THE MINI-ORANGE MAGNETIC β-SPECTROMETER

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Abstract

The brief review available the mini-orange type beta-spectrometers have been made. The various methods for determination of the mini-orange efficiency are discussed. On an example of off-line mini-orange beta-spectrometer of a Department of Nuclear spectroscopy and radiochemistry of Laboratory for Nuclear Problems of JINR, the mini-orange beta-spectrometer as perspective installation for measurement of conversion electrons' spectra from the short-lived neutron- deficient isotopes has been shown.

1. INTRODUCTION

The spectra of electron conversion from β^+ radioactive isotopes are often hidden underneath the background from β^+ ray continua and secondary Compton electrons of γ-radiation. In the case of in-beam target for observation of conversion electrons from nuclear reactions, the influence of protons and neutrons still increased the background. For many nuclear spectroscopy investigations it is valuable to explore methods for elimination or reduction of the background.

In 1972 J. Klinken and Wisshak reported on a new type of spectrometer for conversion electrons combining a silicon solid state detector with a filter of permanent magnets around a central absorber of lead or tungsten.

Application of mini-orange magnetic spectrometer to on-line and off-line nuclear spectroscopy studies of the internal conversion electron spectra from β^+ decay nuclei, gives the possibility to decrease

background connected to the positron radiation and to discover a weak conversion electron transitions.

The advantages of mini-orange β-spectrometer for study spectra of the internal conversion electrons are at the high nuclear transitions, whose conversion coefficients had the small values.

In this paper we are described the experimental set-up with a mini-orange β-spectrometer, methods for an efficiency calibration of a mini-orange spectrometer and some example of experimental investigations carried out with the help of a mini-orange β-spectrometer.

2. MINI-ORANGE TYPE β-SPECTROMETER

Mini-orange type β-spectrometers first were described by J. van Klinken and co-authors [1,2]. In principle, the mini-orange β-spectrometer comprises a radioactive source, magnetic filter and a semiconductor electron detector.

A schematic drawing of magnetic filter and the typical dimensicn and form of $SmCo_5$ magnets were shown in Fig.1.

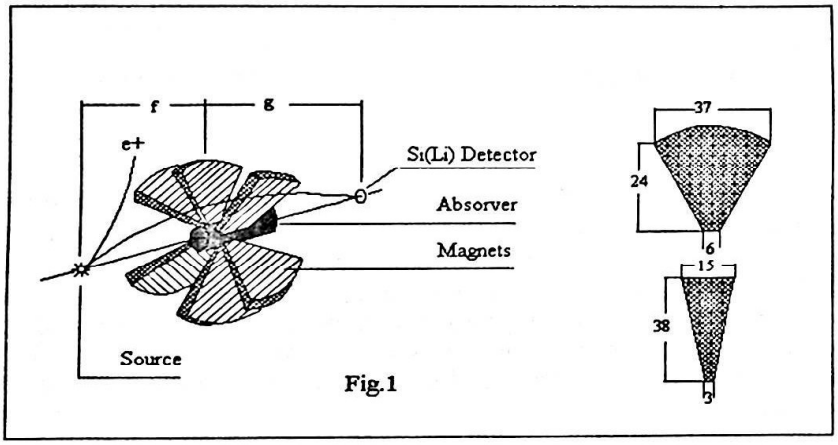

Fig.1

Source or target is located on the system axis in front of the central absorber while the Si(Li) detector has placed at opposite side of the absorber. A magnetic filter consists of wedge-shaped $SmCo_5$ magnets, which is in detail described in [3,4].

There are three different configuration of a magnet (type A, B and C). The magnets of type A and B have a wedge shape and

the magnets of type C has triangle shape. The magnetic filter consisted of A and C type magnets is used for high energies measurements while thinner magnets (type B) must be use for lower energies. The magnetic filter is an extreme version of a toroidal electron spectrometer. The magnets with wedge-shape made of $SmCo_5$ mounted on the aluminum ring by means of standardized holder attached to each magnet. For symmetric configurations with equal gaps between magnets of some type typical field values are 1.4 kG for 6B; 2.8-3.0 kG for 12B and 6A and 4.5 kG for 9A. As shows the experiment on the distance between 10 and 26 mm from the axis the toroidal fields are constant within 10 %. The problem of the decreasing field strength near the edges of magnets and inhomogeneities of the toroidal magnetic field within the gaps are discussed by Ts. Dresel et al. [5].

