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MAGNETIC BETA-RAY SPECTROMETER ON THE BEAM OF THE U-300 HEAVY ION CYCLOTRON

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1. Introduction

In the recent years a rapidly growing interest in the structural studies directly on the beam of the accelerated particles has been observed. Among these an important part is played by the experiments in which the accelerated particles produce a reaction yielding as a final product an interesting excited nucleus. The deexcitation of such a nucleus is studied directly on the beam by measuring the spectrum of gamma rays or the internal conversion electrons/1-5/.

Heavy ions are playing an even increasing part in these studies, since they show certain advantages compared with lighter nuclear projectiles such as deuterons or alpha particles.

The reactions induced by heavy ions provide first of all for obtaining nucleides unavailable in other ways, which lie far off the "stability line" on its neutron-deficient side. In Fig.1 examples of nuclei in the range of $50 < Z < 82$, $50 < N < 82$ which may be obtained using heavy ions, are shown.

Another advantage of applying ions for studying nuclear structure is related with that such ions transfer to the compound nucleus large angular momentum, which does not vary to a larger extent during the subsequent acts of neutron emission. The final nucleus has therefore a relatively low excitation energy and high angular momentum. Owing to these conditions the possibilities arise for

observation of gamma transitions from high-spin states which are unattainable by other methods. Thus, for instance, "in beam " spectroscopy permitted to study rotational bands up to I =18 (Stephens et al[4]).

The transfer of a large angular momentum to the compound nucleus is related with a high degree of alignment (Diamond et al.[6]). Owing to this phenomenon, the gammas and internal conversion electrons emitted from the final nucleus indicate an angular correlation with respect to the incident beam. The study of these correlations is a valuable source of information on the character of the transitions and on the states between which these transitions occur.

The identification of the products of nuclear reactions, i.e. the determination of the values of A and Z of the final nucleus is a problem of primary importance in "in beam" spectroscopy . The identification consists chiefly of investigating the excitation functions, with the object to determine the energy of heavy ions corresponding to the maximum cross section for the process studied (HI , xn) .

When using a magnetic spectrometer as in the measuring system described in the present paper, an additional method based on the measurement of the distances between the lines of internal conversion electrons of the K and L shells may be used for the identification of the nucleus studied. This magnitude is related with the value of Z of the nucleus emitting the internal conversion electrons. The methods considered permit in many cases to determine precisely Z and A without the need for applying radiochemical or magnetic separation.

2. *Description of the Spectrometer*

An iron-free toroidal beta-spectrometer was used in the measurements of electrons from nuclei obtained in reactions with heavy ions. The application of this magnetic instrument (instead of a semiconductor detector) for studying internal conversion electrons provides for:

(a) Elimination of the continuous spectra of positrons, common among neutron-deficient nuclei, which hinder the investigation of the spectra of internal conversion electrons.

(b) Lowering of the background owing to that the detector is distant from the target.

The basic element of the toroidal spectrometer shown in Fig.2 is the magnetic lens composed of 32 sections (each of 50 coils) arranged uniformly on the circle and generating a toroidal magnetic field. In such a lens the magnetic field shows axial symmetry and decreases with the distance r from the spectrometer axis proportionally to 1/r (cf. Kofoed-Hansen et al.[7]).

The electron source (target) and the detector of electrons are positioned on the axis of the magnetic lens at its foci. The shape of the coil (based on the works by Tretyakov et al.[8], Burgov et al.[9]) was adjusted so as to obtain focusing of all electrons of a given energy, emitted from the target at angles lying in a given range (Fig.3).

The lens is placed in a vacuum tight (operational vacuum inside of about 10^{-5} mm Hg) steel chamber, which at the same time serves as a shield protecting from the interfering magnetic fields. Check experiment did not indicate any effect of the diffused field of the cyclotron or magnets shaping the beam, on the shape and position of ^{109}Cd conversion lines (E_K =62.2 keV, E_L =84.2 keV).

The construction of the spectrometer provides for rapid exchanging the source or target (without breaking the vacuum) as well as of the electron detector. Besides, measures have been taken to provide outside control of:

(a) Diaphragms which determine the azimuthal angle of an electrons emitted from the target.

(b) Diaphragms permitting to change the angle β at which the electrons enter the magnetic field (cf. Fig.3).

The spectrometer is fed from a standard system consisting of a D.C. generator and a current stabilizer (BT-4). The maximum current which may be supplied by this system is about 100A, and the

stability is of the order of 2×10^{-4}. To characterize the spectrometer, we should like to mention that electrons of an energy of 624 keV are focused at 16.6A. The current in the spectrometer can be controlled manually or automatically. In the latter case the current is changed either after a given period of time or after a definite charge of heavy ions has collected in the Faraday cup. The system permits to devide the adopted current range into 500, 250 or 125 current steps.

The basic parameters of the spectrometer are listed in Table 1.

3. *On-Line Beta-Ray Spectrometer*

3.1. Cooperation of the Spectrometer with the U-300 Cyclotron

The mounting of the spectrometer with respect to U-300 cyclotron as well as the beam transport system and the equipment for focusing the ion beam are shown in Fig.4.

The considerable distance (approx. 30 m) of the spectrometer from the accelerator provides for the lowering of the background and for the reduction of the effect of the dispersed magnetic field.

The ions leaving the accelerator chamber are passed through two separating and bending magnets and four pairs of quadrupole lenses before they reach the target located in the focus of the spectrometer. The ions having passed through the target enter the Faraday cup located behind a concrete wall (approx. 1 m thick). Directly before the spectrometer there is a wall which reduces the background due to the system of slits shaping the beam and due to heavy ions energy attenuator.

In Table 2 the parameters of the U-300 cyclotron are given (such as maximum ion energy and typical current values/ at the outlet/). If ions of lower energy are required, aluminium degrading foils placed before the last pair of quadrupole lenses QL are used (Fig.5). The aluminium foils are coated with a thin (approx. $0.1 mg/cm^2$) layer of carbon increasing the losses of heat by radiation. It improves the stability of foil to high ion currents.

