ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E15-95-91

A.P.Tonchev, Yu.P.Gangrsky, A.G.Belov,
N.P.Balabanov*, H.G.Hristov*

MEASUREMENT OF ISOMERIC RATIOS IN (γ, n)-REACTIONS FOR THE BARIUM ISOTOPES IN THE GIANT DIPOLE RESONANCE REGION

Submitted to «Ядерная физика»

---

*Plovdiv University, Bulgaria

1995

1. Introduction

Photonuclear reactions producing residual nuclei in specific states have become one of the basic sources of new information on the properties of giant dipole resonances. The distribution of residual-nucleus excited states over energy and spin is determined by the energy, the number and the type of outgoing particles and also by the spin and excitation energy of the compound nucleus, which are practically known at photoexcitation in the Giant Dipole Resonance.

If there are low-lying isomeric states in the nucleus, then the relative population of isomeric and ground nucleus states will be determined by the distribution of above-lying levels over energy and spin. Thus, the measurement of isomeric ratios (IR), viz. the ratios between the reaction cross sections for producing the nuclei in the isomeric and the ground states, provides a possibility to draw conclusions about the parameters describing the dependence of the level density on excitation energy and spin, and also about the transition probability to the isomeric and the ground states.

The goal of the present work is to obtain data on IR for barium isotopes in the wide range of neutron number N. Due to some reasons Ba isotopes have been chosen as the object of investigations. First, with increasing neutron number in them from 74 to 82 the neutron shell is filled for $1h_{11/2}$. Secondly, quadrupole deformation parameters of the ground state decrease with the increase of neutron number. Thirdly, Ba isotopes give us the unique chance to study the population of isomeric states which are produced after photonuclear reactions with neutron escape. And this provides additional data on the level density of these nuclei.

2. Experiment and Data Analysis

The present investigations have been carried out with the beam of bremsstrahlung γ-quanta using the MT-25 microtron of FLNR, JINR, Dubna, in the energy region from 10 to 25 MeV [1]. The electron current (15-20 μA) was directed on a tungsten stopping target (2 mm) and measured continuously during the experiments. The electron energy was determined through measurements of the guiding microtron magnetic field using the nuclear magnetic resonance method.

Samples of natural BaO_2 were packed up in aluminium foil and during the irradiation were placed just behind an aluminium absorber. Natural abundance copper monitors 50 mm thick were placed just behind of the barium samples. The investigation of the isomeric and ground state population was performed using an activation technique. The lines corresponding to the γ-cascades of the isomers were registered by a Ge(Li) detector (with 60 cm^3 volume and an energy resolution of $\Delta E = 3$ keV for $E_\gamma = 1332$ keV ^{60}Co) coupled to a 4096-. multichannel analyser. The detector efficiency was experimentally determined using the OSGI standard sources.

In Table 1 the main nuclear-physical characteristics of the studied isomers are shown [2,3]. As can be seen from the table, the half-life and gamma-energy of the investigated isomers are very different and this allows a simultaneous measurement with natural Ba samples. The irradiation time for short-lived isomers was from 5 to 10 min, and for long-lived ones - up to 5 hours. Repeated measurements to experimentally determine the half-life of the studied radionuclides have been performed. Spectra have been analysed with the help of the ACTIV program [4].

In Fig. 1 a typical γ-spectrum of ^{nat}Ba obtained at maximum energy of $E_{\gamma max}$ = 14 MeV is presented. One can see γ-lines of a series of Ba isomers produced in photonuclear reactions.

Table 1. Half-life, energy, intensity, branching ratio, spin of studied nuclides.