A central absorber is an important part of the magnetic filter. A central absorber usually is made of the heavy metals such as bismuth and lead. Owing to the toroidal field the individual magnets pull towards to the central absorber so that the absorber does not need a special attachment to the ring holder. For a typical configurations of $SmCo_5$ magnets a central absorber has diameter of 10-12 mm. The length of that changes within the certain limits (25-45 mm), according to the special conditions of the given experiments. In some experiments lead absorber had enlarged on each side by gold or tin bars. For many off-line experiments, which are required small f- and g-values its length must be reduced. It is already has been remarked that the central absorber has little influence on the electron transmission. By changing the number and type of the magnets in the magnetic filter, and by varing the distances from the middle plane of magnetic filter to the source (f) or to the detector (g) we may change the strength of the toroidal magnetic field, hence explore the spectra of electrons in the energy range from 50 to 2500 keV.

In a mini-orange spectrometer a magnetic field guides only electrons around a central absorber towards the Si(Li). Majority of measurements on nuclear spectroscopy was carried out by a Si(Li) detectors with a drift depth of 3-4 mm and an active surface area of 200-300 mm^2. The typical energy resolution of such detector was about 2.2 keV at K1063 line of ^{207}Bi when the detector cooling to liquid nitrogen.

The detector has a relative large surface with respect to the magnetic field area and thus it covers a wide energy range of electron passing through the magnet gaps. As mentioned above, the energy

range of the measured conversion electrons depends on the type of magnets and the distances between magnet-source and magnet-detector. The upper limit of high energy of spectrometric system is usually determined by the detector thickness and not by the strength of the magnets. But the thickness of the Si(Li) detector should not exceed the range of the conversion electrons under investigation because of the unnecessary thickness may give a contributions to background. For detection of electrons with high energies up to 10 MeV may be used Si(Li) detector with the thickness of 6-8 mm. The unnecessary thickness of the detector gives a contribution to the total counting rate of the Si(Li) detector, but not much to the background in the region of interest, when this region is covered by a narrow- range configuration the background can be made very low. Protection against the background contribution from direct γ-rays may be as follows: The central absorber should be as long as the distance between source and detector permit and it should be made of a dense material.

The peak-to-background ratio of k-conversion lines in mini-orange spectra can be better than the corresponding ratio for γ-ray in typical Ge(Li) spectra if the conversion coefficients are not too small and if there is no interference from β^- continua.

Main background components are:

- A continuum of electrons from Compton scattering events in surface layer of magnets, central absorber, diaphragms and source or target materials,
- A Compton continuum of γ-rays, which reach the detector after penetration through the central absorber,
- Some straggled photoelectrons from surface layers of magnets, absorber and diaphragm, which may be reach the detector also.

The enumerated sources of background usually increase low energy region of conversion electron spectra.

It is worthwhile to mention also a few precautions against Compton electrons and photoelectrons surface layers:

- Unnecessary material in the surrounding of the source and in the space between source and magnets should be avoided,
- Source thickness much larger than 1 mg/cm^2 result not only in line broading, but also in enhancing the Compton continuum,
- Source and target must be attached to a thin backing or must be self supporting,
- The thickness of the Sl(Li) detector should not exceed the unnecessarily range of the conversion electrons under investigation.

In order to obtain sufficient stopping power high energetic electrons and at the same time small dimensions (narrow geometry), materials of high density preferred. In other hand it must be avoided the use of dense materials of high Z in which photoelectrons may be created ($\sim Z^5$). Therefore for in-beam measurements the diaphragm and surface layer of the central absorber made from tin or copper.

3. EXPERIMENTAL SET-UP

Our experimental set-up in principle comprises a magnet filter of mini-orange type, radioactive source and a Si(Li) detector. The magnet filter was assembled from the wedge shaped $SmCo_5$ magnets, which made in Switzerland. The wedge shaped $SmCo_5$ magnets similar to that described in [4] were mounted on aluminum ring. As above mentioned a central absorber represents a tungsten or lead bar. Mini-orange magnetic spectrometric system was designed at the Institute of Nuclear Physics of the Hungarian Academy of Sciences (Debrecen) [6]. In our experiments we have used tungsten and lead absorbers with a diameter of 12 mm and length of 24 mm.

