LOW SPIN-LOW ENERGY PHASE TRANSITIONS IN ATOMIC NUCLEI (NEW RESULTS SINCE LEYSIN CONFERENCE OBTAINED AT CERN AND ORSAY)

V. Berg, C. Bourgeois, R. Foucher, J.P. Husson, W. de Wieclawick
I.P.N., 91406 Orsay, France.

J. Dionisio, C.F. Liang, A. Peghaire, C. Vieu
C.S.N.S.M., 91406 Orsay, France.

W. Watzig
Ints. F. Kernchemie, Lahnberge 3550 Marburg (R.F.A.)

A. Hoglund
Institute of Physics, University of Stockholm (Sweden)

A. Wojtasiewicz
Institute of Experimental Physics, 69 HOZA, 00681 Warsaw (Poland)

The great interest focused on heavy transitional nuclei in the last few years is connected with some experimental findings and theoretical developments which appeared during 1967-1970

- Proposal of prolate oblate shape transition around the ^{192}Os and Pt[1]).

- Signs of a prolate oblate transition from the levels positions in light Pt nuclei appearing also in the calculation by Kumar[2,3]) around the mass 186.

- Change of the sign of the quadrupole moment of 2_1^+ state between ^{192}Os and Pt as predicted by Kumar and Baranger[4]).

- Establishment of $9/2^-$ states issued from $h9/2^-$ orbital in Tl nuclei[5]).

- Discovery and interpretation of negative parity states in Ir nuclei[6]).

- Discovery of unexpectedly large retardations of transitions in Ir and Pt nuclei[7]).

- Possibility of detailed on-line spectroscopy[8]).

- Systematic calculation of potential energy surface by Lund group[9]) and Dubna group from rare earths to heavy nuclei (the γ parameter was not systematically taken into account at the beginning)[10]).

This interest was increased by the large isotopic shift measured between ^{185}Hg and ^{187}Hg [11]), interpreted as a sign of prolate oblate transition in "Supersoft" nuclei[12]) previously suspected to appear in Hg isotopes with mass lighter than 192[13]).

Already ^{114}Cd and ^{115}In, which are the corresponding nuclei of the $28<Z<50$, $50<N<82$ shell, showed large quadrupole moment[14]) and evidence of rotational bands[15]). And previous calculation of nuclear deformation by Kumar and Baranger[16]) raise the question of oblate nuclei in other major shell, as well as the sign of the quadrupole moments in the ^{28}Si [17]).

The study of the ^{189}Au at Isolde in 1972, in particular γ half lives, permits us to detect a highly retarded transition between a $9/2^-$ and a $11/2^-$ states which gives a clue to the understanding of the isomers found previously in Ir isotopes: $9/2^-$ level appeared clearly like a particle state in a Pt core, $11/2^-$ level like a hole state in a Hg core - the reasons were the regularity of the hindrance factor, previously measured in ^{191}Au [18]), the regularities in the Hg isotopes to the mass 190 found by the Dubna group[19]), in our systematic of Pt nuclei[20]) and the neutron number[21]) dependence of the β_{rms} measured for the two levels.

At the same time, we measured the sign of E2/M1 ratios in the $3_1^+ \to 2_1^+$ and $2_2^+ \to 2_1^+$ transitions from 186 to 192 Pt at Isolde after the same measurements on ^{192}Pt by J. Hamilton et al.[22]), and by Steffen and Krane[23]). These measurements were another test of the Kumar-Baranger predictions[24,25]).

All these facts led us in 1973 to make more precise the previous proposals[1,2,3,13]) of the existence of instable oblate shape nuclei inbetween W and Pb. They lie between ^{208}Pb and a line joining ^{182}Hg to ^{194}Os. It was the same for each region major shell, taking into account a strong correlation between the value of prolate oblate difference calculated semi microscopically[26]) and the energy difference between 4_1^+ and 2_γ^+ levels[27,28]).

The finding of a sharp decrease of the 0_2^+ states in light Pt isotopes, not forseen by any models, led us to propose a region of "critical nuclei", instable against shape and pairing around the masses 182-186 for Hg, Au, Pt isotopes i.e. at the limit of prolate, oblate, spherical, normal and superconducting nuclei in 1971[12,29]) (also [25,27,28])). Also the measured alpha width, β strength function and masses show "anomalies" in this region[29]).

The experiments performed since that time by heavy ions $xn\gamma$, $\alpha xn\gamma$, p-t reactions and by radioactivity at ISOCELE (Orsay), UNISOR (OakRidge), ISOLDE (CERN), in the YASNAPP program (Dubna), in ^{184,186,188,190}Hg [31-36]), ^{185,187,189,191,193}Au[37-44]), ^{185,187}Pt[45]), ^{182,186,188,190,191,192,193,194,195}Pt [25,46-49]), $^{185-187}$Ir[50,51]) prove that the phase transitions suggested for even even Os, Pt, exist [32,52]) in function of E, j and that they occur also in odd mass Au, Pt and Ir isotopes. Except for the Pt nothing was known on these nuclei at the time of Leysin Conference. New alpha activities have been found at Isocele in ^{185,186,187}Tl isotopes with very large hindrance factors[53]). For the first time we have found, also, full sequences of 5-, 6-, 7-, 8-, 9- states and we have some evidence of octupole or octupole quadrupole states in Pt and Hg. May be a quadrupolar-octupolar shape transition occurs in addition around A = 186 Hg.

The large intensity of the mass separated ion beam obtained at Isolde and Isocele, the on-line γ half lives and angular correlation measurements, the on-line and semi on-line (with a rabbit) use of Gerholm type and semi-circular β spectrometer as well as the paradoxal use of heavy ion reactions for studying the characteristics of low spin intrinsic states were of prime importance to solve the apparent extreme complexity of the level schemes of the heavy transitional nuclei.

Nevertheless the spin of a number of levels is not fully certain even if the level itself is fairly well established; also we performed a statistical analysis of the low lying states. From the variation of the level density, phase transitions appear very well also[54]).

Inside a given class of nuclei, the stability or the smoothness of the variation of the majority of the states is remarkable ; certain states appear to be more sensitive and shows very clearly when the phase transition approaches. What we learned from $h9/2^-$ particle states and $h11/2^-$ hole states ? That they seem to be very good spectators ; the variation of the core properties deduced for the even even core of odd Z nuclei are near the same as those deduced from the study of adjacent even even nuclei, in particular the γ_{rms} values which are so important the even even core looks more rigid, nevertheless, than the even even adjacent isotopes, even if the γ_{rms} and β_{rms} values are the same. What it means? [55,56]

In conclusion, the two phase transitions proposed in 1968-1971 exist but they are not as well understood as it was thought at the beginning ; the pairing plays certainly an important role but the proton neutron interaction in these nuclei might be also important mainly for the neutron-deficient isotopes. The fact that large regularities can be found in the systematics from very light to heavy nuclei suggests that semi-microscopic approaches might be suitable as soon as they take into account the main symmetries. Kumar's remarks on the model independent way to know β_{rms} and γ_{rms} from experiment is of basic importance for drawing right conclusion from the data analysis [57]. Due to the possibility to go far from the stability line, classes of nuclei appear much easier than before. The need to study very well now the nuclei which are at the center or at the border line of the classes give a great importance to the production of radioactive target for pt, tp, pd... reaction which are now necessary to go farer in the understanding of these classes, for example the tp experiments performed on Pt isotopes have to be pushed to the very light one at least to the ^{188}Pt to know the nature of the very low 0^+ state in ^{186}Pt. On the contrary it is may be not important to study very well the ^{190,192,194}Hg which seem to belong to the same class of nuclei that the heavier ones but a very detailed knowledge of Tl, Hg, Au, Pt around the mass 196 as well as around 184 seems necessary to distinguish the relative importance of pairing, clustering... If that is true, we will have during the next years a double evolution to prepare one towards nuclei farer from the stability but also one towards the stability, in the Pb to Os region. As a consequence not only on-line mass separator have to be developped but also the production of difficult targets for nuclear reactions. The two are not necessarily incompatible.

