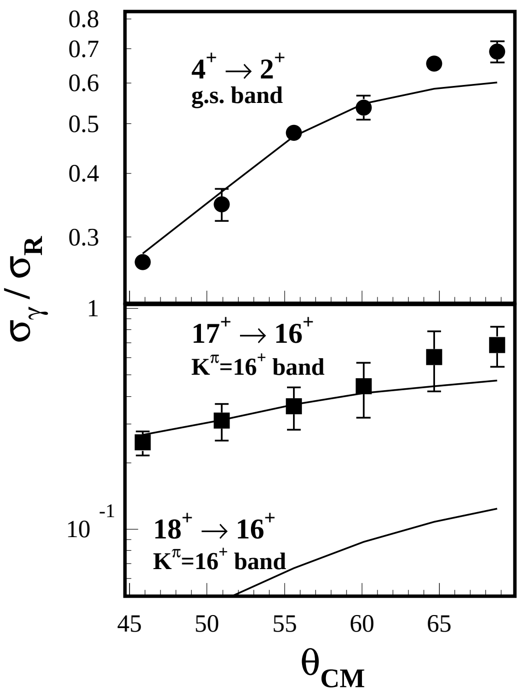

Fig. 3. The γ-ray intensity per scattered particle for the $4^{+} \rightarrow 2^{+}$ ground state band transition, $17^{+} \rightarrow 16^{+}$ and $18^{+} \rightarrow 16^{+}$ in the $K^{\pi} = 16^{+}$ band as a function of the CM scattering angle. The solid line represents the calculated cross section ratios of $\frac{\sigma_{\gamma}}{\sigma_{Ruth.}}$. The $18^{+} \rightarrow 16^{+}$ transition has a much lower excitation probability and was not observed experimentally due to low statistics.

The M1 matrix elements were determined from g_K and $g_R \approx \frac{Z}{A}$ values derived from the known magnetic moment of the $K^{\pi} = 16^{+}$ state [12]. The E2 matrix elements were calculated within the rigid rotor model depending only on one free parameter, namely, the intrinsic electric quadrupole moment Q_0. By comparing of the calculated Coulomb excitation cross sections, based on the assumptions given above, with the experimentally extracted γ-ray yields normalized to the number of scattered Pb particles and measured for different impact parameters, the Q_0 can be determined. For normalization purposes the measured isomeric to ground state ratio of $\frac{^{178m2}Hf}{^{178}Hf}$=0.024(4) and the analysis of the $4^{+} \rightarrow 2^{+}$ transition in the ground state band were used. The semiclassical Coulomb excitation calculations for the ground state band were based on the known level energies (up to $I^{\pi} = 18^{+}$) and the transition matrix elements calculated from $\langle 2^{+}||M(E2)||0^{+}\rangle = 2.204\pm0.011$ eb [23]. The experimental results together with the theoretical calculations are shown in Fig. 3 for the $4^{+} \rightarrow 2^{+}$ and $17^{+} \rightarrow 16^{+}$ transition. The best fit to the experimental data was obtained for $Q_0(K{=}16) = 8.2\pm1.1$ b which yields a matrix element of $\langle 17^{+}||M(E2)||16^{+}\rangle = 5.9 \pm 0.8$ eb. The error includes not only the statistical uncertainties of the measured γ-ray yields but also errors in the isomer to ground state ratio. The intrinsic electric quadrupole moment obtained in the present experiment agrees with the $Q_0 = 7.2 \pm 0.1$ b derived from the spectroscopic quadrupole moment obtained in the collinear laser spectroscopy experiment [12] as well as with the theoretically predicted value of $Q_0 = 7.3$ b [10]. The collectivity of the rotational band built on the $K^{\pi} = 16^{+}$ isomeric state is as strong as in the ground state band ($Q_0(K{=}0_{gs}) = 6.99\pm0.05$ b) and it seems not to be affected by the four quasiparticles with their spins aligned along the symmetry axis. While the quadrupole moment stays rather constant in the ground state band, the effective moment of inertia increases from the first excited state to the state with I=16 by 50% [24]. In this band the nucleus rotates around an axis perpendicular to the symmetry axis. This is quite in contrast to the isomeric state. Nevertheless, the moment of inertia calculated from the γ-ray energy of the $17^{+} \rightarrow 16^{+}$ transition is almost identical with the one of the ground state band at the same angular momentum.

4. Summary

For the first time a heavy-ion multiple Coulomb excitation experiment has been successfully performed on a target containing a microweight quantity of very exotic nuclei. In ^{178}Hf, an excited state built on the $K^{\pi} = 16^{+}$ isomeric state has been observed at an excitation energy of 357.4±0.3 keV above the isomeric state. The large collective strength measured for this transition suggests an existence of a rotational band with the new nuclear state being the first excited level.
On the basis of gained experience conclusions for future experiments can be drawn. Especially greater γ-ray detection efficiencies and higher γ-fold coincidences offered by the existing and currently developed 4π Ge spectrometers, e.g. EUROBALL, will play a key role in future measurements. A high-efficient isotope separation and the developed target production technique are essential for the success of the planned nuclear structure experiments as well.