We have two version of experimental set-up (on-line and off-line). The on-line version of experimental set-up is described in [8]. At off-line experiments a radioactive source transported into the vacuum chamber through a vacuum sluice without deterioration of a high vacuum in the vacuum chamber, that is important when the Si(Li) is cooled and when the short lived radioactive isotopes are studied. The off-line version of the experimental set-up is described [7].

At off-line experiments a radioactive source transported into the vacuum chamber through a vacuum sluice without deterioration of a high vacuum in the vacuum chamber, that is important when the Si(Li) is cooled and when the short lived radioactive isotopes are studied. The magnetic filter and Si(Li) detector located inside of cylindrical shaped vacuum chamber with a diameter of 165 mm and height of 165 mm, which evacuated with help of a magnetic discharge pump of a type Nord-100. The residual pressure in the vacuum chamber is about $2 \cdot 10^{-4}$ Pa. There is cooling trap in which liquid nitrogen is, between the chamber and the magnetic discharge pump. Preliminary vacuum in chamber was obtained by oil pump with a cooling trap.

As above mentioned for measurements of conversion electrons spectra we are used Si(Li) detector with active surface area of 100 mm^2 and drift depth of 3 mm. An optimum resolution of Si(Li) detector is 2.1 keV on the K1063 line of ^{207}Bi.