Acknowledgments.

We thank very much all the colleagues from Isocele and Isolde collaborations who help us, Drs Seltz, Vergnes and collaborators, who have communicated their results in p,t reaction before publication, Pr Alaga, D. Bes, R. Broglia, K.Kumar, B. Mottelson, S.G. Nilsson, V. Paar, A.Sobiczewski for illuminating discussions on "elementary" and "collective" excitations and also all the colleagues who have attended the Orsay Colloquium in transitional nuclei in 1971.

References.

1 K. Kumar and M. Baranger, Phys. Rev. Letters 17 (1966) 1146, Nucl. Phys. A92 (1967) 608, Nucl. Phys. A122 (1968) 273.

2 R. Foucher, R. Henck, J.P. Husson, A. Johnson, J. Jastrebski, J.M. Kuchly, P. Siffert, G.Astner, E. Hagebo, J. Kjelberg and P. Patzelt 1969 International Conference on properties of nuclear states, Montréal p.682.

3 K. Kumar 1969 International Conference on properties of nuclear states, Montréal, p.82.

4 R.D. Pryor and J.X. Saladin, Phys. Rev. 1C (1970) 1573.

5 J.O. Newton, S.D. Cirilon, F.S. Stephens and R.M. Diamond, Nucl. Phys. A148 (1970) 593.

6 A. Backlin, V. Berg, S.G. Malmskog, Nucl. Phys. A156 (1970) 647.

7 B. Erdal, M. Finger, R. Foucher, J.P. Husson, J. Jastrebski, H. Johnson, C. Sebille, R.Henck, R. Regal, P. Siffert, G. Astner, E. Beck, A. Kjelberg, F. Munnich, P. Patzelt, Conference on properties of nuclei far from the stability, Leysin, 1970 (CERN report n°70-30) p.1045.

8 French german and CERN Collaboration (1970) CERN report 70-29 for the Hg isotopes.

9 S.G. Nilsson, C.F. Tsang, A. Sobiczewski, Z. Szymanski, S. Wycech, C. Gustafsson, I.L.Lamm, P. Möller and B. Nilsson, Nucl. Phys. A131 (1969) 1.

10 D.A. Arseniev, L.H. Malov, V.V. Pashkevich, V.G. Soloviev, Isv. Akad. Nauk. SSR 32 (1968) 886. D.A. Arseniev, A. Sobiczewski and V.G. Soloviev, Nucl. Phys. A126 (1969) 15.

11 J. Bonn, G. Huber, H.J. Kluge, U. Kopf, L. Kluger and E.W. Otten, Phys. Lett. 36B (1971) 41.

12 R. Foucher, Institut de Physique Nucléaire, (1971) Rapport 71-09 (Orsay).

13 R. Foucher, Proposal to Physics III Commettee nov. 1969 (CERN).

14 J. de Boer, R.G. Stockstad, G.D. Symons and A. Winther, Phys. Rev. Lett. 14 (1965) 546.

15 A. Backlin, B. Fogelberg and S.G. Malmskog, Nucl. Phys. A96 (1967) 539.

16 K. Kumar and M. Baranger, Phys. Rev. Lett. 12 (1964) 73.

17 Bromley, See D. Cline, Intern. Colloq. on Transitional Nuclei 1971 IPN Orsay.

18 A. Hoglund, private communication.

19 F. Fenyes, I. Mahunka, M. Mahunka, Z. Maté, A. Piotrowski, L. Tron, H. Tyrroff, J.Vandlik and N.G. Saitseva, International Conference on properties of nuclei far from the stability line Leysin 1970 (CERN report 70-39) and Dubna preprint (1974) P6/8078

20 M. Finger et al., French Isolde Collaboration, Nucl. Phys. A188 (1972) 369.

21 V. Berg, R. Foucher and A. Hoglund, Proceedings of International Conference on Nuclear Structure and Spectroscopy, Amsterdam Sept.1974, p.112.

22 J.H. Hamilton, Angular correlations in nuclear desintegration, edited by H. Van Krugten and B. Van Nooijen (1971) 181.

23 K.S. Krane and R.M. Steffen, Phys. Rev. C3 (1971) 240.

24 K. Kumar, Phys. Lett. 29B (1969) 25.

25 M. Cailliau, Thesis Orsay (1974).

26 S.G. Nilsson, private communication.

27 R. Foucher, Villars Winter School, Feb.1970 and internal report IPN Orsay (1973) 73-01.

28 M. Cailliau, R. Foucher, J.P. Husson, J. Letessier, Proceedings International Conference on Nuclear Structure, München August 1973 p.128.

29 R. Foucher, M. Cailliau, J.P. Husson, Proceedings International Conference on Transitional Nuclei Orsay (1971), p.185, edited by Institut de Physique Nucléaire (Orsay).

30 P.G. Hansen (references in) 8° International Conference on Isotope Separator, Skovde (Sweden) June 1973.

31 N. Rud, D. Ward, H. Andrews, R. Graham and J. Geiger, Phys. Rev. Lett. 31 (1973) 1421.

32 D. Proetel, R. Diamond, P. Kienle, J. Leigh, K. Maier, F. Stephens, Phys. Rev. Lett. 31 (1973) 896.

33 D.H. Hamilton and UNISOR Collaboration : Reactions between Complex Nuclei (North Holland) 1974 vol.1 p.178 and Phys. Rev. Lett. (1975) and this conference.

34 R. Beraud et al., ISOCELE Collaboration, Colloquium on the French Physical Society Dijon June 1975, Journ. Phys., Colloq. 36 (1975) C5.

35 C. Bourgeois et al., ISOCELE Collaboration, Proceedings Intern. Symposium on particle and Collective states, Bolatonfured (Hungary) Sept. 1975 and Journ. Phys. 37 (1976) 49.

36 T. Fenyes, I. Mahunka, Z. Maté, R.V. Jolos, V. Paar, Nucl. Phys. A247 (1975) 103.

37 M.A. Deleplanque et al., ISOCELE Collaboration, Journ. de Phys. Lett. 36 (1975) 205.

38 V. Berg, C. Bourgeois, M.G. Desthuilliers, P. Kilcher, J. Letessier, Intern. Symposium on particle and collective states, Bolatonfured (Hungary) Sept. 1975.

39 V. Berg, C. Bourgeois, R. Foucher, Journ. de Phys. 36 (1975) 613.

40 V. Berg, R. Foucher, A. Hoglund, Nucl. Phys. A244 (1975) 462.

41 A. Hoglund, V. Berg, B. Erdal, J.Jastrzebski, P. Kilcher, S.G. Malmskog, Annual Report IPN (Orsay) 1975 p.5 and to be published.

42 H. Beuscher, P. Jahn, R.M. Lieder, C. Mayer-Boricke, Intern. Colloq. on Transitional Nuclei June 1971 Orsay p.15, edited by IPN Orsay.

