ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
СО АН СССР

EXPERIMENTS WITH AN INTERNAL TARGET IN THE STORAGE RING OF CHARGED PARTICLES

S.G.Popov

ПРЕПРИНТ 81-122

Новосибирск

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S.G.Popov

Institute of Nuclear Physics,
630090, Novosibirsk,USSR

I. INTRODUCTION

Experiments on the interaction of electrons with the various, more complex objects, including atomic nuclei, continue to rouse interest due to the comparatively simple interpretation of data. The development of this metodics in the direction of increasing an experimental accuracy, obtaining more complete information on the objects under study as well as widening the range of the used energies (it is noteworth that the interest for the low and medium energies does not decay and even grows). This is evidenced by that in the last years numerous projects of the devices have become available which extend the possibilities of the existing sources of accelerated electrons (or those under construction), for example, modern high-current linear accelerators /1/.

The matter is that the operation of detection apparata under the conditions when the concentrated-in-time beam interacts with the target is substantially complicated in comparison with the case of using the continuous-in-time beam. In a number of cases one has to lose in the mean intensity, that reduces the rate of accumulating statistics and eventually an accuracy of the experi-

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* Talk presented at the Vth Seminar on Electromagnetic Interac~~tions of Nuclei at Low and Medium Energies, Moscow,~~ June 15-17, 1981.

ment. These losses are so essential that the authors suggest rather high expenses for building up special cyclic devices, stretchers, to be justified. These devices convert the particle beam of large duty factor to the practically continuous-in-time beam, though, with unavoidable losses in the mean intensity and phase density of the beam. It is important that under such an arrangement of the experimental apparata all the experience concerning the experimental setup on linear accelerators remains commonly used and, hence, is usable in this particular case.

In the present paper we discuss the possibilities of the method when the target is located directly on the track of the cyclic device-storage ring. In principle, the latter is comparable, in its functions, with a stretcher and provides some unique additional experimental possibilities.

II. Using an Internal Target in a Storage Ring

It is clear that the repeatedly intersected internal target in a storage ring must have a very small thickness. For example, it can be a gas jet with a pressure of the order of $10^{-1} \div 10^{-2}$ Torr. At first glance, the reaction yield seems to be very low. To describe this characteristic of the device, it is convenient to introduce the luminosity L defined as follows:

$$N = L\cdot\sigma \qquad (1)$$

where N is the counting rate for the process with the cross section σ. For a conventional experimental setup with the emitted beam $L = n\cdot J$, where n is the target thickness (cm^{-2}) and J is the beam intensity (particles per sec.). For a carbon target of 100 mg/cm^{2} thickness in the accelerator with the 100 μA mean emitted current the luminosity exceeds 10^{37} cm^{-2}sec^{-1}.

In calculating the luminosity for the internal target in a storage ring the average vacuum, along the trajectory of the beam, is assumed to be determined by the target, i.e. the particle losses are determined by the interaction with the nuclei and the electrons of the target. If one introduces σ_n, the total, for all the processes, effective cross section of the interactions determining the particle losses, it is obvious that the counting rate of the process with the cross section σ will be

$$N = J\cdot\frac{\sigma}{\sigma_n} \qquad (2)$$

where J is the mean injection rate of particles into the storage ring, i.e.

$$L = \frac{J}{\sigma_n} \qquad (3)$$

It is seen from the comparison of this expression with the foregoing one that the role of a target thickness is played here by the quantity $\frac{1}{\sigma_n} = n_{eff}$ and this expression does not include the actual target thickness because the effective thickness is a product of the target thickness by the mean number of its intersections by each particle. It is clear that the number of intersections is inversely proportional to the target thickness. Another interpretation of this paradox consists in that the lifetime of the particle decreases (increases) proportionally with increasing (decreasing) the target thickness and, hence, the stored and circulating in the storage ring current is much higher, in magnitude, than the injected one.

III. Realisation of the Super-Thin Target Regime in an Electron Storage Ring

The main processes which determine the particle losses in an electron storage ring are: the simple and multiple scattering of electrons from the nuclei of the target at the angles larger than those permissible by the aperture of the storage ring, ionization losses and the bremsstrahlung. In taking into account the multiple energy losses one has to bear in mind that a r.f. cavity in the storage ring makes up for the mean energy losses. In view of this, significant become only the fluctuations of ionization losses, bremsstrahlung and synchrotron radiation, which eventually contribute to the lifetime and energy spread of the beam.