Nuclide	$T_{1/2}$	E_γ, keV	I_γ, %	Branch.,%	J^π
^{129m}Ba	2.13 h	182.34	47.0	0	$7/2^+$
^{129g}Ba	2.20 h	214.30	9.9		$1/2^+$
^{131m}Ba	14.6 m	108.12	55.0	100	$9/2^-$
^{131g}Ba	11.8 d	496.26	44.0		$1/2^+$
^{133m}Ba	38.90 h	276.09	17.5	99.99	$11/2^-$
^{133g}Ba	10.54 yr	355.99	62.2		$1/2^+$
^{135m}Ba	28.8 h	268.27	15.6	100	$11/2^-$
^{135g}Ba	stab.				$3/2^+$
^{137m}Ba	2.552 m	661.66	90.1	100	$11/2^-$
^{137g}Ba	stab.				$3/2^+$

The yields $Y^m(E_{\gamma max})$ of the reactions (γ,n) were obtained by means of the relative method comparing γ-ray photo-peak areas of the isomers and ground state:

$$Y^m(E_{\gamma max}) = \chi\, Y(E_{\gamma max}), \tag{1}$$

$$\chi = \left[\left(\frac{S_\gamma^g\ \varepsilon_\gamma^m\ I_\gamma^m\ \lambda_g f^m(t_i, t_c, t_m)}{S_\gamma^m\ \varepsilon_\gamma^g\ I_\gamma^g\ \lambda_m f^g(t_i, t_c, t_m)} - p\frac{\lambda_g}{\lambda_g - \lambda_m}\right) + p\frac{\lambda_m}{\lambda_g - \lambda_m}\right]^{-1}$$

where m and g correspond to the metastable and ground states respectively, S_γ is the photopeak area, ε_γ - the detector efficiency, I_γ - the γ-line intensity, λ - the decay constant. The time factor $f(t_i, t_c, t_m)$ is equal to:

$$f(t_i, t_c, t_m) = (1 - e^{-\lambda t_i})\, e^{-\lambda t_c}\, (1 - e^{-\lambda t_m}), \tag{2}$$

where t_i, t_c, t_m are the irradiation, cooling and measuring times. The yield is related to the cross section by means of the following with integral relation:

$$Y(E_{max}) = \int_{Eth}^{E\,max} \sigma(E)\, N(E, E_{max})\, dE, \tag{3}$$

where E_{th} is the threshold of the reaction, E_{max} is the maximum energy of the γ-quanta, σ(E) is the reaction cross section, $N(E,E_{max})$ is the energetic dependence of the bremsstrahlung spectrum [5].

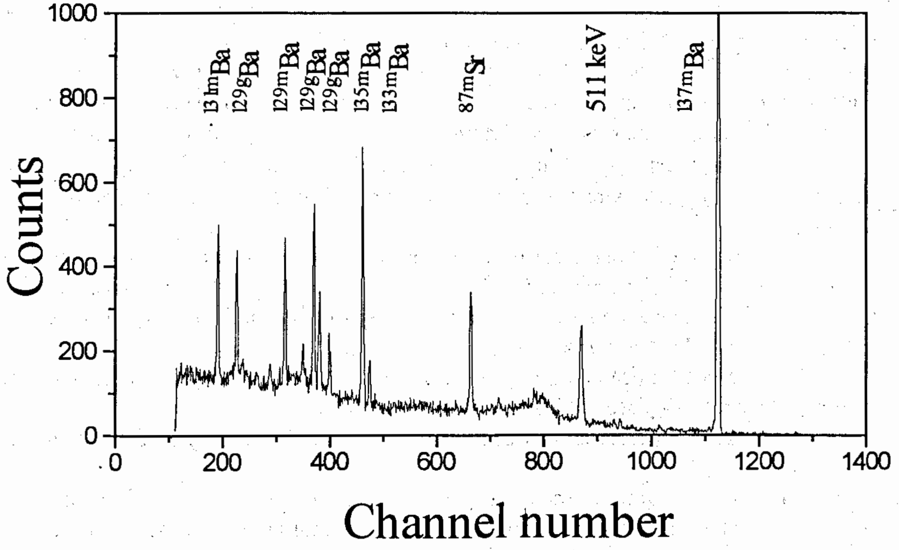

Fig. 1. A γ-spectrum of ^{nat}Ba produced after the irradiation by bremsstrahlung γ-quanta with E = 14 MeV and cooling time of 13 min. The time of spectrum collecting is 5 min.