43 E.F. Zganjar and UNISOR Collab. Phys. Rev. Lett. 58B (1975) 159 and this conference.

44 Ch. Vieu and J.S. Dionisio, Proc. of the typical Conference on Problem of vibrational nuclei, Zagreb (1974) Fizika 7 (1975) 180.

45 C. Bourgeois et al., ISOCELE Collaboration (this conference).

46 J.P. Husson et al., ISOLDE Collaboration (this conference).

47 M. Cailliau, R. Foucher, J.P.Husson et J. Letessier, Journ. Phys. Lett. 35 (1974) 1233.

48 S.W. Yates, J. Cunnane, R. Hochel, P. Daly, Nucl. Phys. A222 (1974) 101.

49 M. Vergnes, G. Rotbard, J. Kalifa, J.Vernotte, G. Berrier, R. Seltz, H.L. Sharma, N.M. Hintz, BAPS 1976.

50 C. Sebille and French ISOLDE Collaboration, Nucl. Phys. A212 (1973) 45.

51 C. Sebille et al. (this conference).

52 S. Frauendorf and V.V. Pashkevich, Phys. Lett. 55B (1975) 365.

53 C.F. Liang and Isocele Collaboration Reference in H. Gauvin, Y. Le Beyec, J. Livet, J.L. Reyss, Ann. Phys. 9 (1975) 241.

54 W. de Wieclawick, J.S. Dionisio, R. Foucher, A. Hoglund, Ch. Vieu et W. Watzig, Journ. Phys. Colloq. (June 1975) C5 p.83.

55 G. Alaga and V. Paar, Phys. Lett. 61B (1976)129

56 J. Meyer-ter-Vehn, Nucl. Phys. A249 (1975) 111

57 K. Kumar, Phys. Rev. Lett. 28 (1972) 249 and Physica Scripta 11 (1975) 179.

58 M.A. Mariscotti, G. Scharff-Goldhaber and B. Buck, Phys. Rev. 178 (1969) 1864.
G. Scharff-Goldaber and A.S. Goldhaber, Phys. Rev. Lett. 24 (1970) 1349(c).

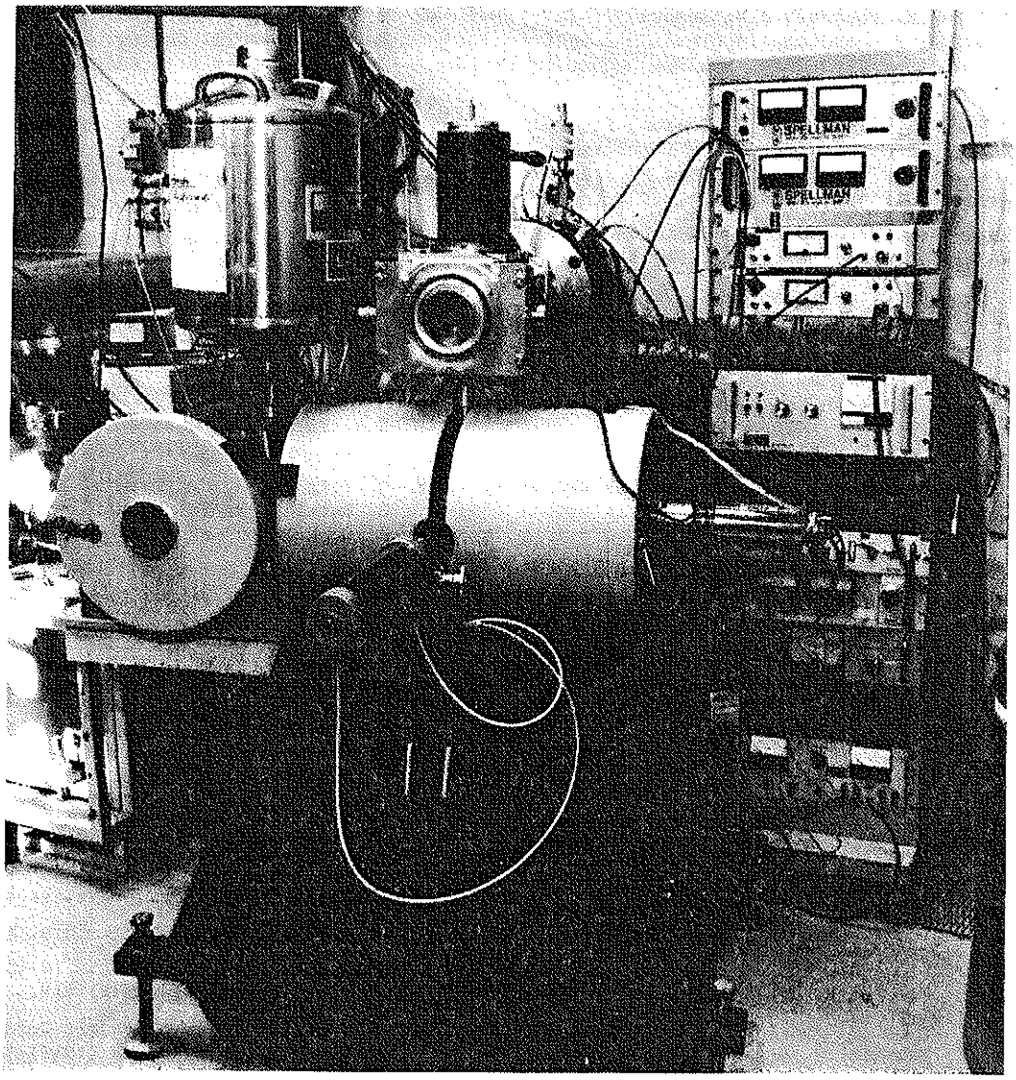

Fig.1. Gerholm type spectrometer, on-line at ISOCELE (Orsay) the same type of spectrometer has been used semi-on-line at Isolde for γ half life determination and very low energy e^--γ coincidences.

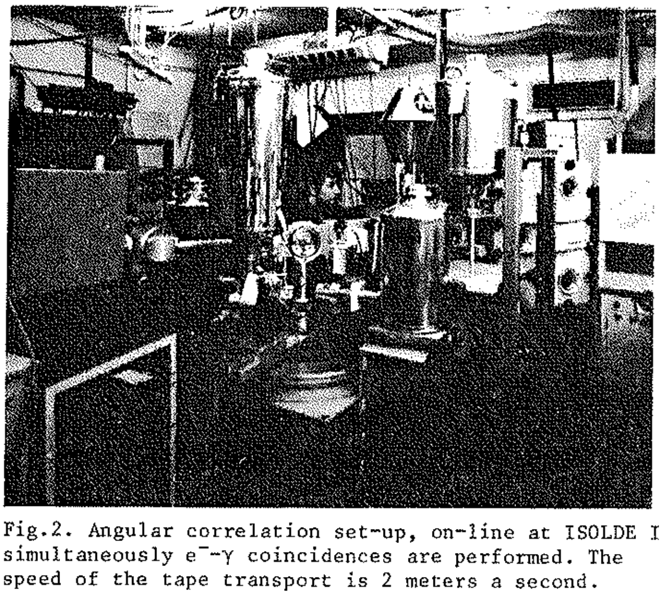

Fig.2. Angular correlation set-up, on-line at ISOLDE I, simultaneously e^--γ coincidences are performed. The speed of the tape transport is 2 meters a second.