Owing to the considerable distance between the cyclotron and the spectrometer and to the complexity of the beam focusing system the useful ion current entering the spectrometer is lower by a factor of about 10 as compared to that at the outlet of the cyclotron chamber. However, in view of the thermal stability of the target material, it is sometimes necessary to limit the current further. A system of quadrupole lenses (QL, QL_1, QL_2, QL_3 and two sets of movable slits placed behind the last pair of quadrupole lenses (QL) have been used for shaping the beam. The beam shape was controlled by introducing into the beam tube a quartz plate, which can be inspected on the cyclotron control desk owing to TV equipment. The intensity of the beam is monitored in two ways. For the use of the cyclotron operator the current from the Faraday cup is measured, whereas for determining the time of measuring the electron spectra, the ions scattered from the target are recorded. For this monitoring a semiconductor detector placed at an angle of 18° to the beam at 70 cm from the target is used.

3.2. Systems of Detection

A. Detection of Electrons

The system of detection consists of a detector, charge preamplifier, amplifier and single channel analyser (Fig.7). The standard pulse from the one-channel analyser is transferred to a multichannel analyzer and electronic scaler whose indications are automatically printed after the measurement has been conducted.

A semiconductor Si (Li) detector is used in the magnetic spectrometer for electron detection. The diameter of the detector is close to that of the electron focus in the beta-ray spectrometer and amount to 18 mm. The depletion layer of the detector is 3 mm thick. In order to reduce the noise level, the detector is cooled with liquid nitrogen. The considerable dimensions are decisive for that the resolution of the detector is about 10 keV.

The choice of the semiconductor detector operating here in a spectrometric mode was dictated by the specificity of "in beam" work. The good resolution of the detector made it possible to improve the effect to background ratio by selecting /using a one-channel analyzer/ only the part of the spectrum corresponding to the full loss of energy by the electron in the detector. This is illustrated in Fig. 6, where the spectrum from a semiconductor detector measured during irradiation of a ^{116}Sn target with ^{12}C ions is presented.

The spectrum from electron detector is taken in by the analyzer window 9V wide /what corresponds to approx. 40 keV in energy scale/. The effect to the background ratio is in the case of a 9V window five times larger than that when the window extends from 5 to 100V.

This points to the advantages resulting from applying by us an additional pulse height analysis of the spectrum from the semiconductor detector. However, this brings about the necessity of considering the variation of the efficiency of the system with electron energy. The monoenergetic electron spectra as measured using the semiconductor detector show a low-energy tail due to backscattered electrons (Fig. 6). When using the one-channel analyzer, only the line of "full energy" if recorded. The factor determining the ratio of the electrons counted in the window to all the electrons incident on the detector was found experimentally.

B. Heavy Ion Monitor

The heavy ion detection system consists of a semiconductor detector, charge preamplifier, threshold discriminator. The standart pulses from the discriminator are transferred to the pulse scaler (Fig. 7). The number of heavy ions recorded in this way determines the time of measurement.

3.3. Experimental Procedure

The electronic apparatus (Fig. 7) combined with the beta-ray spectrometer and U-300 cyclotron makes it possible to measure the electron spectrum and its time analysis. The beam incident on the target is a pulsed one; the cyclotron operates in time dependent mode producing current pulses with a duration of $\tau \approx 1.5$ ms, and frequency $\nu = 50$ to 300 cps.

The measurement of the spectrum of internal conversion electrons is performed as follows: the pulses from the electron detector are counted and at the same time subjected to time analysis (in a multichannel time analyzer) at a given current in the spectrometer and predetermined charge (number of heavy ions scattered from the target).

The pulses from the electron detector are transferred to one of the two channels, depending on whether they were generated during the current pulse of the cyclotron or in the interval between the beam pulses.

After a predetermined number of pulses due to heavy ions scattered from the target has been collected by the monitor, the recording of electrons is interrupted, the information collected is recorded by a printing machine, the current in the spectrometer is increased by a strictly defined increasement upon which the apparatus is made ready for a subsequent measurement. After an elapse of approx. 7 sec from the end of the former measurement (time sufficient for fixation of the current in the beta-ray spectrometer) the subsequent measurement is started automatically.

In this way it is possible to:

a) measure the electron spectra during the cyclotron beam pulses,
b) measure the electron spectra in the intervals between beam pulses,
c) perform multichannel time analysis.

The spectrum of internal conversion electrons measured in the intervals between the heavy ion beam pulses provides informa-

tion on the "slow" transitions (in beta decay or in isomeric state decay). On the other hand, the spectrum obtained during the beam pulses provides additional information on "prompt" transitions (i.e. decay of states with $T_{1/2} < 1$ ms) and contains components of "prompt" and "slow" transitions.

The multichannel time analysis performed during the measurement of the spectrum, or separately for selected parts of the electron spectrum, allows the determination of the level life-time.

Under normal operating conditions the U-300 cyclotron gives current pulses of $\tau \approx 1.5$ ms duration and frequency $\nu = 50$ to 300 cps.

In this mode of operation when performing time analysis the width of the channel of the time analyzer ranges from 0.2 to 2 msec. To provide for the measuring longer life-time, an external system has been constructed for the control of the time regime of the cyclotron. This system makes it possible to increase the time of irradiation to $\tau \approx 10$ msec - 100 sec, and the ratio of the time interval between the beam pulses to the time of irradiation may be controlled in the range of 1-10. The width of the time channel in this mode of operation varies from 1 msec to 10 sec, and the number of time channels is 2, 4, 8, 16, ..., 256.