This work was partly supported by the IN2P3 – GSI, JINR and Polish laboratories agreement as well as the EC contract ERBCIPD-CT-940091.

References

1. Helmer, R.G., Reich, C.W.: Nucl. Phys. A**114**, 649 (1968)
2. Helmer, R.G., Reich, C.W.: Nucl. Phys. A**211**, 1 (1973)
3. de Boer, F.W.N., Goudsmit, P.F.A., Meijer, B.J., Kapteyn, J.C., Konijn, J., Kamermans, R.: Nucl. Phys. A**263**, 397 (1976)
4. Khoo, T.L., Løvhøiden, G.: Phys. Lett. B**67**, 271 (1977)
5. van Klinken, J., Venema, W.Z., Janssens, R.V.F., Emery, G.T.: Nucl. Phys. A**339**, 189 (1980) and references therein
6. Oganessian, Yu.Ts., Karamian, S.A., Gangrski, Y.P., Gorski, B., Markov, B.N., Szeglowski, Z., Briançon, Ch., Le Du, D., Meunier, R., Hussonnois, M., Constantinescu, O., Subbotin, M.I.: J. Phys. G**18**, 393 (1992)
7. Wollersheim, H.J.: Future Directions in Nuclear Physics with 4π Gamma Detection Systems of the New Generation, Strasbourg, France, 4-16 March 1991
8. Briançon, Ch.: Proceedings of Eigth Intern. Symp. on Capture Gamma-Ray Spectroscopy, Fribourg, 20-24 Sept. 1993, Ed. J. Kern, World Scientific (1994) p. 192
9. Oganessian, Yu.Ts., Karamian, S.A.: Proc. Int. Conf. on Nucl. Shapes and Nucl. Structure, Antibes, France, June 20-25, 1994
10. Quentin, P. et al.: Proc. Int. Conf. on Nucl. Shapes and Nucl. Structure at Low Excitation Energy, Cargèse, 1992, Ed. M. Vergnes et al., Plenum Press, New York (1992)
11. Girod, M. et al.: Proc. Int. Conf. on Nucl. Shapes and Nucl. Structure, Antibes, France, June 20-25, 1994
12. Boos, N., Le Blanc, F., Krieg, M., Pinard, J., Huber, G., Lunney, M.D., Le Du, D., Meunier, R., Hussonnois, M., Constantinescu, O., Kim, J.B., Briançon, Ch., Crawford, J.E., Duong, H.T., Gangrski, Y.P., Kühl, T., Markow, B.N., Oganessian, Yu.Ts., Quentin, P., Roussière, B., Sauvage, J.: Phys. Rev. Lett. **72**, 2689 (1994)
13. Deylitz, S., Valnion, B.D., El Abiary, K., de Boer, J., Gollwitzer, A., Hertenberger, R., Graw, G., Kulessa, R., Briançon, Ch., Le Du, D., Meunier, R., Hussonnois, M., Constantinescu, O., Fortier, S., Kim, J.B., Rosier, L.H., Rotbard, G., Oganessian, Yu.Ts., Karamian, S.A., Wollersheim, H.J., Folger, H., Gerl, J., Happ, Th., Hategan, C.: accepted for publication in Physical Review
14. Wollersheim, H.J.: GSI Preprint, GSI-88-47,1988
15. Happ, Th. et al.: Jahresbericht B.L., 65 (1992) and GSI Annual Report, 91 (1992)
16. Browne, E.: Nucl. Data Sheets **60**, 227 (1990)
17. Browne, E.: Nucl. Data Sheets **68**, 747 (1993)
18. Browne, E.: Nucl. Data Sheets **72**, 221 (1994)
19. Baglin, C.: Nucl. Data Sheets **72**, 617 (1994)
20. Browne, E.: Nucl. Data Sheets **71**, 81 (1994)
21. Grosse, E., Bałanda, A., Emling, H., Folkmann, F., Fuchs, P., Piercey, R.B., Schwalm, D., Simon, R.S., Wollersheim, H.J.: Phys. Scr. **24**, 337 (1981)
22. Pelte, D., Schwalm, D.: Heavy ions collisions, vol. 3, ed. R. Bock, North-Holland 1982
23. Ronningen, R.M., Hamilton, J.H., Ramayya, A.V., Varnell, L., Garcia-Bermudez, G., Lange, J., Lournes, W., Riedinger, L.L., Robinson, R.L., Stelson, P.H., Ford, Jr, J.L.C.: Phys. Rev. C**15**, 1671 (1977)
24. Hamilton, J.H., Ramayya, A.V., Ronningen, R.M., Sayer, R.O., Yamada, H., Maguire, C.F., Colombiani, P., Ward, D., Diamond, R.M., Stephens, F.S., Lee, I.Y., Butler, P.A., Habs, D.: Phys. Lett. **B 112**, 327 (1982)

This article was processed by the author using the LaTeX style file *cljour2* from Springer-Verlag.