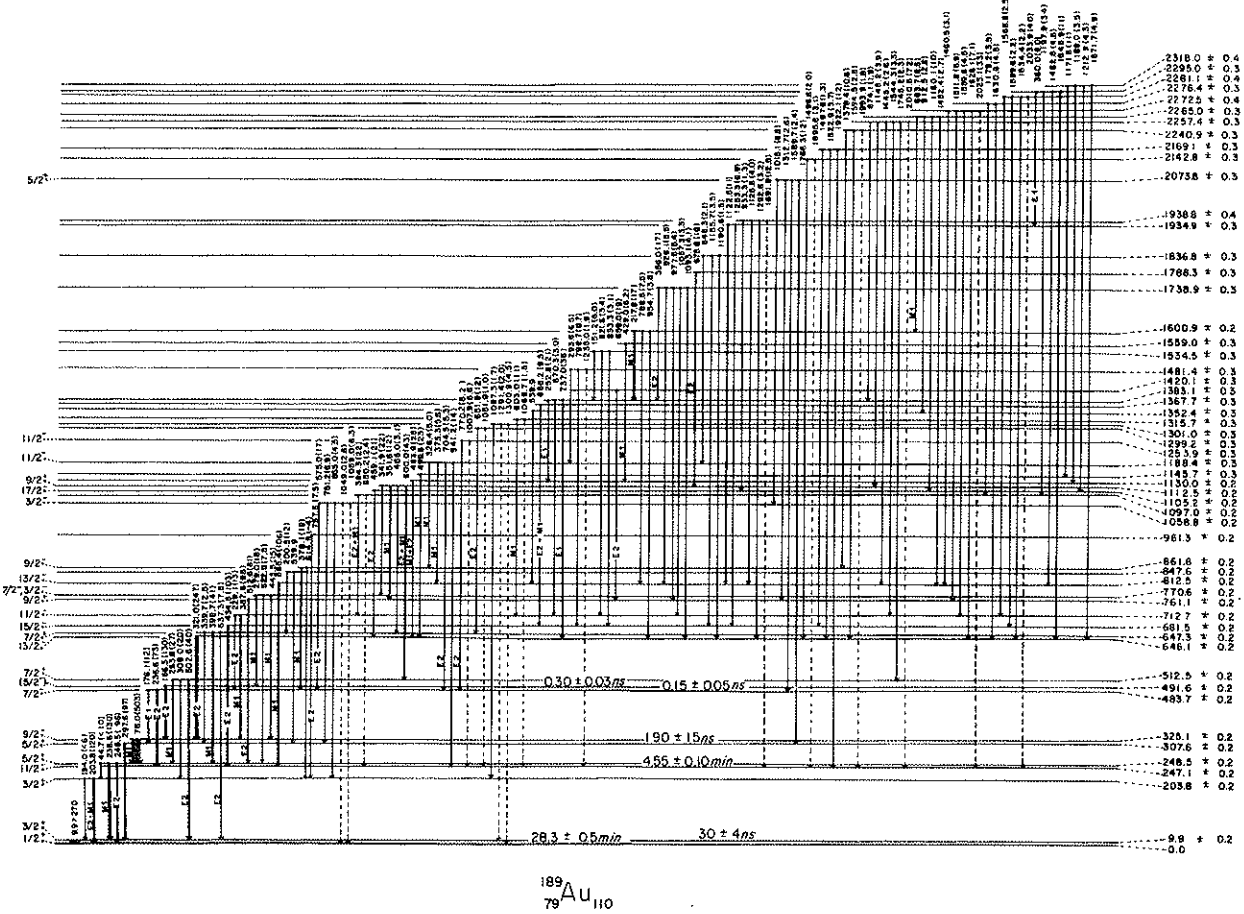

Fig.3. Normal type of complex decay scheme in transitional odd mass nuclei. 2.4 hours of Isolde beam was used to establish it. Two other experiments ran at the same time.

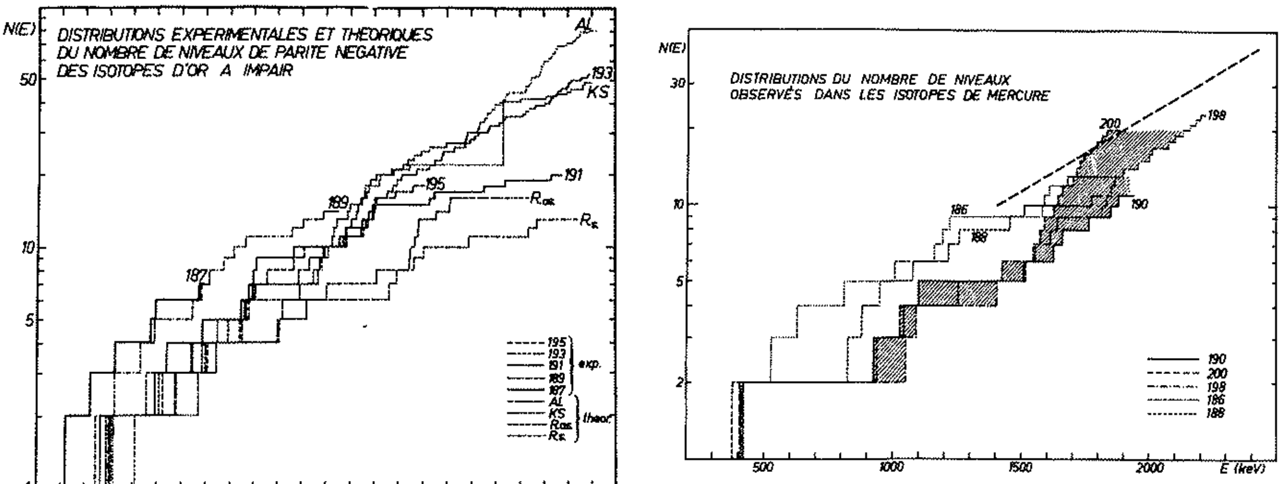

Fig.4. Even if some spins are not certain, as soon as the levels are well established, it is possible to look for phase transition by statistical energies ; two exemples are given ; one for even even, the other for odd mass isotopes.

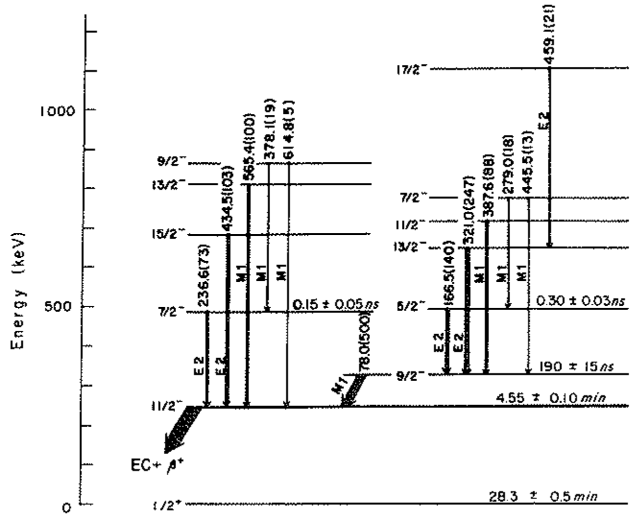

Fig.5. Parallel sequences of negative parity states in ^{189}Au

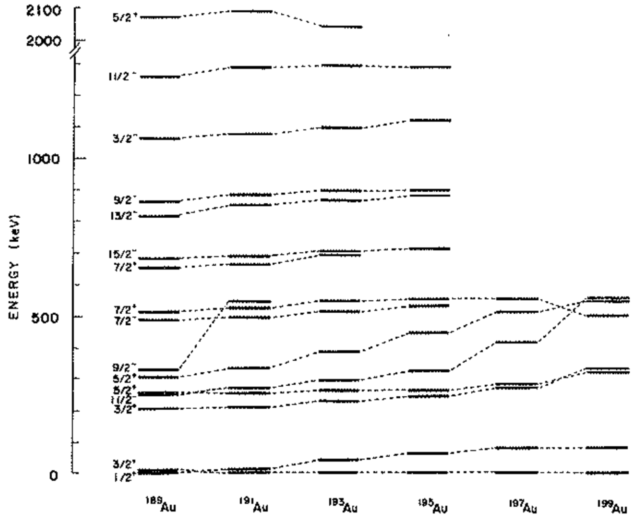

Fig.6. Quasi stability of all levels except h9/2$^-$ bands.