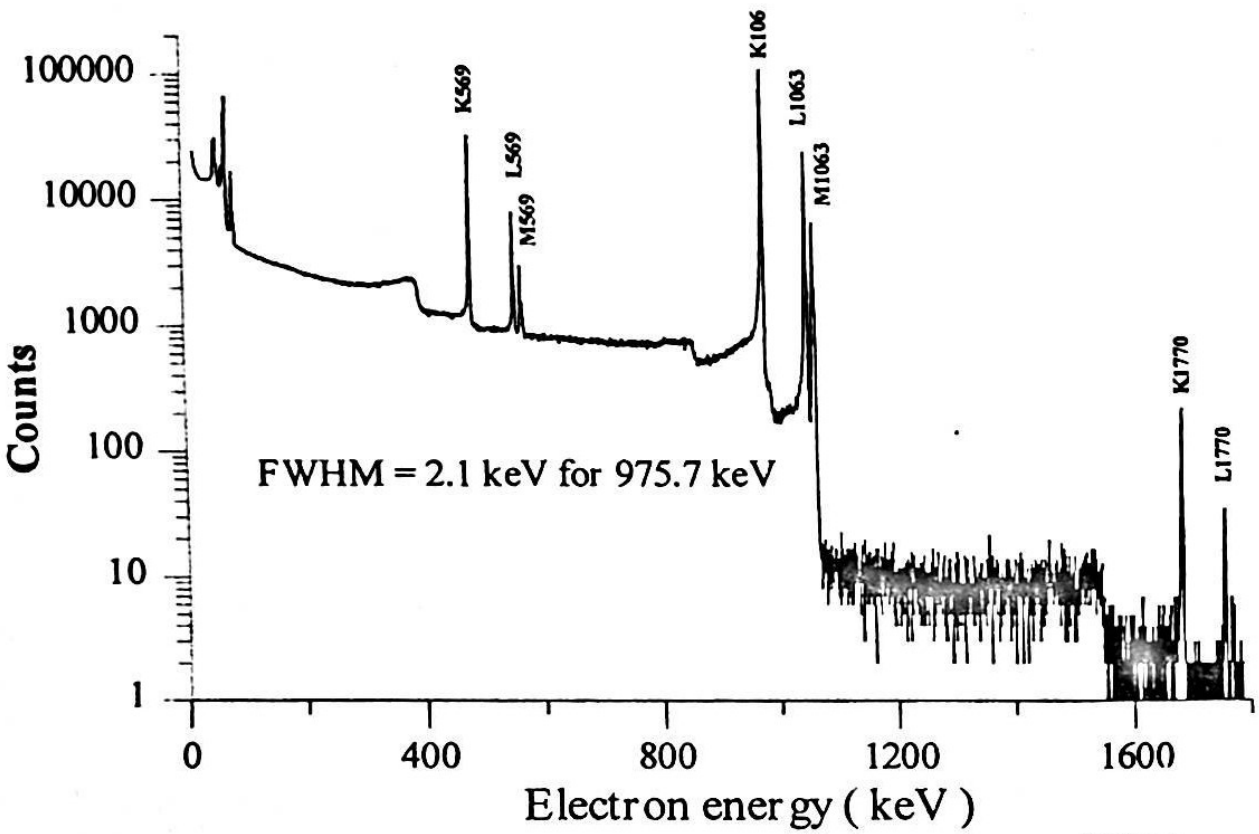

Fig.2. The Conversion Electron Spectrum of ^{207}Bi

In Fig.2.shows internal conversion electron spectrum of ^{207}Bi measured by our spectrometric system with Si(Li) detector.

4. EFFICIENCY (TRANSMISSION) OF A MINI-ORANGE β- SPECTROMETER

The most important parameter of mini-orange spectrometer is efficiency or transmission as function of the electron energy. It depends on the magnetic field strength and geometrical proportion of setup, the surface area and counting efficiency of detector. We define transmission T as the observed counting rate of electrons contributing to measured peak divided by the total (4π) emission rate of electrons from a radioactive source. The transmission when measuring a single line is defined as:

$$T = \frac{N_{m0}}{A} \qquad (1)$$

where N_{mo} the count rates in the line with mini-orange (MO) in operation and A is the activity of the source. Activity may be expressed in terms of the count rate N_o measured without the MO, the solid angle Ω subtended by detector. Moreover the transmission is diminished by back scattering of the electrons at detector surface. Thus the measured counting rate must be corrected.

$$A = \frac{N_0}{1-k}\frac{4\pi d^2}{S}$$

Inserted into equation (1) this yields

$$T = \frac{N_{m0}}{N_0}(1-k)\frac{S}{4\pi d^2}$$

where S represents the sensitive area of the detector used d the distance between the source and the detector and **k** denotes the back-scattered fraction of the incoming electrons. In magnetic filter design we distinguish two basic version: (1) the spectrometric systems with transmission in a narrow energy range and (2) the broad range systems. Ttransmission curves in which the absolute efficiency is plotted against the electron energy were presented in [3]. The numbers at the curves for the 4B, 6B and 6A assemblies indicate source position (f) and those at the curves for the 9A assembly indicates the detector position (g). Using these plots may select the number of magnets in the filter and adjust the necessary range of electron energy. As seen in Fig.4 from [3], the transmission curves of the magnet configuration have been shifted by variation of the distances f and / or g the respective distances of source or detector with respect to the middle of magnet configuration. The highest transmission of the magnet filters always occurs for a value f which is smaller than the corresponding g-value, typically for f ≈ 15 mm while g takes a value between 25 and 40 mm.

The broad range transmission may be obtained by different ways [3] by using:

- Magnets with a broad base near the central absorber,
- Circular magnets (type C),
- Configuration with different gap widths combined A and B of type magnets.

The results of measurement on the efficiency of our mini-orange spectrometer were published in [8,9]. The spectrum of internal

conversion electrons (ICE) of ^{169}Yb ($T_{1/2}$=32 days) measured by the mini-orange magnetic spectrometer with the filter of 6B type and without the filter. Distance from the middle plane of the magnet filter to the source and detector were f =15 mm and g = 25 mm, respectively. According to these data the efficiency of the spectrometer respect to the K307 line, increases more than 15 times in the case of using the magnetic filter. The efficiency was defined as the ratio of ICE peaks, measured with and without magnetic filter. The results of efficiency calculations are presented in [7]. For the given assembly of magnets ensures the efficiency up to ten percent over the energy range from 180 to 310 keV. It is worth to emphasize that the efficiencies of a mini-orange β-spectrometer with and without a magnetic filter are usually compared for the same distances between source and detector. For a given design of mini-orange spectrometer, minimum fixed distance between the source and detector is 34 mm. The central absorber has length of 24 mm. The middle of magnet base is placed at the distance of 6 mm from the absorber end, which turned to the source. So that the distance between the source and the middle of magnet filter is 19 mm at close geometry, when the outward edge of magnets had crossed the source plane. But magnet filter may be moved toward the source for 5 mm yet, after the establishment of the source. This operation usually has been performed manually. Therefore a minimum distance between the source and the magnet filter, to which we are reached, is 14 mm. Asymmetric arrangement of the source and detector leads to some broading of the energy range at the expense of decreasing maximum possibly efficiency. The energy range covered by varing the distance f, g and number of magnet segments extends from 50 to 2500 keV. The maximum transmission is about 12 – 15 %. At large distances the transmission curves become low and relatively narrow; low because θ_b becomes limited by the size of the magnets and narrow because the detector becomes relatively small again. In this procedure for an efficiency calibration, in order to span a wide energy range is required a large number of well-known and suitable standards, which are well distributed in given energy range and available long half- life. In the energy range of 120 to 1800 keV there are well known sources of the conversion electrons, such as ^{207}Bi (T_s =32 y) and ^{152}Eu (T_s =13.5 y) [10]. Eu-152 has more than ten conversion lines in energy range from 197.8 to 1361.2 and with relative intensities of 0.1- 0.5. For calibration of a spectrometer in the energy range from 200 up to 1400 keV usually have been used Eu-152. In the