One should note some interfering processes which can affect the yield, and therefore, the absolute values of the given reaction cross sections. Such are (n, γ), (n,n'), (γ,γ'), (γ,2n) reactions and (γ,p) reactions with β^- decay. As it is known, in bremsstrahlung experiments neutrons are present, which in reactions like (n,γ) and (n,n') on other Ba isotopes can produce the same states which are populated in the (γ,n) reactions. Neutron flux with each γ-quanta energy has been determined by capture reaction ^{115}In(n, γ)^{115}In. The most major contribution to the population of isomeric states after radioactive capture one can observe in the reaction ^{130}Ba(n,γ)^{131}Ba at γ-energy of 25 MeV and it amounts to 6%. For IR of ^{133}Ba the contribution of radiative capture reactions at the same maximum gamma-quanta energy amounts to 4%. As we approach the closed shell N = 82 the capture cross section significantly decreases [6], and the interference at the maximum gamma-quanta energy becomes less than 1%. The same low contributions (< 1%) have (n,n') and (γ,γ') reactions. (γ,2n) and (γ,p) reactions become important (1-3%) only for the maximum gamma-quanta energy.

3. Results

The dependence of the yields of barium isomers on bremmstrahlung γ-rays is presented in Fig. 2. They are obtained from the ratio of the isomer yield and the monitor reaction and present initial information on the cross section. One of the methodical solutions, which gives a possibility to achieve a certain progress in the systematic study of the dependence of phoronuclear reaction cross sections on the excitation energy and nucleon content of nuclei, lies in using a relative method of measurements with respect to a cross section, which is well known and taken as a standard. As well as in our previous measurements [7,8] the cross section of the reaction ^{65}Cu(γ,n)^{64}Cu measured by the direct procedure with the use of quasimonochromatic γ-quanta is employed as a standard [9].

The advantages of using a copper monitor involves the measurement of annihilation radiation peak with the energy of 511 keV at short- and long-term irradiation, as well as the absence of resonance structure near the threshold region for even-odd nuclei.

The relative method certainly has some advantages:

1) there is no necessity to measure gamma-quanta yield at the given electron energy, which are required at absolute measurements;

2) there is no necessity to account for uncontrolled changes of beam shape and size.

To recover the reaction cross sections the iteration method of minimizing the directed divergence has been applied [10]. To realize it one needs to know the bremsstrahlung spectrum N(E,E_{max}). For this purpose we have taken the results from ref. [5]. The interval of recovering the cross section was 1 MeV.

In Fig. 3 excitation functions of the investigated isomeric states are shown. The deduced Giant Dipole Resonans parameters the for the (γ,n) reactions are presented in Table 2. All dependences have a single-humped shape the maximum of which is in the region of 15 MeV. The same value have analogous parameters for the ground states. Excluding the excitation function for ^{137}Ba(γ,n), all other dependences are given for the first time.