Availability of the magnetobremsstrahlung (synchrotron) radiation in an electron storage ring, which results in the appearance of the damping of oscillations for all degrees of freedom, influence essentially the various multiple processes. If, for example, the target thickness is so small that during the time of damping the betatron oscillations as a result of the multiple scattering on the target nuclei, the transverse dimension does not achieve the admissible sizes, then this process does not contribute to the lifetime and one can speak only of the stationary transverse size of the beam (the angular spread). Also, the said above concerns the appearance of the stationary energy spread due to the mentioned above mechanisms of energy losses (to be true, due to the fluctuations of these losses).

In the present paper such a regime of operation is referred to, in contrast to the thin target regime, as the super-thin target regime. In this case, in the sum of the processes, (eq.(3)), determining the luminosity of the device the multiple processes should not be taken into account and, hence, the luminosity, generally speaking, increases with decreasing the target thickness in the transition to the super-thin regime of operation.

This transition (from the thin target regime to the super-thin target one) is observable when changing the magnitude of the limiting scattering angle, for example, artificially diminishing the aperture of the storage ring. In Fig.1 the yield of bremsstrahlung "monochromatized" ("tagged") γ-quanta (by coincidence with the electron which has lost its energy) in the narrow range of energies is plotted as a characteristic of the luminosity. Measurements have been carried out at the VEP -1 facility /2/ at an energy of 100 MeV. All the curves in this figure are the calculated ones (I is for the limiting value of intensity for $n_{eff} = 0.15\, X_0$; II is for the thin target regime; III is for the super-thin target; IV stands for the transient curve for the case under description), the experimental values are for the thin target regime (aluminium foil) and for the transient regime (quartz thread). The transition from the thin target regime to the super-thin target one is crearly observed. Fig.2 shows the calculated energy dependence of the luminosity for two regimes of operation. The calculation has been made for the VEPP-2 facility with the oxygen target. Curve I corresponds to the limiting (with respect to the bremsstrahlung cross section) effective target thickness, curves II and III to the thin and super-thin target regimes for this facility. At high energies these luminosities become equal and energy-independent because σ_n (3) is determined by the bremsstrahlung cross section being practically independent of the energy. All comments on the angular and energy parameters of the beam hold in this case, too. On the ordinate axis the quantity $\frac{1}{\sigma_n} = \frac{L}{J} = n_{eff}$ is plotted. For the region determined by the bremsstrahlung it is equal to 0.15-0.2 rad unit length. Mention should be made of

Fig.1.