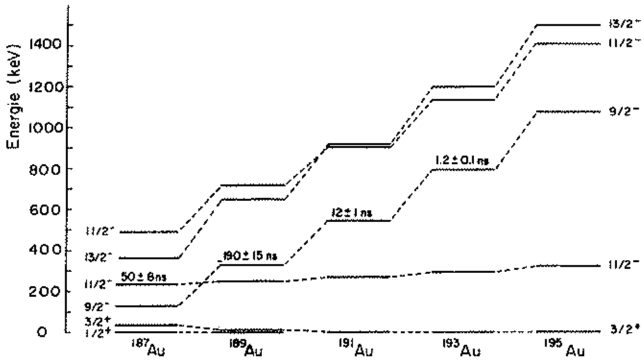

Fig.7. γ half-life measurements permit to find the h9/2$^-$ sequences.

They reveal with data in Fig 5,6 simplicity

behind appearent complexity of Fig 3

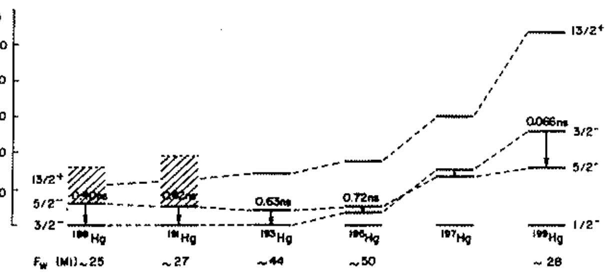

Fig.8. Some half-lives in Hg isotopes.

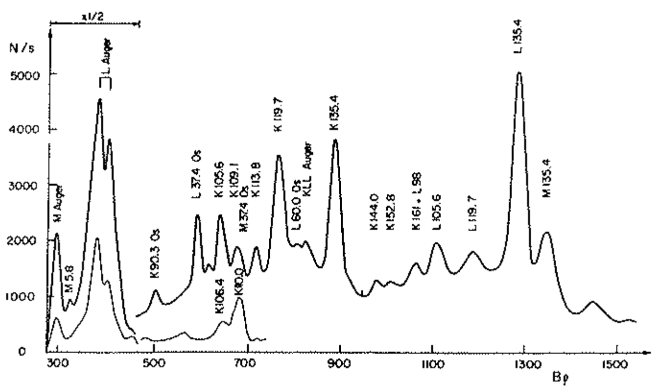

Fig.9. The key transition in ^{185}Ir is the 5.8 keV which appears at right.

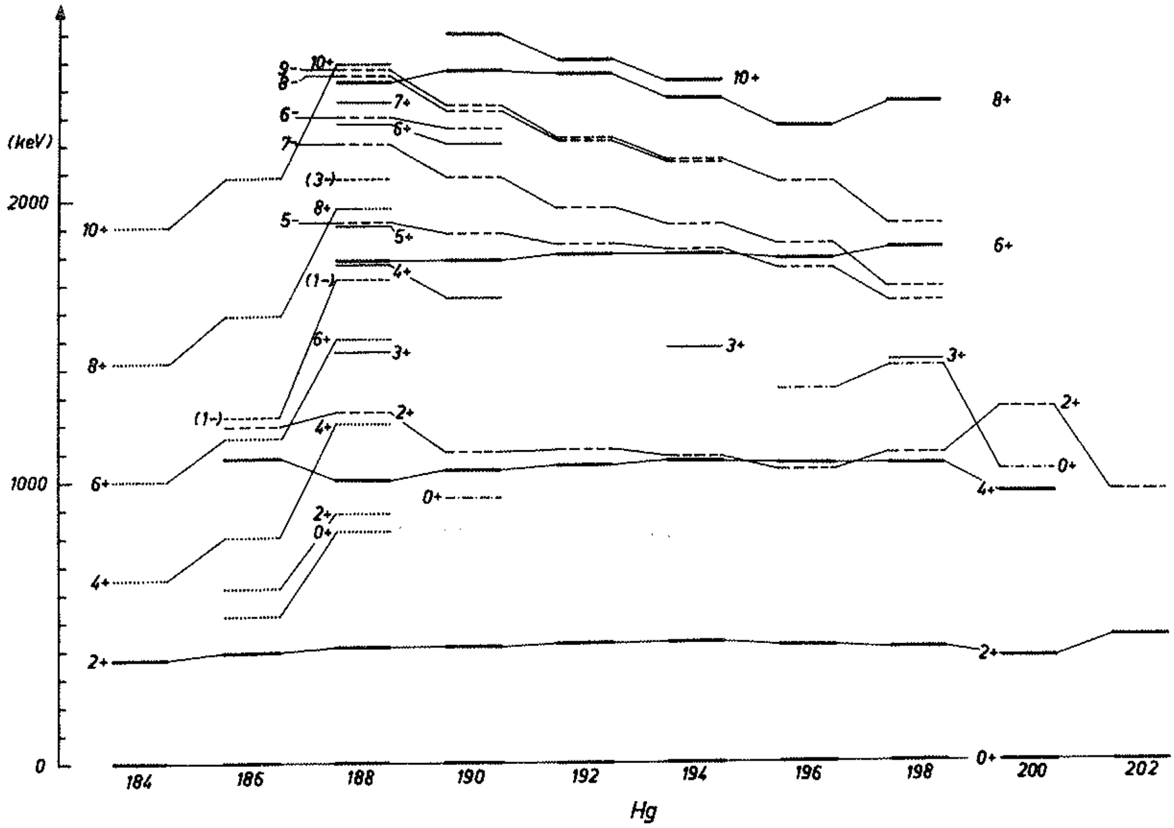

Fig.10. This figure drawn in august 1975 shows how the phase transition between the $^{190-198}Hg$ nuclei and the critical nuclei occurs. The work has been performed with the Isocele facility.