range of energies from 1 up to 2 MeV not had almost calibration sources with an enough long live time. Use of a continuous β - spectrum from a radioactive source for calibration of a β-spectrometer of a type a mini-orange appears attractive [13,14].

The calculations of the efficiency for a mini-orange type β-spectrometer were first carried out by Van Klinken et al. [1], who calculated the trajectories of the particles moving through the magnetic field. The calculations very well predict position of maximum and width of the transmission curve, while the measured absolute values of the transmission are 2 to 3 times smaller than calculated.

The theoretical transmission for certain energy E is given in percent of 4π by:

$$T = 50\ (1\text{-}b)\ (1\text{-}k)\ \Sigma\ [(\cos\theta_{ai} - \cos\theta_{bi})]$$

The bloking factor b represents the fraction of the solid angle of the mini-orange, which is covered by the magnets; A bloking factor depends on number of magnets in configuration of the filter. For 6A filter, bloking factor is equal 0.5. A fraction **k** of the detected electrons may be back scattered by the Si(Li) detector, so that they do not contribute to the full energy peak. The effect of back-scattering on the spectroscopy of electrons with Si(Li) detectors has been investigated by various authors. N.Waldschmidt and S.Wittig [11] find that for energy of electrons above 200 keV back scattered electrons nearly energy independent but strongly depending on the angle of incidence ϕ. W.Neumann et al. [12] have deduced a formula upon the experimental data of N.Waldschmidt and S.Wittig in which back scattering coefficient k varies linearly from 22 to 51 %, with the incident angle ϕ between 0° and 60°.

$$k(\phi) = 0.483 \cdot 10^{-2}\ \phi + 22 \qquad (0° \le \phi \le 60°)$$

An alternative approach to predict the transmission of mini-orange spectrometer was taken by K. Farzin et al. [13] who parameterized the shape of the transmission function and determined the set of parameters from experimental data. The position of the maximum and width of calculated and measured transmission curve agree very well, while the amplitude differs by more than factor of 2.

The differences between calculated and measured transmission curves may be caused by:

- Inhomogeneities of the field near the edge of magnets;
- Inhomogeneities of the toroidal magnetic field within the gaps because of radial and axial components of magnetic field defocus the electrons;
- Impact angle dependent back-scattering of electrons from the detector surface.

The inhomogeneities of toroidal magnetic fields near the edges of magnets and within the gaps and back scattering effects were taken into account by Th.Dresel et al. [5] and has been obtained very good agreement between the theoretical results and the measured data. The calculated efficiency function directly compared with experimental absolute transmission values, which are defined as:

$$T = \frac{I_s}{I_0} \frac{S}{4\pi d^2}$$

In this relation, S represents the sensitive area of the detector used, d the distance between the source and the detector, I_s the intensity measured with magnetic filter inserted between source and detector, and I_o the intensity measured with magnetic filter removed.

5. MEASUREMENT OF CONVERSION ELECTRON SPECTRA AT THE DECAY OF ^{147G}Tb.

The ^{147g}Tb (T_s=1.6h) source was produced by spallation of tantalium in the internal beam of 660 MeV protons from the JINR phasotron. ^{147}Tb separated from other terbium isotopes on the electromagnetic separator of the ISOL-facility YASNAPP-2 [15]. The internal conversion electron spectrum of ^{147g}Tb decay was measured using the mini-orange magnetic filter [7].