The targets (Fig. 8) used in our experiments are either self-supporting foils approx. 3 mg/cm^2 thick, or consist of a layer of substance approx. 1 mg/cm^2 thick deposited on 5 μ aluminium foil. The metal foils of small quantities of separated isotopes were obtained by rolling/10/. The surface of the target is at an angle of 30^0 with respect to the beam. This angle is a result of a compromise between the following two requirements:

(1) The effective thickness of the target with respect to outcoming emitted electrons and heavy ions should be possibly small, but at the same time,

(2) The effective thickness should be sufficiently high to stop the recoil nuclei, which is particularly significant when isomers are studied, since then the activity should remain in the target.

4. Results

The reduction of the background (due to gamma radiation and neutrons) is one of the basic technical problems involved when using an "in beam" spectrometer. This problem is particularly pronounced when "prompt" transitions are studied, that is when the measurements are taken during the heavy ion beam pulses. In our case the background has been largerly reduced by placing the spectrometer at a considerable distance from the systems which may be the source of such background (slits, degradator, Faraday cup), and by constructing thick concrete shields. A further factor contributing to the reduction of the background is the energy analysis of the spectrum from the electron detector which has already been mentioned in section 3.2. A).

The spectrum of the background observed when a beam of heavy ions passes through the spectrometer is shown in Fig. 9a; and in Fig. 9b the ratio of the expected effect to the background is presented (in arbitrary units). The calculations were made for E2 transitions in xenon under the assumption that the conversion takes place at the K shell.

It follows from Fig. 9b that the low-energy range is most suitable for "in beam" measurements of internal conversion electrons.

In Fig. 10 a spectrum of internal conversion electrons for "prompt" transition from the excited states in ^{124}Ba is presented. This nucleus was obtained in the $^{116}Sn(^{12}C, 4n)^{124}Ba$ reaction, the energy of the bombarding ions being about 83 MeV. The self-supporting target approx. 3 mg/cm^2 thick used in this case was made of tin enriched in the isotope with A = 116 up to 93%. The lines observed in the spectrum correspond to transitions in the "quasi-rotational" band. For instance, the 576 keV line corresponds to the transition from the level 6^+ to the level 4^+. If we compare the internal conversion spectrum with the gamma spectrum obtained from the Ge(Li) counter/11/, it may be seen that effect to background ratio is in the case of the beta-ray spectrometer several times as high as that for the

Ge(Li) counter, especially in the range of low-energy electrons.

In Fig. 11 the spectrum of internal conversion electrons as measured in the intervals between the beam pulses is shown. Actually, it is the spectrum obtained for the decay of the ^{135}Ce isomeric state/12/. The isomeric state (with $T_{1/2}$ = 20s) was produced in this nucleus in the ^{128}Te(^{12}C,5n) ^{135}Ce reaction. The target was obtained by depositing a Te layer 1 mg/cm^2 thick on 5 μ aluminium foil. The spectrum was measured in the electron energy range of 35-340 keV.

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References

1. H.Morinaga, P.C.Gugelot. Nucl. Phys., 46, 210 (1963).
2. D.Ward, F.S. Stephens, J.O. Newton. Phys.Rev.Lett., 19, 1247(1967).
3. M.G.Betigeri, H.Morinaga. Nucl. Phys., A95, 176 (1967).
4. F.S.Stephens, N.L.Lark, R.M.Diamond. Nucl. Phys., 63, 82(1965).
5. G.Bertram Hansen, B.Elbek, K.A.Hagemann, W.F.Hornyak, Nucl. Phys., 47, 529 (1963).
6. R.M.Diamond, E.Matthias, J.O.Newton, F.S.Stephens. Phys.Rev. Lett., 16, 1205 (1966).
7. O.Kofoed-Hansen, J.Lindhard, O.B.Nielsen. Mat.Fys.Medd.Dan. Vid.Selsk., 25, No 16, 1950.
8. E.F.Tretyakov, L.L.Goldin, G.I.Grishuk. PTE, 6, 22 (1957).
9. N.A.Burgov, A.V.Davydov, G.R.Kartashov. Nucl.Instr. and Meth., 12, 316 (1961).

10. Frank J.Karasek. Nuclear Science & Engineering., 17, 365 (1963).
11. Jack E.Clarkson, R.M.Diamond, F.S.Stephens, I.Perlman. Nucl. Phys., A93, 272 (1967).
12. Z.Wilhelmi, Ch.Droste, J.Lewitowicz, T.Morek, S.Chojnacki. JINR Preprint, P6-4499, Dubna 1969.

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Table 1

Basic parameters of the electron spectrometer

Parameter	Value
Parameter b*	0.67
Focal length, f	500 mm
Number of coils	1600
Number of sections	32
Width of the coil, d	40 mm
Range of angles	45°-60°
Asimuthal angle under "in beam" operation	90°
E_{max} of the focused electrons	3 MeV
Transmission	2%
Resolution	1%
Target diameter	15 mm

* The parameter b is defined as follows:

$$b = p.c. / 0.2n. I,$$

where p -electron momentum, c -velocity of light, n -number of coils, I -current intensity.

Table 2

Basic parameters heavy ions with cyclotron U-300

Heavy ions	$^{10}B^{+2}$	$^{11}B^{+2}$	$^{12}C^{+2}$	$^{15}N^{+3}$	$^{18}O^{+3}$	$^{20}Ne^{+4}$	$^{22}Ne^{+4}$	$^{40}Ar^{+6}$
E_{HI}^{max} MeV	100	91	83	150	125	200	182	225
I cycl. [μA]	6	6	20	5	10	5	6	5