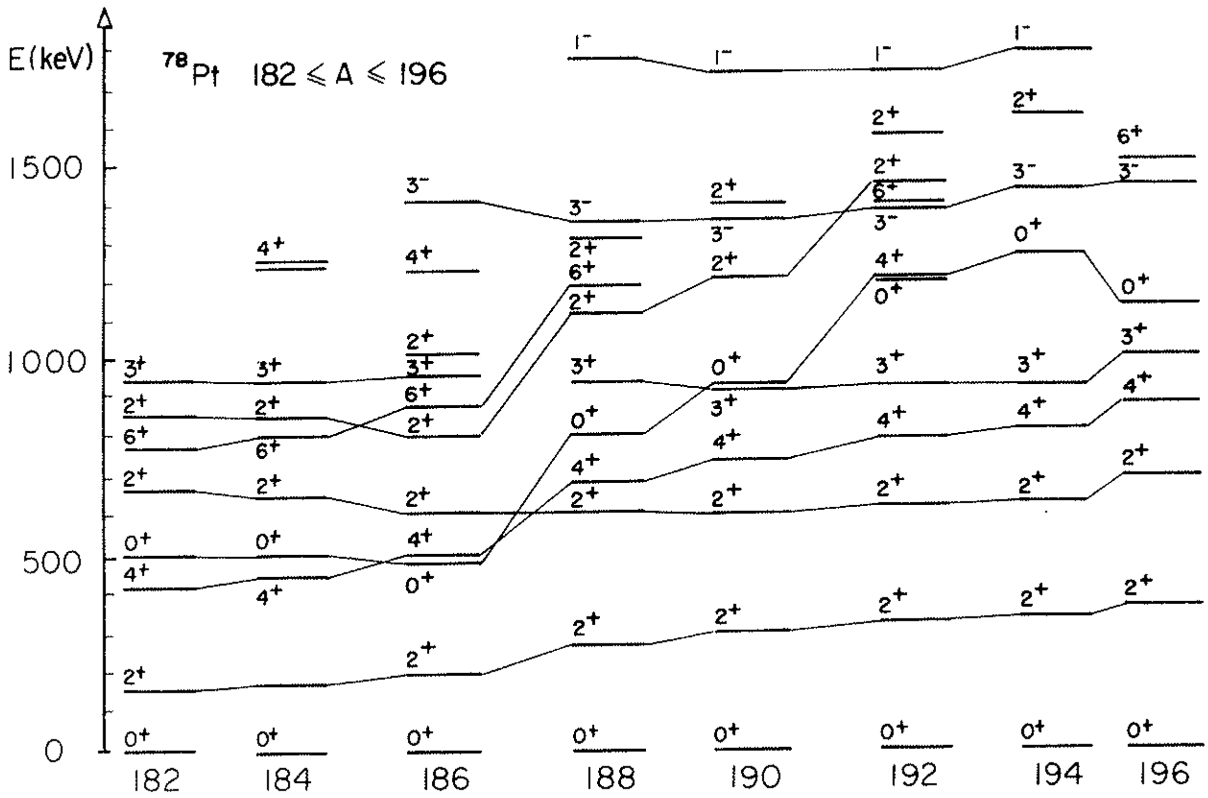

Fig.11. Phase transition between ^{186}Pt and ^{188}Pt like it appeared after the 1972 on-line angular correlation measurements.

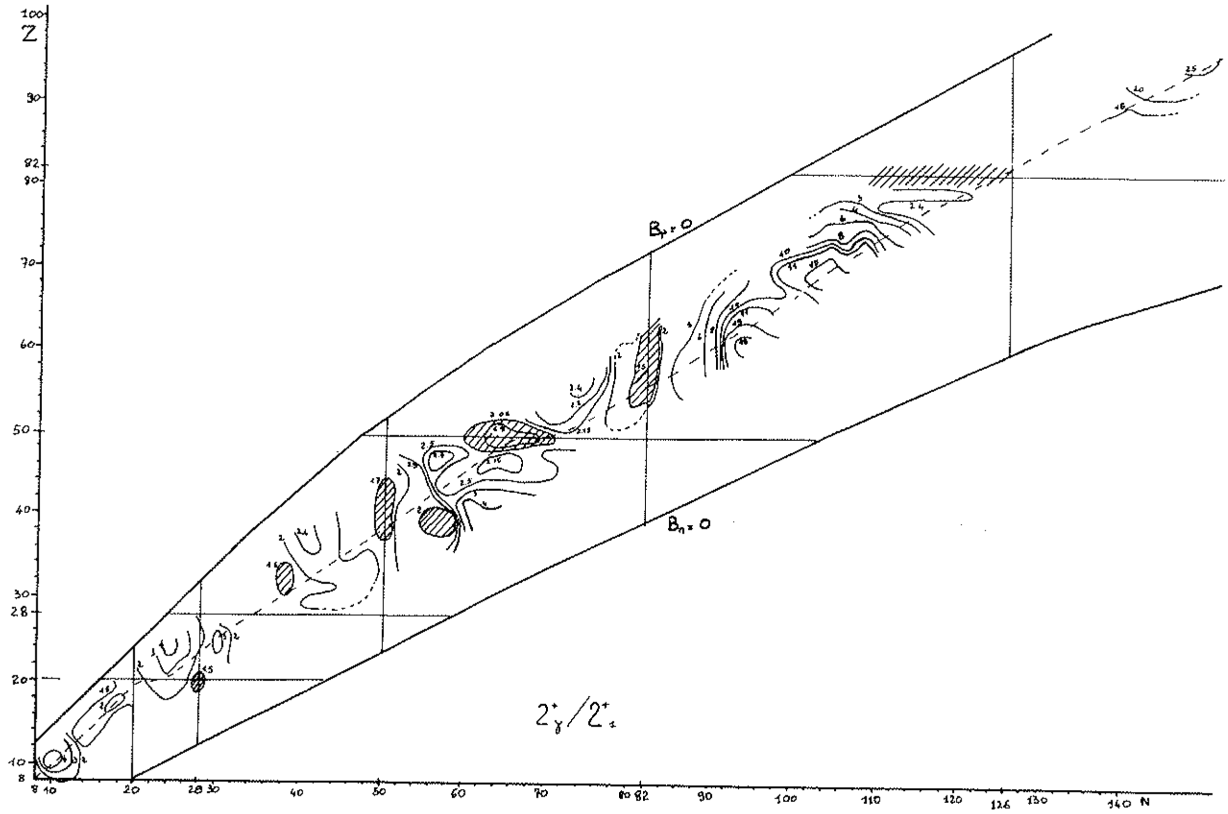

Fig.12. Ratio of the energies of the 2^+_γ and 2^+_1 levels.