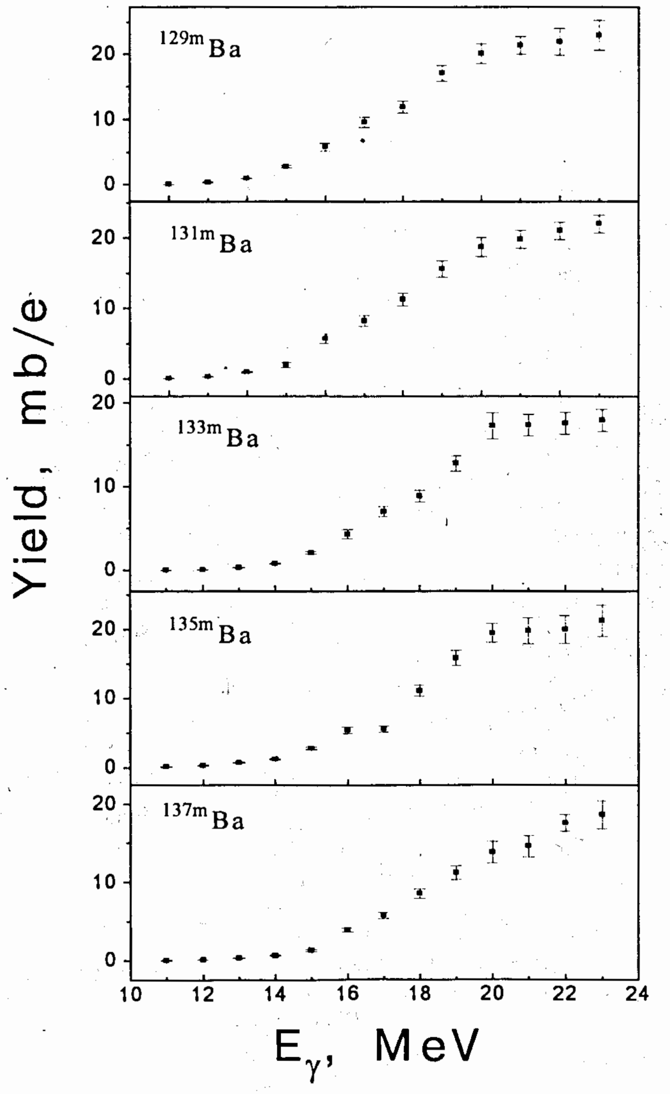

Fig. 2. Dependence of barium isomer yields on the from bremsstrahlung spectrum.

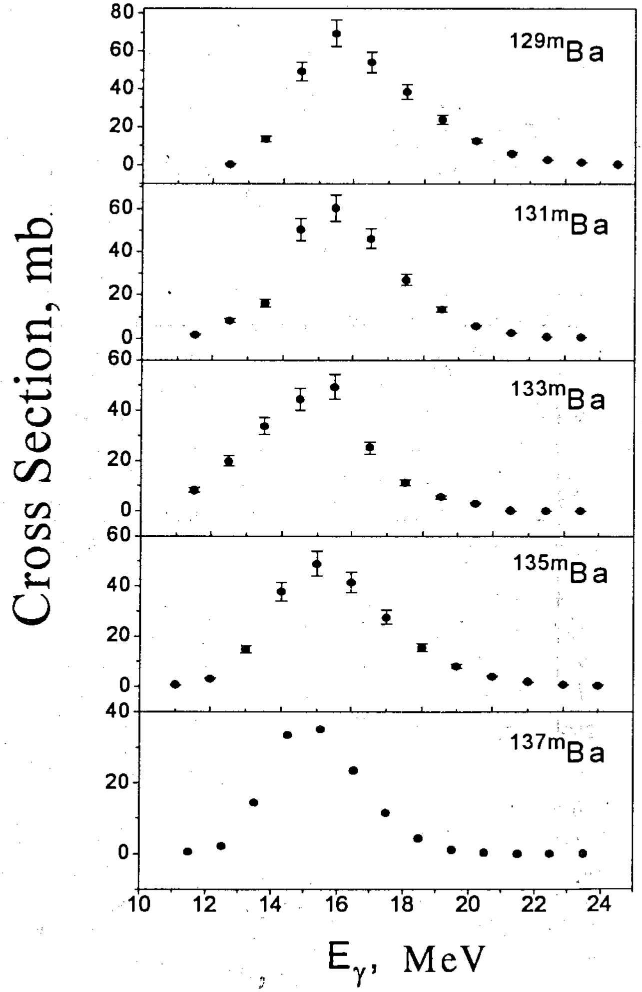

Fig. 3. Excitation functions for the studied isomers.

Table 2. Giant Dipole Resonans parameters for (γ,n) reactions on barium isotopes.

Reactions	E_0, MeV	Γ_0, MeV	σ_{max}, mb	σ_{int}, MeV.mb
^{130}Ba(γ,n)^{129m}Ba	15.3	3.1	72	347
^{132}Ba(γ,n)^{131m}Ba	15.1	2.9	64	293
^{134}Ba(γ,n)^{133m}Ba	15.1	3.1	52	256
^{136}Ba(γ,n)^{135m}Ba	15.2	3.2	52	259
^{138}Ba(γ,n)^{137m}Ba	15.2	2.6	39	162

4. Discussion and Summary

As already noted above, the excitation functions for (γ,n) reactions with the formation of nuclei in isomeric and ground states have the some behaviour, and the Giant Dipole Resonans parameters in both cases have are close values. That means that the mechanism of population of isomeric and ground states is the same - a neutron is emitted from the Giant Dipole Resonance to the levels with several MeV excitation energy, followed by a cascade of γ-quanta. The dependence of IR on γ-ray energy for different Ba isotopes is given in Fig. 4. Two regions of IR behaviour are recognised. The first region - from the neutron escape threshold to γ-quanta energy of 16-17 MeV. In this region the isomeric ratio increases sharply.