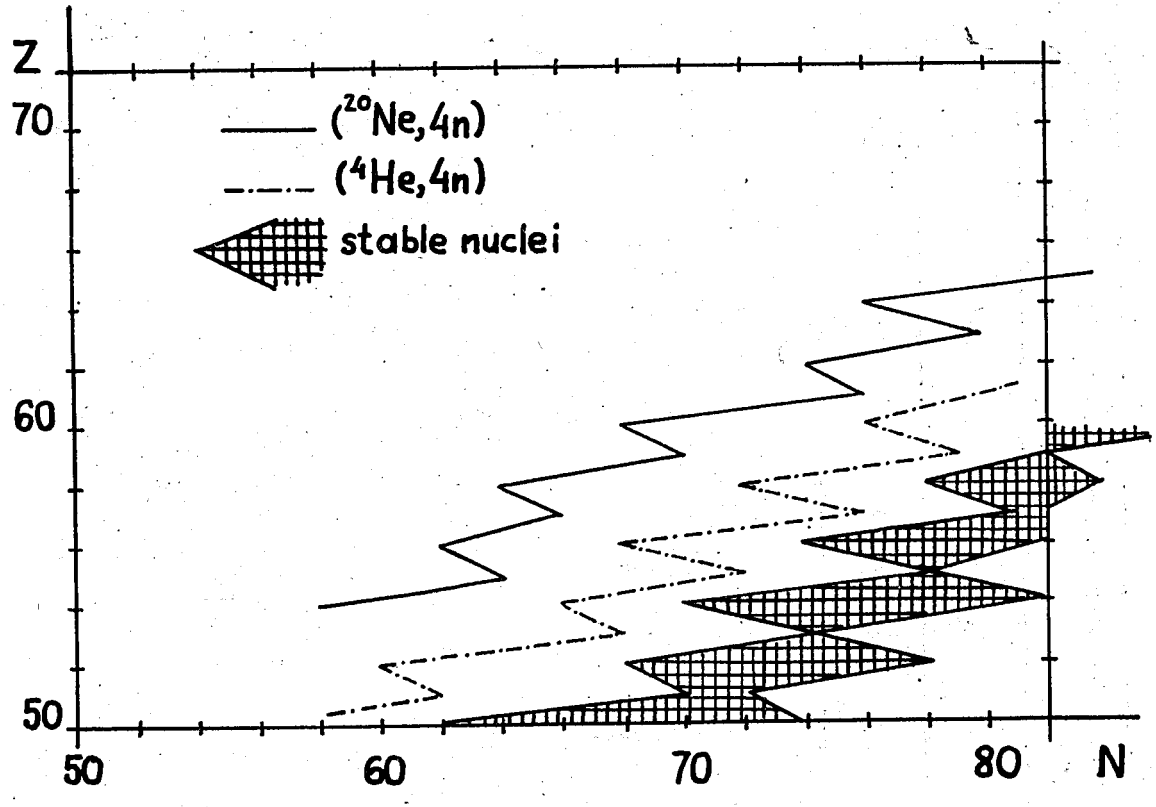

Fig. 1. Nuclei in the region of $50 < Z < 82$, $50 < N < 82$ which could be obtained by using heavy ions.

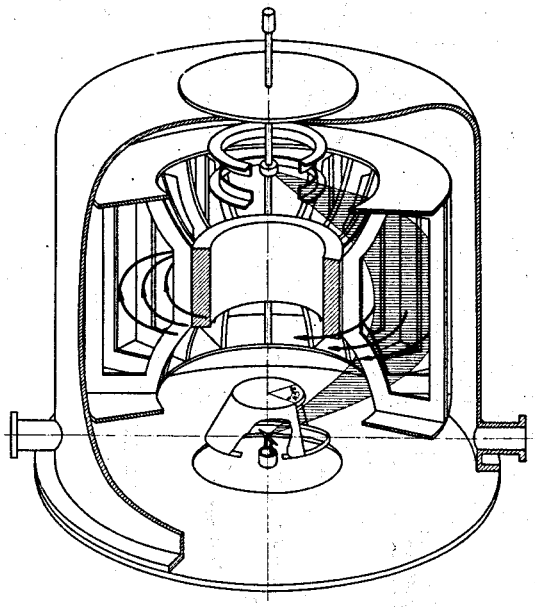

Fig. 2. Schematic view of toroidal β-spectrometer.