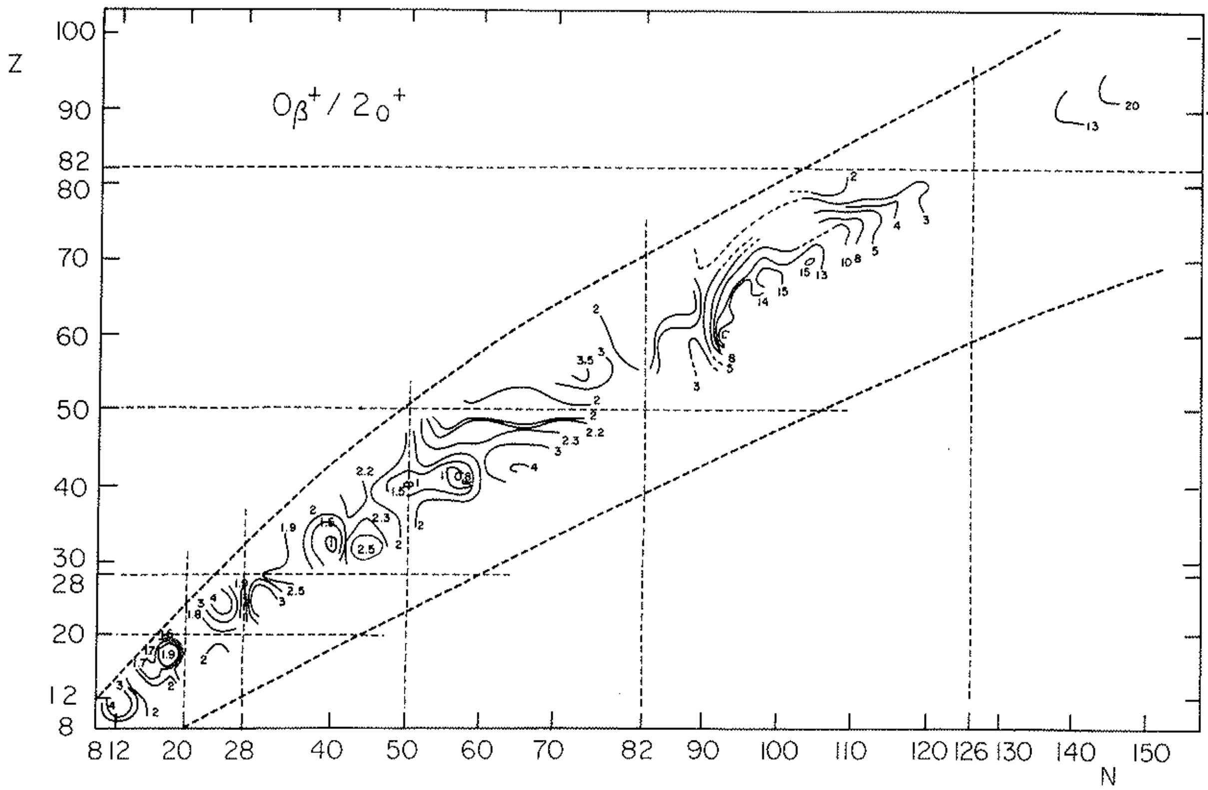

Fig.13. Ratio of the energies of the first 0^+ and 2^+ excited states. Spherical and deformed shell effects are clearly seen

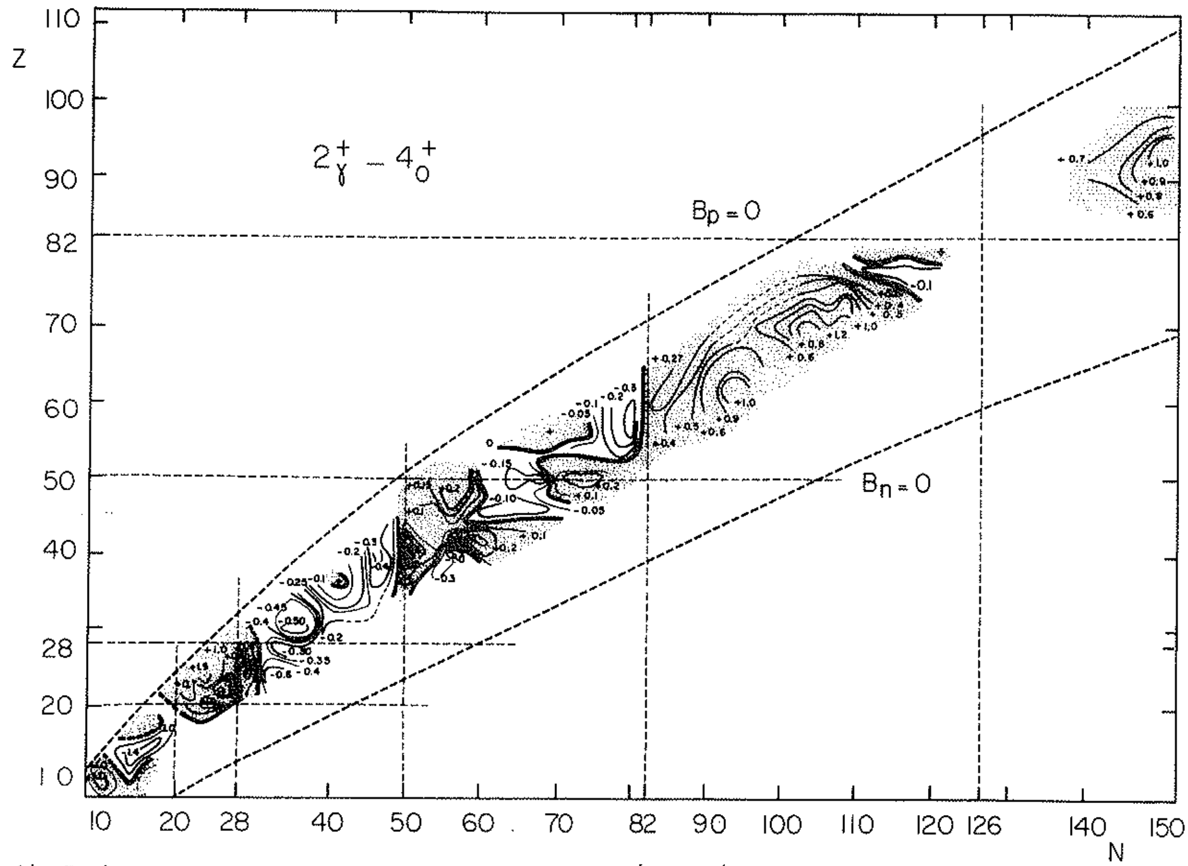

Fig.14. It is clear that the sign of the difference $E(2^+_\gamma) - E(4^+_1)$ remains constant in large regions.

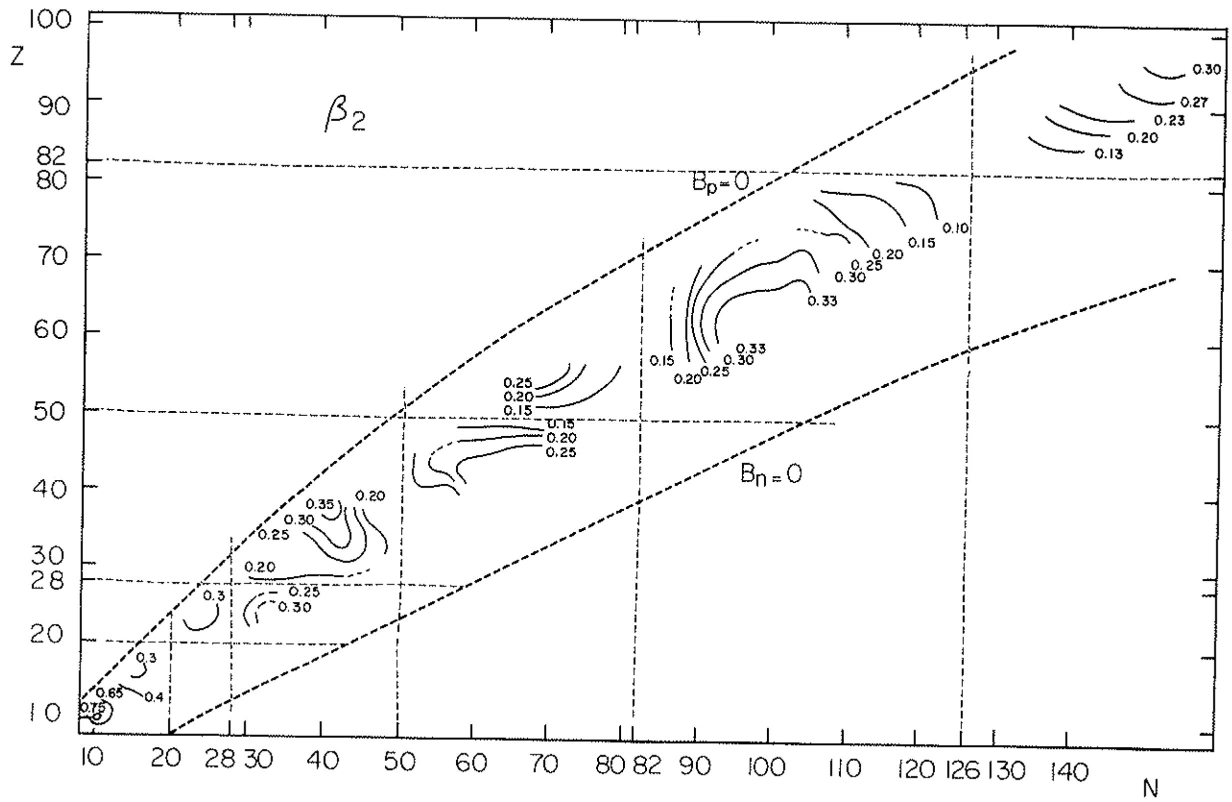

Fig.15. Quadrupolar deformation.