The presence of a significant angular momentum in the residual nuclei (Table 1) in comparison with the 1^- momentum of the excited nuclei ^{130,132,134,136,138}Ba, leads to the formation of a substantial threshold in J for these reactions. As the emitted neutrons in the first region have a low energy ε_n (as a rule this is true for *s* and *p* neutrons), the low angular momentum *l* is carried away by these neutrons. It follows that in this region the metastable level are populated via a limited number of transitions. With increasing the excitation energy in the compound nucleus, the energy of the emitted neutron increases also and hence the distribution of the level density of residual nuclei. over angular momentum is enhanced. In the second region (beyond 17 MeV) IR changes slightly.

One would mark one more distinguishing feature in the behaviour of the IR energy dependence. This is the difference in IR values for various Ba isotopes. ^{129}Ba has the highest IR. Then this ratio decreases with increasing the mass number A and has a minimum value for the semimagic nucleus ^{138}Ba.

One can assume the existence of several reasons, which can affect the behaviour of IR dependences. The first one could be the different values of neutron binding energy for Ba isotopes. As known, with increasing the mass number A the neutron binding energy B_n decreases. Thus, this dependence should influence inversely the IR dependence at the same excitation energy. Therefore this is not a positive argument in

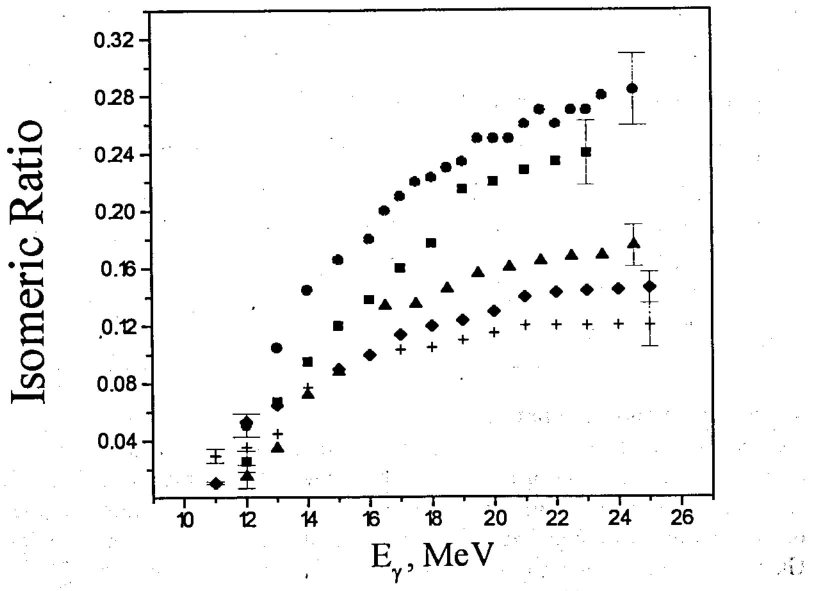

Fig. 4. Dependence on γ-energy of Ba isomeric ratios in the region of giant resonance for ^{129m,g}Ba ●, ^{131m,g}Ba ■, ^{133m,g}Ba ▲, ^{135m,g}Ba ♦ and ^{137m,g}Ba +.

interpreting the experimental dependences. Secondly, approximately the same difference in spins of isomeric and ground states should not affect the IR dependence, too. Thirdly, if one takes into account the level density of ^{131,133,135,137}Ba isotopes, then it can be seen (Fig. 5) that it correlates with the detected IR dependence. The dependence in Fig. 5 has been obtained on the base of describing the level density by a phenomenological method taking into account the influence of shell effects and their attenuation with the increase of excitation energy [11].