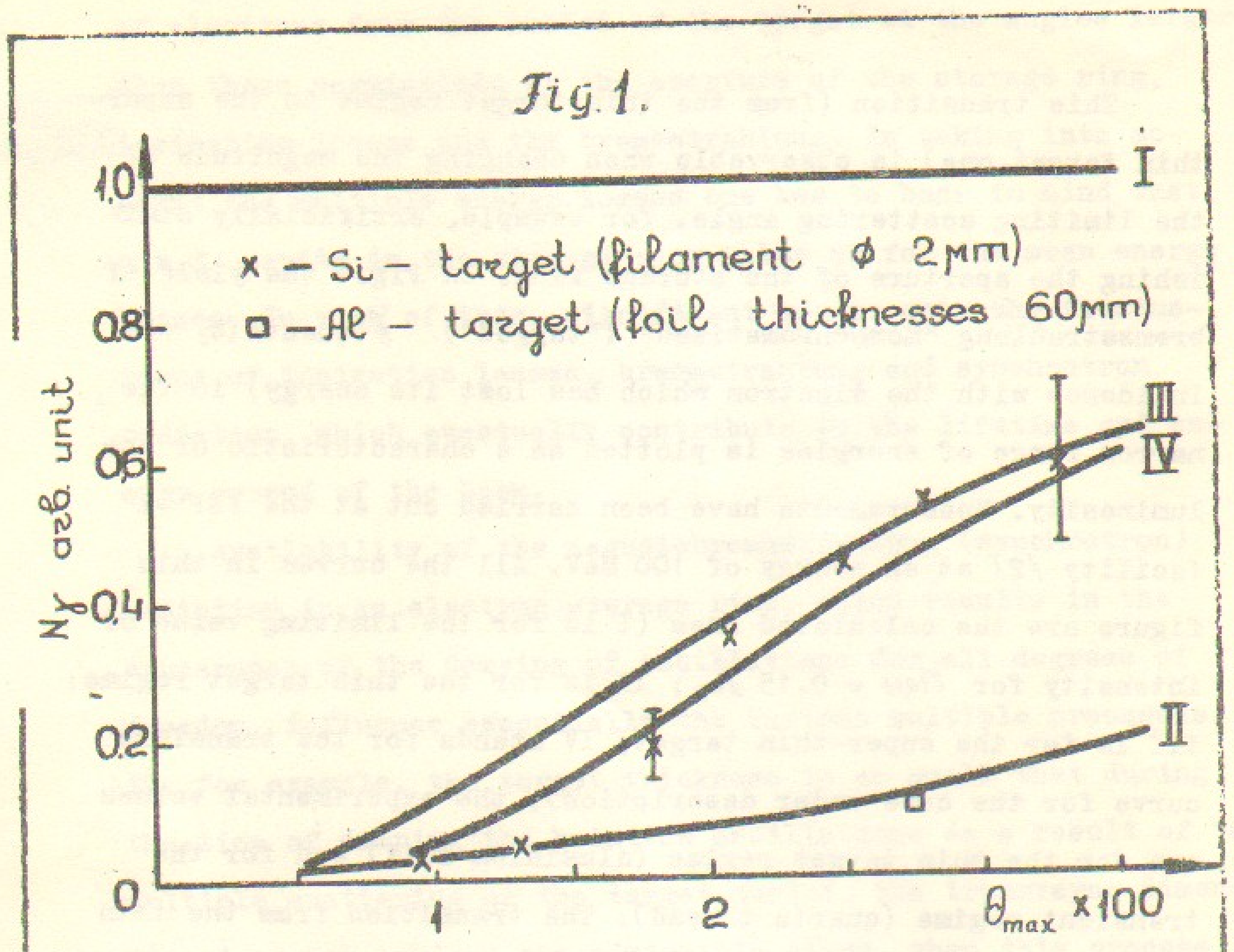
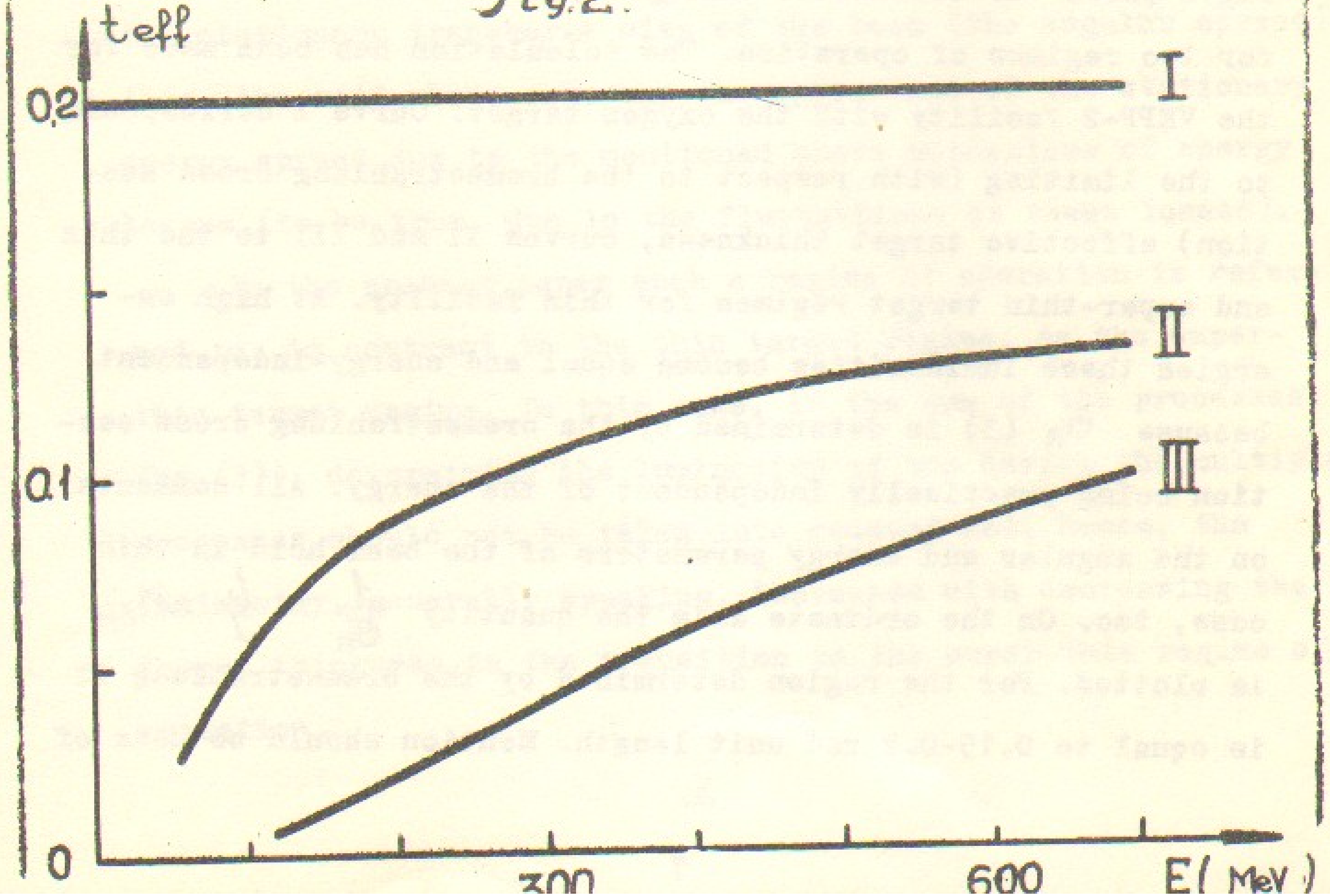