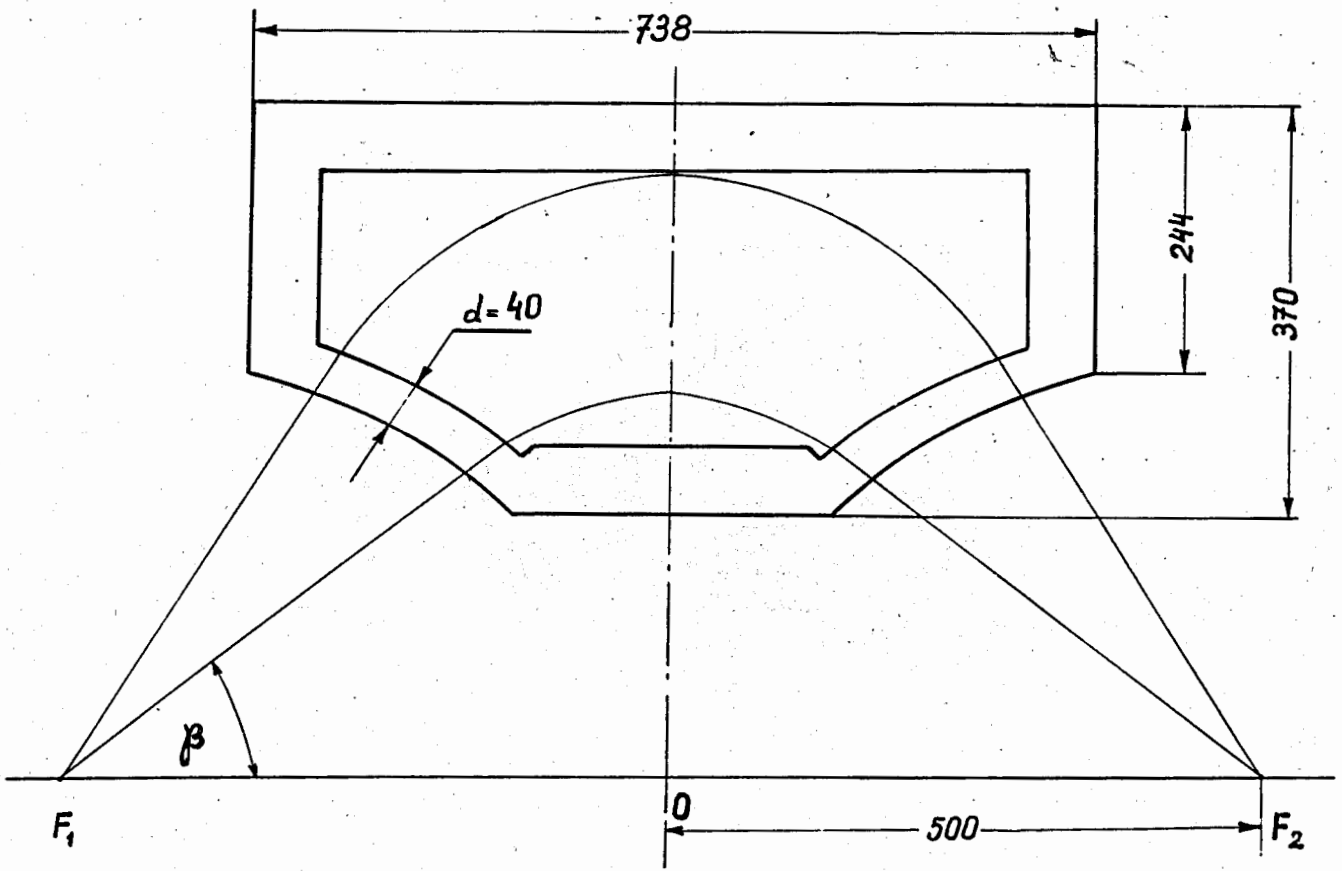

Fig. 3. Shape of β-spectrometer lens coil.

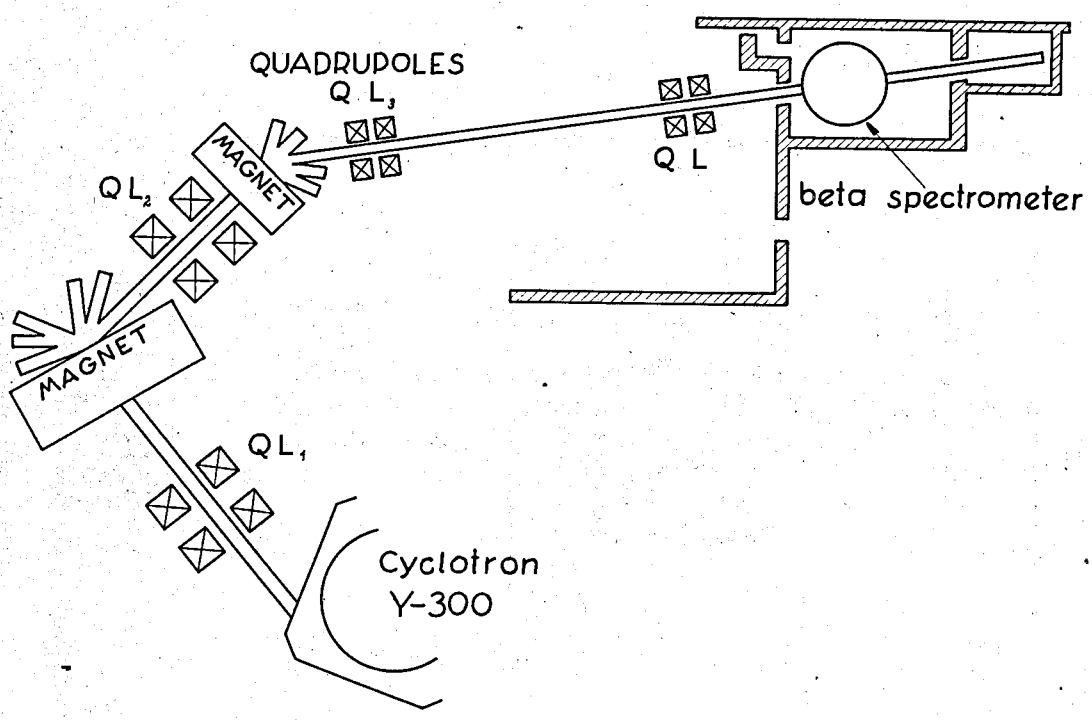

Fig. 4. Disposition of beam transport system and setups focusing the ion beam about the cyclotron U-300.

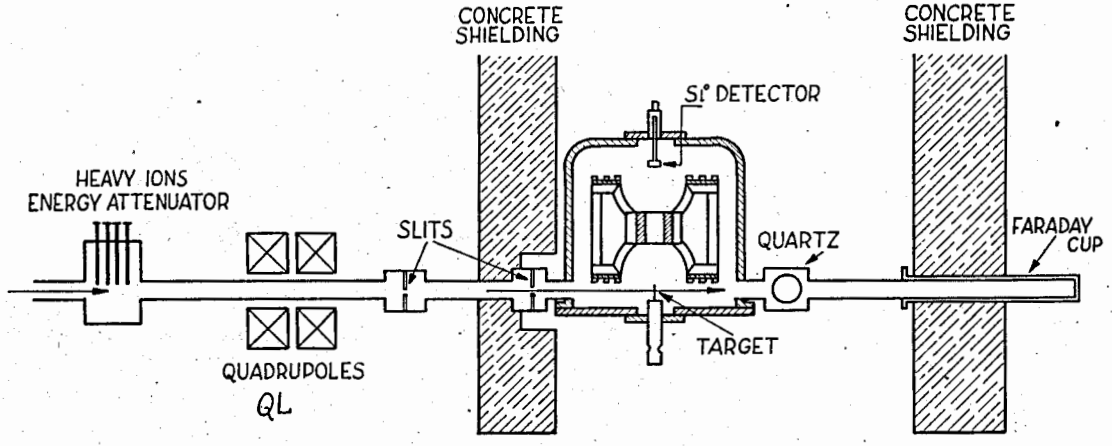

Fig. 5. Schematic view of the magnetic spectrometer "on beam".