To calculate the level densities of a nucleus, ρ (U,J), having a given excitation energy U and angular momentum J, the Fermi gas model [12] has been used:

$$\rho\,(U,J) = f(J)\,\frac{\exp[2\,\sqrt{a(U-\Delta)}\,]}{\sigma\, a^{1/4}\,(U-\Delta)^{5/4}} \qquad (4)$$

where the spin dependence in (4) equals to:

$$f(J) = \frac{(2J+1)}{2\,\sigma^2}\,\exp[-\frac{(J+1/2)^2}{2\sigma^2}] \qquad (5)$$

where the spin cutoff parameter is determined via:

$$\sigma^2 = \frac{6}{\pi^2}\,k\,A^{2/3}\,\sqrt{a(U-\Delta)} \qquad (6)$$

Thus, the nuclear level density (4) is determined by two parameters: level density parameter a and the average taken over angular momentum projections of single particle states in the Fermi energy $<m^2> = k\,A^{2/3}$. Δ is the pairing energy (in MeV). A is the mass number. On the other hand, spin cutoff parameter is connected with moment of inertia I by the ratio:

$$\sigma^2 = IT/\hbar^2, \qquad (7)$$

and moment inertia is presented by the dependence:

$$I = 2/5\ M R^2\ (1 + 1/3\beta) \qquad (8)$$

where M, R and β are the mass, radius and quadrupole deformation coefficient, respectively.

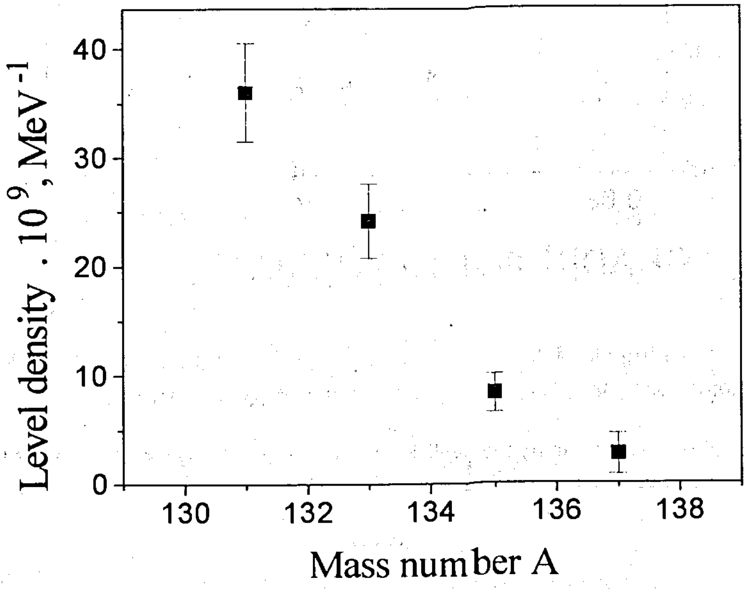

Fig. 5 Level density for ^{131,133,135,137}Ba at excitation energy of 16 MeV.

The level density parameter depending on excitation energy is described by the ratio:

$$a(E) = a\ [\ 1 + f(E)\ \delta W/U\ ], \qquad (9)$$

where a is an asymptotic parameter value at high excitation energies.

IR correlate with the quadrupole deformation parameter. With the decrease of the neutron number and the increase of IR, both the dynamical quadrupole deformation the primary even-even nuclei [13], and the static deformation in the residual odd nuclei [14] increase.

A similar dependence has been observed in γ-inelastic scattering [15].