Fig.2.



that the thin target regime has been partially realized in the experiments of Nikitin et al. /3/.

IV. Specific Features of the Super-Thin Target Regime

If one assumes that the whole injected (from the linear accelerator) beam is utilized in the storage ring (like it is supposed to be in the stretchers), then at sufficiently high energies the formal luminosity of the device is equivalent to the luminosity of the corresponding linear accelerator with a target of 0.2 rad unit length. Usually, much thinner targets are used. Moreover, an increase in the energy accuracy requires, as a rule, not only an increase in the thickness of a target but an increase in the intensity because a part of the energy spectrum of the particles is isolated at the accuracies better than 1%. In the storage ring the relative energy spread is of the order of 10^{-3} (at an energy of several hundreds of MeV) and grows linearly with increasing the energy.

Realization of such a high luminosity in a storage ring with the internal target faces purely accelerator difficulties since a high current must be stored in the ring. In the actual experiments described below the device's luminosity was 10^{33} + 10^{34} cm^{-2} sec^{-1}. However, a specialized facility would allow this parameter to be approached the calculated one.

A more detailed description of possible characteristics of the beam (sizes, angular and energy spreads) requires taking into account the concrete parameters of a storage ring. The matter is that the modern devices have a few "degrees of freedom" for optimizing the experimental conditions with respect to the parameters mentioned above. For example, the angular spreading has a little influence on the luminosity if the target is located in the place where the beta-function is small. The increased Ψ-function reduces, in a given azimuthal direction, both the energy spread of a storage ring and its luminosity if the latter is determined by energy losses and so on.

Thus, one can summarize the following specific features of the operation of a storage ring with the internal target used in the super-thin regime:

a) practically continuous regime of operation;

b) high luminosity at a high experimental accuracy; it is noteworth that the possibilities of modern accelerators enable one to increase substantially the experimental energy resolution compared with the energy spread in the beam /13/ by measuring the coordinate of the outgoing electron, the beam is formed with a given coordinate dependence of energy deviation;

c) the convenient possibility of detecting the secondary particles (including the slow ones) due to a small thickness of the target and the continuous-in-time operation regime;

d) the possibility of using unique targets (for example, gas polarized jets) and unique stored beams (for example, positrons, antiprotons, polarized electrons /4/).

V. First Experiments in the Electron Storage Ring

In the Nuclear Physics Institute (Novosibirsk) a series of experiments on studying the electron interactions with nuclei at 100-130 MeV initial electron energies have been carried out with the use of the methods described above and in the range of 55°-125° angles /6,7/.

The continuous regime of operation made it possible to use spark chambers in the magnetic electron spectrometer /8/ which was substantiated for the proportionally drift ones later on. As a result, the measurements were carried out simultaneously in a wide energy interval from $E_{max}/2$ to E_{max}. The solid angle of the spectrometer is about 10^{-2} sterad, the energy resolution is 150-200 keV (FWHM).