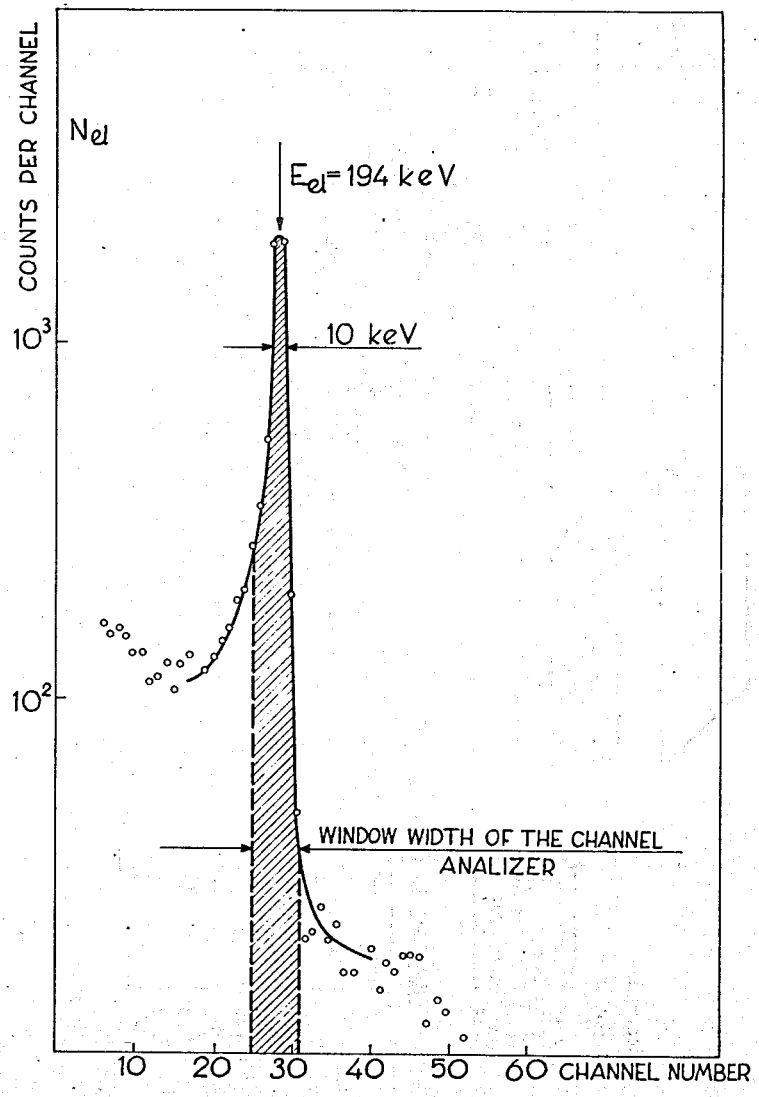

Fig. 6. Spectrum from the semiconductor detector obtained in the bombardment of ^{116}Sn by ions of ^{12}C .

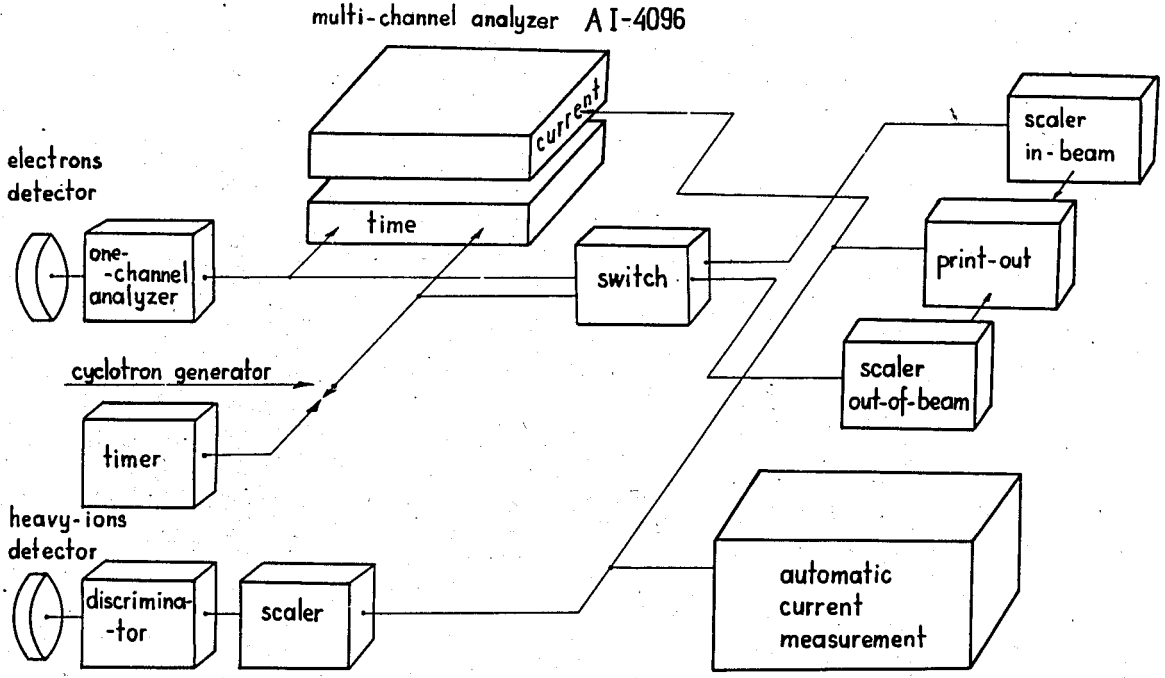

Fig. 7. Block diagram of electronic setup operating in cooperation with the β -spectrometer and the cyclotron U-300.