Experimental results known until April 1976 are included

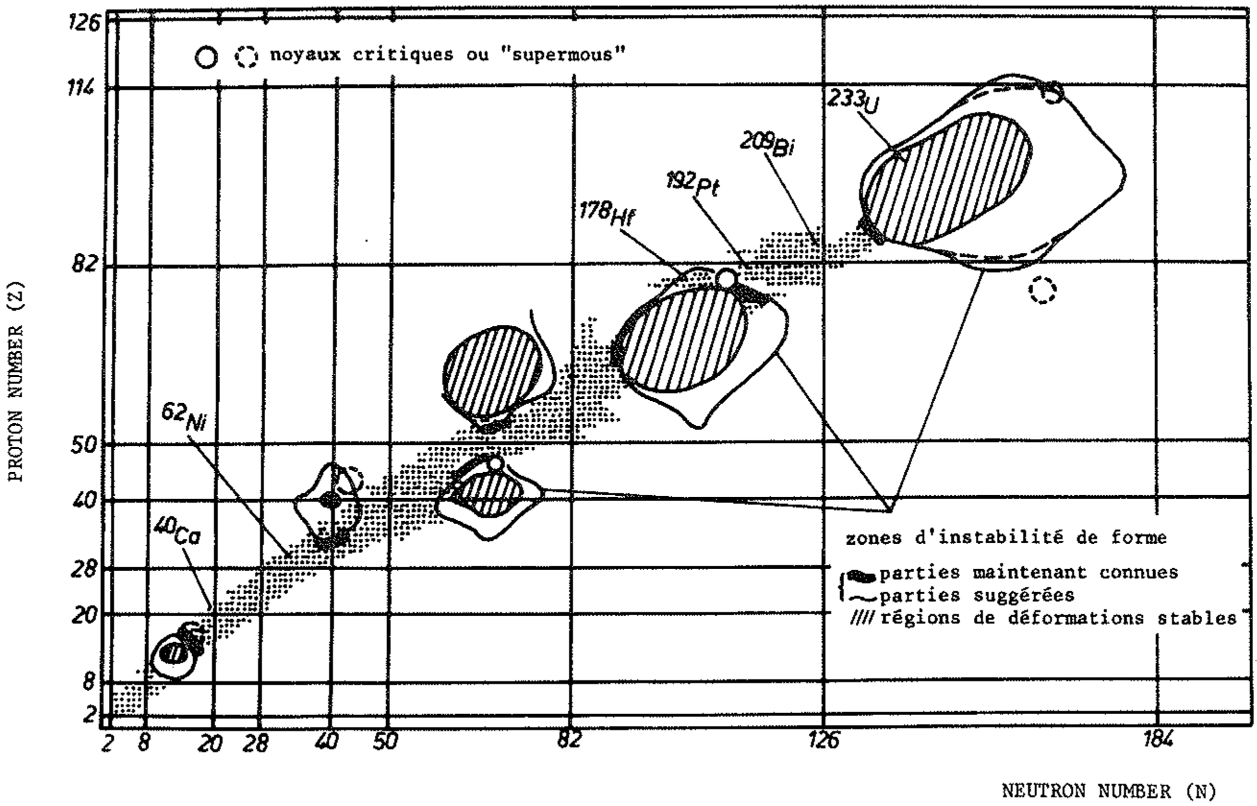

Fig.16. Valleys of shape instability suggested in 1971.

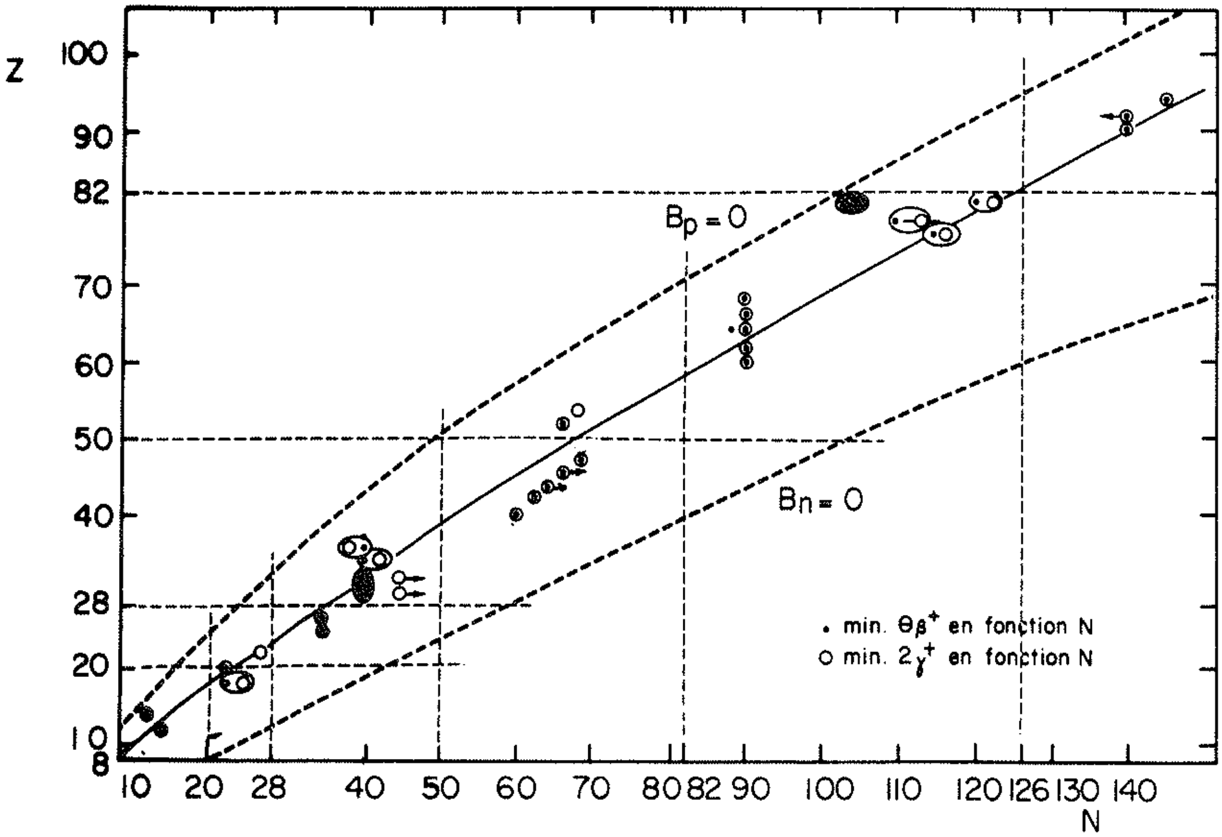

Fig. 17 - Minimum of the energy of 0^+_β and 2^+_γ in function of N occurs in the same or neighbouring nuclei with few remarkable exceptions. It justifies, may be, the unique softness parameter of VMI model[58].