The efficiency values of the β-spectrometer with a magnetic filter of 6A (f = 35 mm and g = 45 mm respectively) were calculated on the basis of measurements as carried out using the ^{207}Bi source with the known activityand the spectra of conversion electrons of ^{166}Tm and ^{152}Tb. Such assembly of magnets ensures satisfactory condition for the measurements of ICE spectra within the energy range from 1.0 to 2.0 MeV. The mini-orange spectrometer allowed the spectrum purified from positrons. Use of the magnetic filter produces about 15- fold

increase in the efficiency for ICE measurements in the energy range selected.

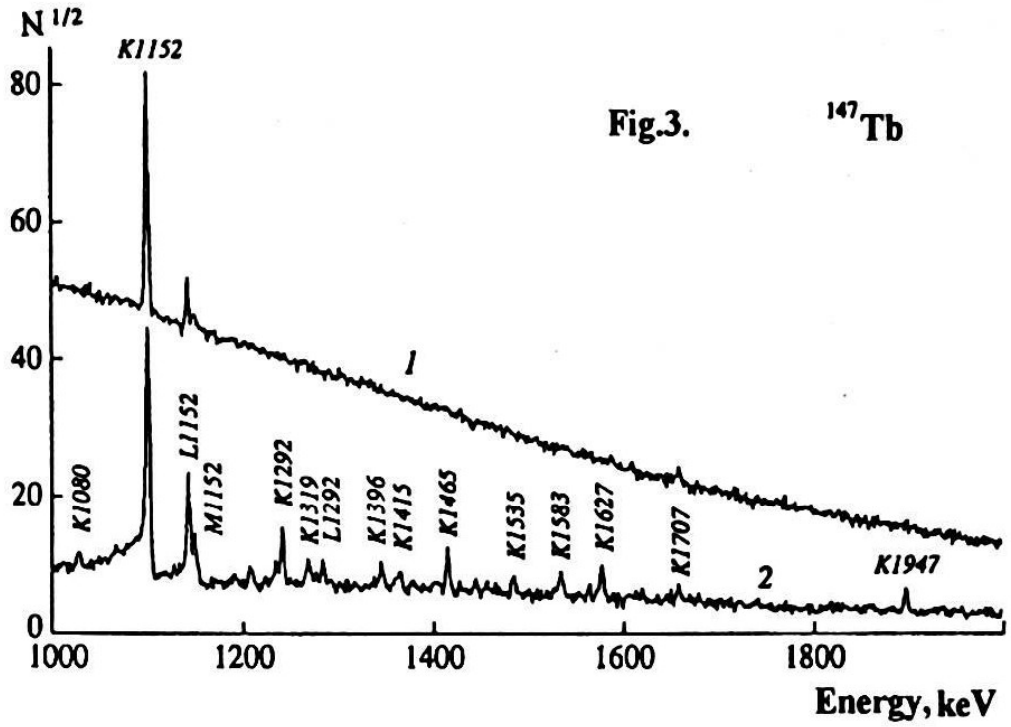

Fig.3. ^{147}Tb

Fig.3 shows spectra of internal conversion electrons of ^{147g}Tb, measured with the help of mini-orange spectrometer. Upper spectrum is obtained without magnetic filter and down spectrum is measured with 6A magnetic filter. As is seen, in the upper spectrum display only the K and L lines of the most intense γ-transition (about 100% per decay) of 1152 keV energy. The weaker ICE lines due to the other γ-transitions are not seen in this spectrum. In down spectrum, which measured with magnetic filter, a numerous weak peaks are distinguished. Accurate determination of intensities of internal conversion electrons is allowed to determine α_K and α_L. Therefore, multipolarity of about 15 high energy transitions are determined [16].