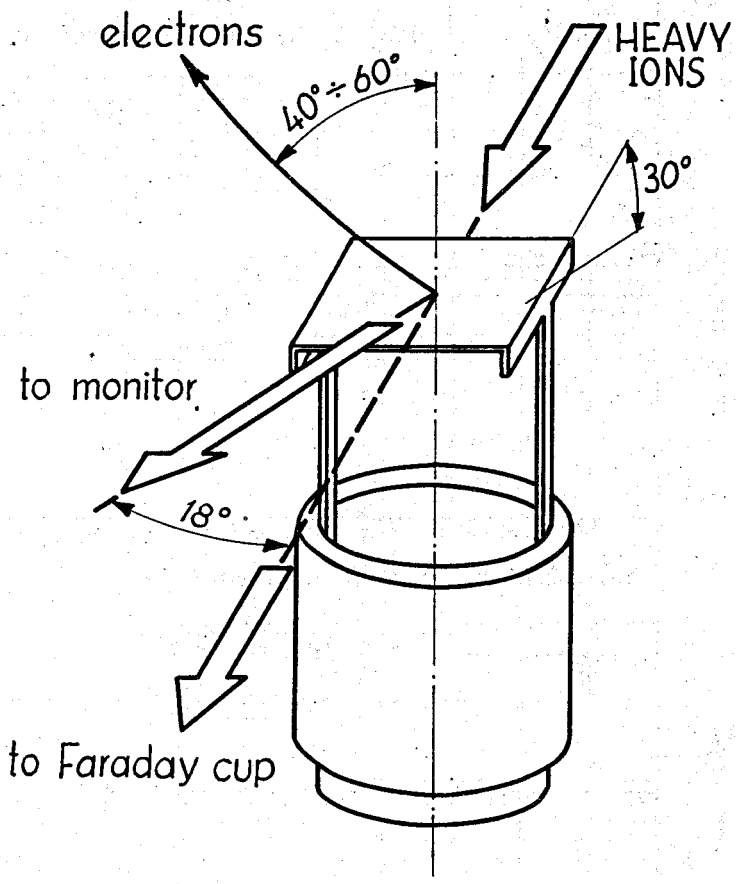

Fig. 8. Target applied for electron spectrum measurement.

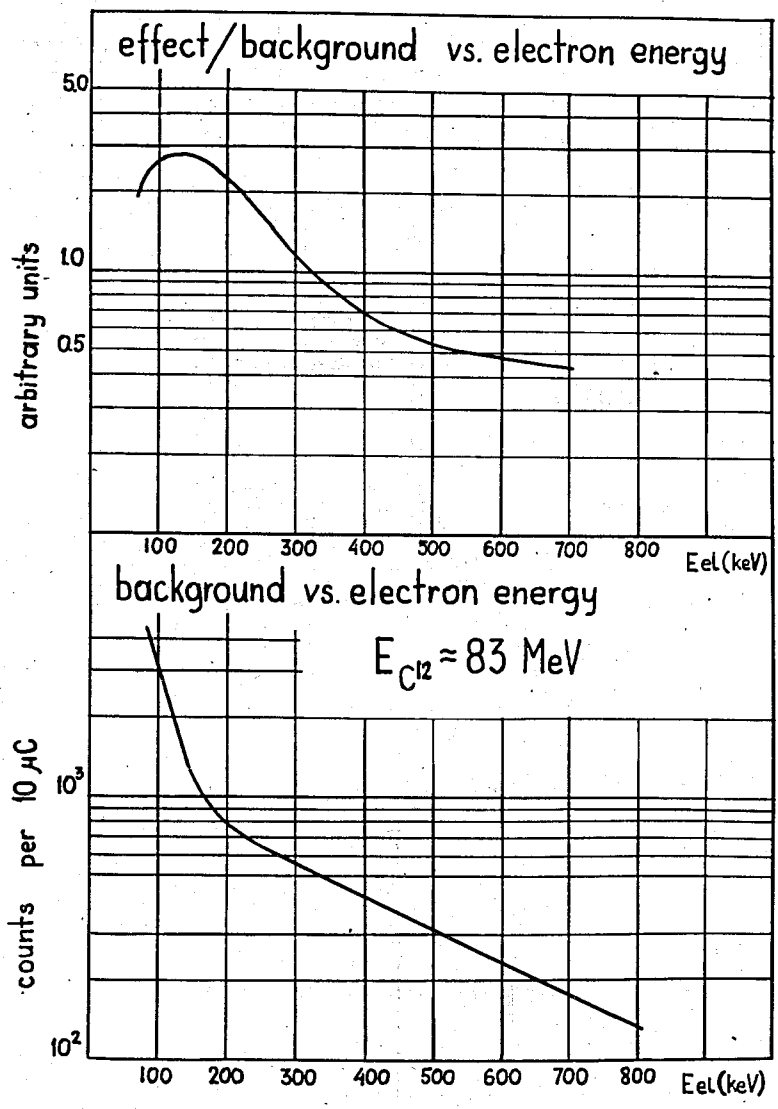

Fig. 9. a) Background spectrum observed in passing of the ^{12}C ion beam through the spectrometer.
b) Ratio of expected effect to the background.