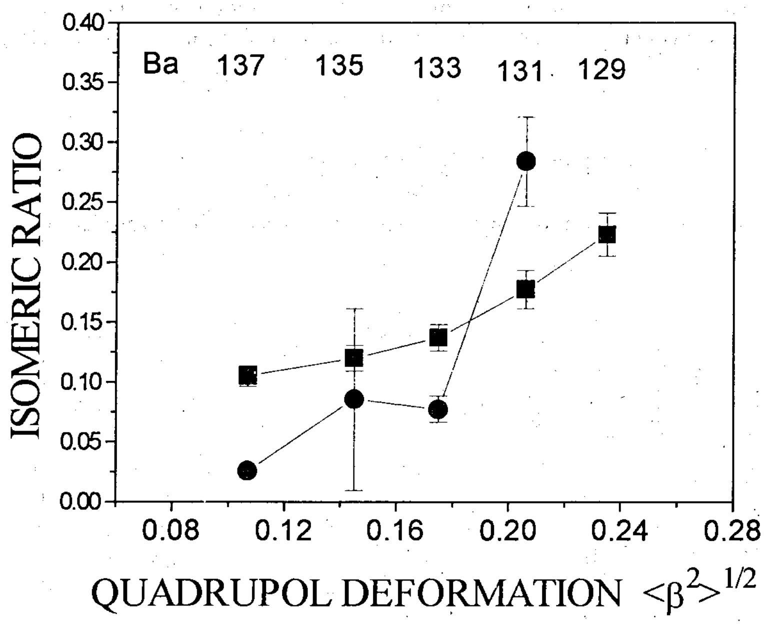

Fig. 6. IR versus quadrupole deformation coefficients $<\beta^2>^{1/2}$ for (γ,n) reactions ■ and for neutron capture ones ●. The maximum γ-quanta energy is 16 MeV.

This dependence is similar to the well known cross section systematics in which a correlation with the neutron excess (N-Z)/A is observed [16,17,18].

$$\ln(IR) = B - C\,\frac{(N-Z)}{A} \qquad (10)$$

where B and C are constants, N, Z are the neutron and proton numbers. This dependence shows a sensitivity of IR to the nuclear structure of atoms.

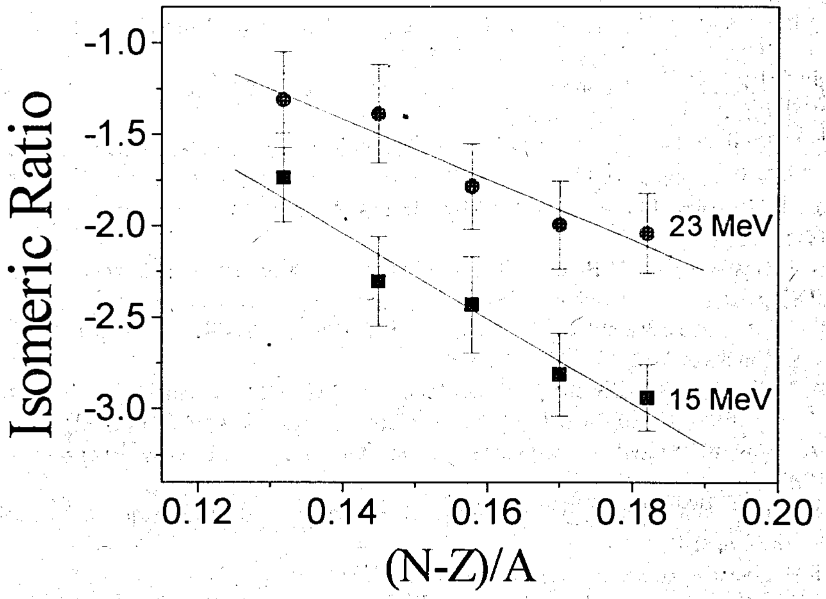

Fig. 7. Dependence of the IR of barium isotopes in (γ,n) reactions on the neutron excess (N-Z)/A.

5. Conclusion

The isomeric ratios obtained for the nuclei ^{130,132,134,136,138}Ba confirm our assumption concerning the role of deformation. One should note that Ba isotopes have no high static deformation, although some experimental results indicate the increase of the static deformation coefficient. In this region of nuclei the quadrupole deformation coefficient is basically associated with dynamic deformation.

Thus, the existence of deformation should result in occurrence of vibrational and rotational states, in this case rotational bands most efficiently manifest themselves in aligned states, i.e. in states with the maximum spin. Therefore, the concentration of high-spin states increases and this leads to the decrease of IR, which is observed in the experiment.