6. MEASUREMENT OF CONVERSION ELECTRON SPECTRA AT THE DECAY OF ^{160}Er→^{160}Ho →^{160}Dy

The study of radioactive decay of ^{160m,g}Ho, which lasts during 5 years, has been completed. Ultimate aim of the work was determination of level scheme of ^{160}Dy from the radioactive decay of

^{160m,g}Ho. We were carried out a large program of γ-rays spectrum measurement of ^{160m}Ho using the spectrometers with HPGe -detectors of different volume (from planer x-ray of volume 2 cm^3 to the large volume 200 cm^3), as well as □nticompton spectrometer. In the gamma-spectra were observed 870 γ-transition, accuracy of determination of their energy and relative intensities, was 50 eV and 5% accordingly. Scheme of ^{160}Dy is contained 162 levels.

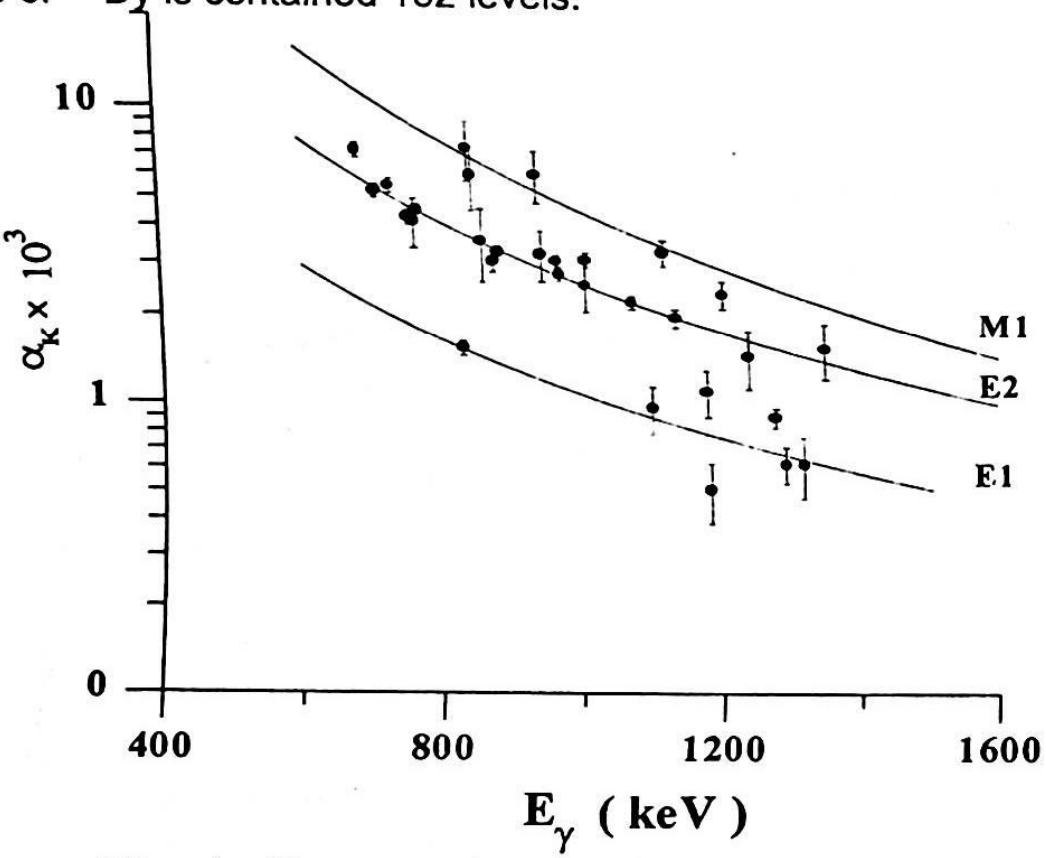

Fig.4. Comparison of the measured values of α_K with the calculated ones

Types of multipolarity of observed transitions in γ- spectrum have determined from measurements of spectra of conversion electrons using beta-spectrograph with high resolution and «mini-orange» type β-spectrometer. For the verification of location γ-transitions in the level scheme of ^{160}Dy a matrix of γγ - coincidences measured and analyzed. Were observed a coincidence with very weak γ- rays (» 0,003 % on the

disintegration). Successful realization of experiments was ensured by the radioactive sources of high quality prepared in Dubna and Rjej (Chehy). Comparison with the present calculations on the base of quasi-particle – phonon models is made. Special attention was given to the excited states with 0^+.
In the Fig.4. was shown comparision of theoretical and experimental values of α_K in energy range from 700 to 1400 keV.

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