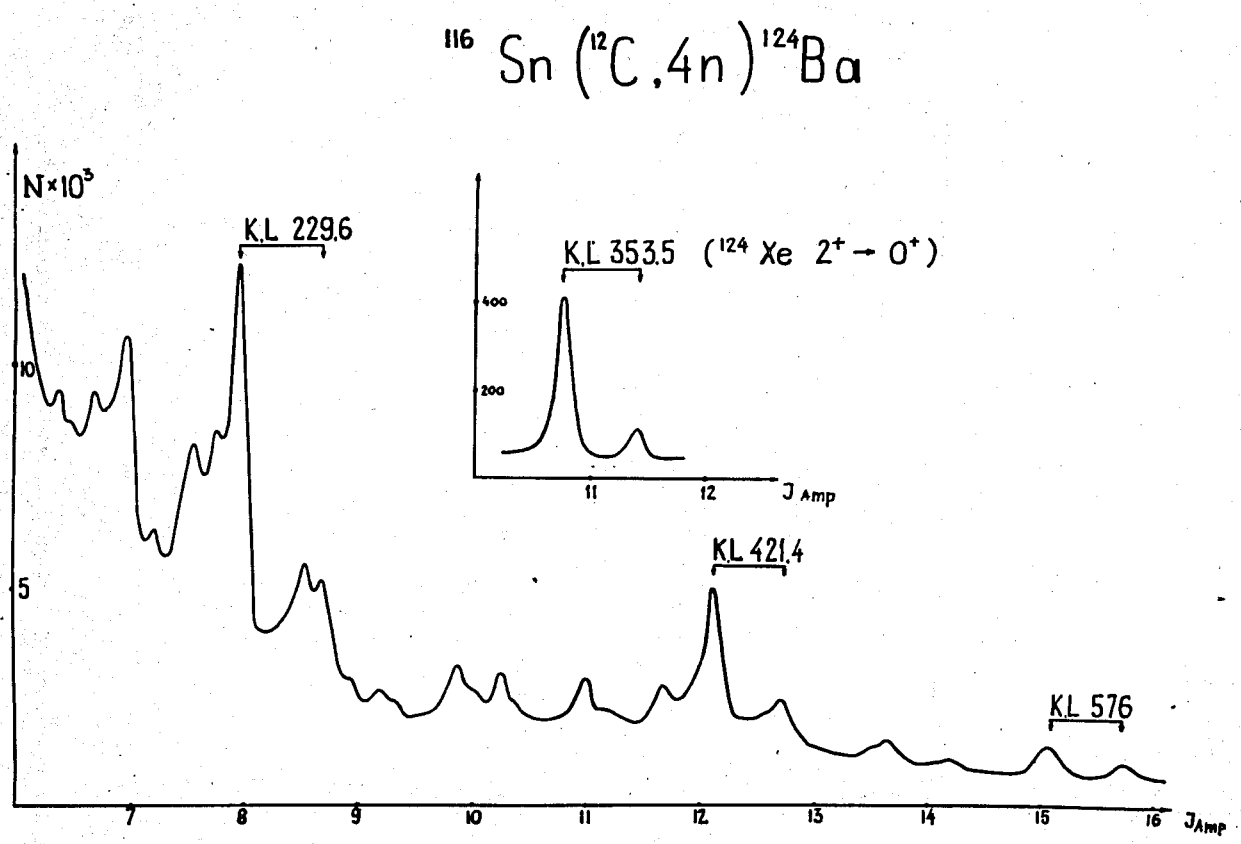

Fig. 10. Internal conversion electron spectrum of transitions from excited states in ^{124}Ba .

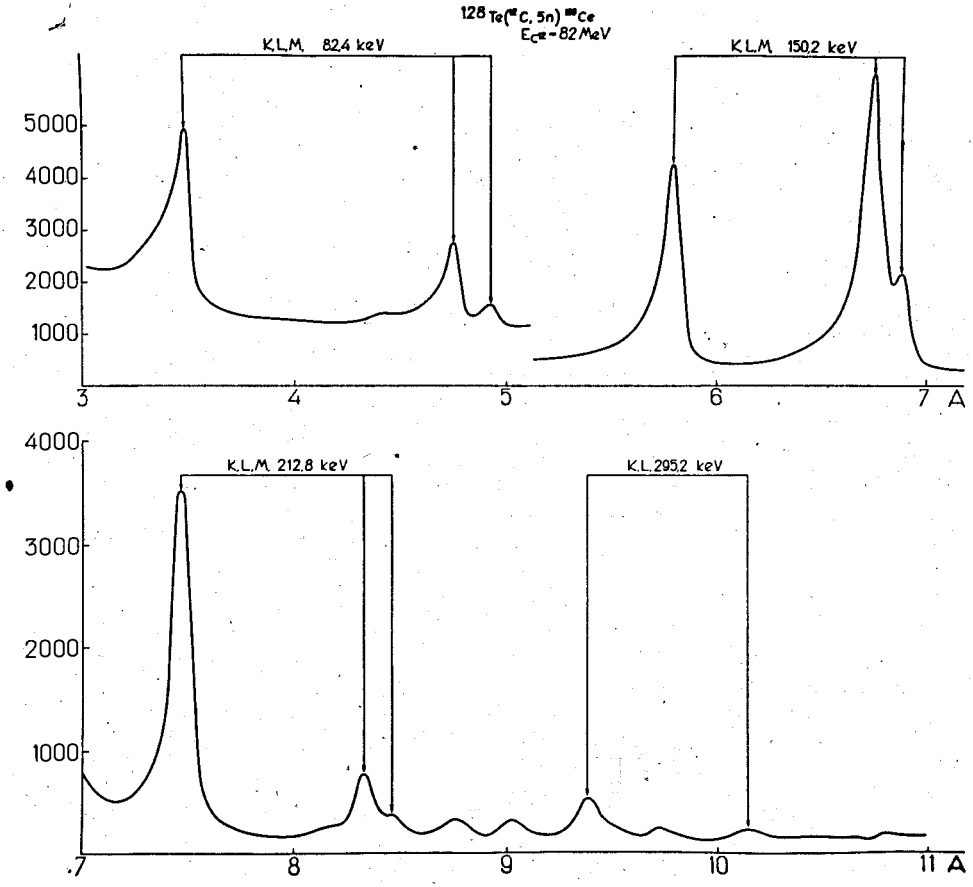

Fig. 11. Internal conversion electron spectrum of the isomeric transitions in ^{135m}Ce.