The authors are grateful to a Profs. Yu. Ts. Oganessian and Yu. E. Penionzhkevich for interest in the present investigations. Thanks are also due to Drs S.A. Karamian and R.G. Kalpakchieva for helpful discussions.

References

1. A.G.Belov, Workshop on application of microtrons in niclear physics, Plovdiv, 1992, D 15-93-80, p.12.
2. E.Browne and R.B.Firestone, Table of Radioactive Isotopes, edited by V.S.Shirley (Wiley, New York, 1986).
3. U.Reus and W.Westmeier, Atomic Data Nuclear Data Tables V. 29 (1983) 205.
4. V.Zlokazov, Com. Phys. Comm., V.28 (1982) 27.
5. Ph.G.Kondev, A.P.Tonchev, Kh.G.Khristov and V.E.Zhuchko, Nucl.Instr. and Methods in Physics Research B71 (1992) 126.
6. E.Gryntakis, D.E.Cullen, G.Mundy: Handbook on Nuclear Activatinon Data N 273. IAEA. Viena. 1987.
7. Yu.P.Gangsky, H.G.Hristov, F.G.Kondev, A.P.Tonchev et. al.Physica Polonica, V. B21, N12 (1990) 1041.
8. N.P.Balabanov, A.G.Belov, Yu.P.Gangrsky, F.G.Kondev, A.P.Tonchev , Preprint JINR E15-93-370, Dubna, 1993.
9. S.C.Fultz, R.L.Bramblett, J.T.Caldwel, R.R.Harly, Phys.Rev. 133, B 1149 (1964).
10. V.E.Zhuchko, Yad. Fiz. 25 (1977) 299.
11. A.S. Iljinov, M.V.Mebel, N.Bianchi, E.DeSantis, C.Guaraldo, V.Lucherini, V.Muccifora, E.Poli, A.R.Reolou and P.Rossi, Nucl. Phys., A543 (1992) 517.
12. A. Ignatjuk "Statistical properties of excited nuclei". Moscow, Energoatomizdat 1983.
13. S.Raman, W.C.Nestor, Jr.S.Kahane, and K.H.Bhatt, At. Data Nucl. Data Tables V. 42 (1989) 1.
14. P.Raghavan, At. Data Nucl. Data Tables, V.42 (1989) 189.
15. C.B.Collins, J.J.Carroll, K.N.Taylor, D.G.Richmond, T.W.Sinor, M.Huber, P.von Neuman-Csel, A.Richter, and W.Zigler, Phys.Rev.C, V.46,N3,1992,p.952.
16. Levkovsky V.N, Yad. Fiz. 18 (1973) 705.
17. Trofimov Yu. N, Yad. Fiz. 75 (1993) 33.
18. Gopich P.M., Zalubovsky I.I., Kuzin E.A., Sorokin B.I., Sotnikov V.V., Fomin E.A, Atomnaj Energija 74 (1993) 78.

Received by Publishing Department
on March 1, 1995.

Тончев А.П. и др. E15-95-91
Измерение изомерных отношений в реакциях (γ, n)
на изотопах бария в области гигантского дипольного резонанса

Представлены результаты измерений сечений реакций (γ, n) в области гигантского дипольного резонанса, приводящих к основным и изомерным состояниям $h_{11/2}$ в нечетных изотопах Ba с $A = 129 - 137$. Использовался метод измерения наведенной активности продуктов реакций. Получена зависимость изомерного отношения от энергии γ-квантов и массового числа изотопа. Обсуждаются различные факторы, влияющие на величину изомерного отношения.

Работа выполнена в Лаборатории ядерных реакций им. Г.Н.Флерова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1995

Tonchev A.P. et al. E15-95-91
Measurement of Isomeric Ratios in (γ, n)-Reactions
for the Barium Isotopes in the Giant Dipole Resonance Region

The cross sections of (γ, n)-reactions in the range of the Giant Dipole Resonance, leading to the isomeric states $h_{11/2}$ in odd isotopes of Ba with mass number $A = 129 - 137$, are presented. An activation method of measurement has been used. The dependence of the isomeric ratio on γ-energy and mass number of the isotopes has been obtained. Different factors influencing the value of the isomeric ratio are discussed.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 1995