Measuring the inelastic formfactors and even the elastic one /6/ is substantially simplified when using a spectrometer with a large energy acceptance and hydrogen-content targets because there appears a convenient monitoring to the electron-proton scattering peak whose formfactor is well known within a wide range of the momentum transfer.

In addition, the storage ring contains the telescopes of semiconductor detectors and the NaI(Tl) counters for detection, identification and energy measurement of the secondary particles by coincidence with the electron. Fig.3a shows the inclusive spectrum of the electrons scattered by the H_2O target. Figs.3b and 3c show the electron spectra by coincidence with the secondary particles detected by semiconductor detectors (the solid angle is $5\cdot10^{-2}$ sterad) located in the vicinity of the direction of the momentum transfer and the NaI detectors (the solid angle is 0.3 sterad) located in the opposite direction. The detection thresholds for charged secondary particles are 1.5 and 5 MeV, respectively. In front of a NaI counter there is a layer of substance (60 mg/cm^2) practically not transmitting α and heavier particles with possible, in our case, energies. Arrows in the figure denote the known peaks in the giant dipole resonance region and, at the lower energies of excitation, the resonances with quantum numbers 2^+, whose intensity is enhanced in the

Fig. 3.

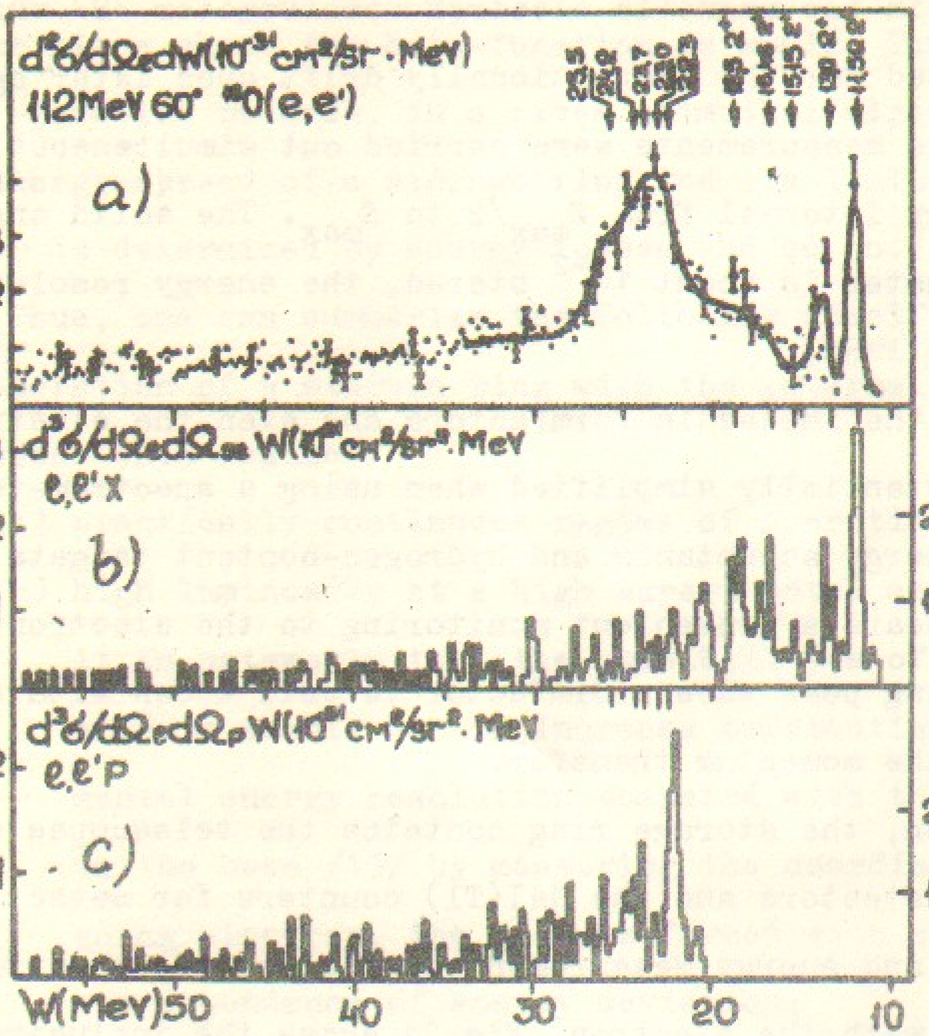
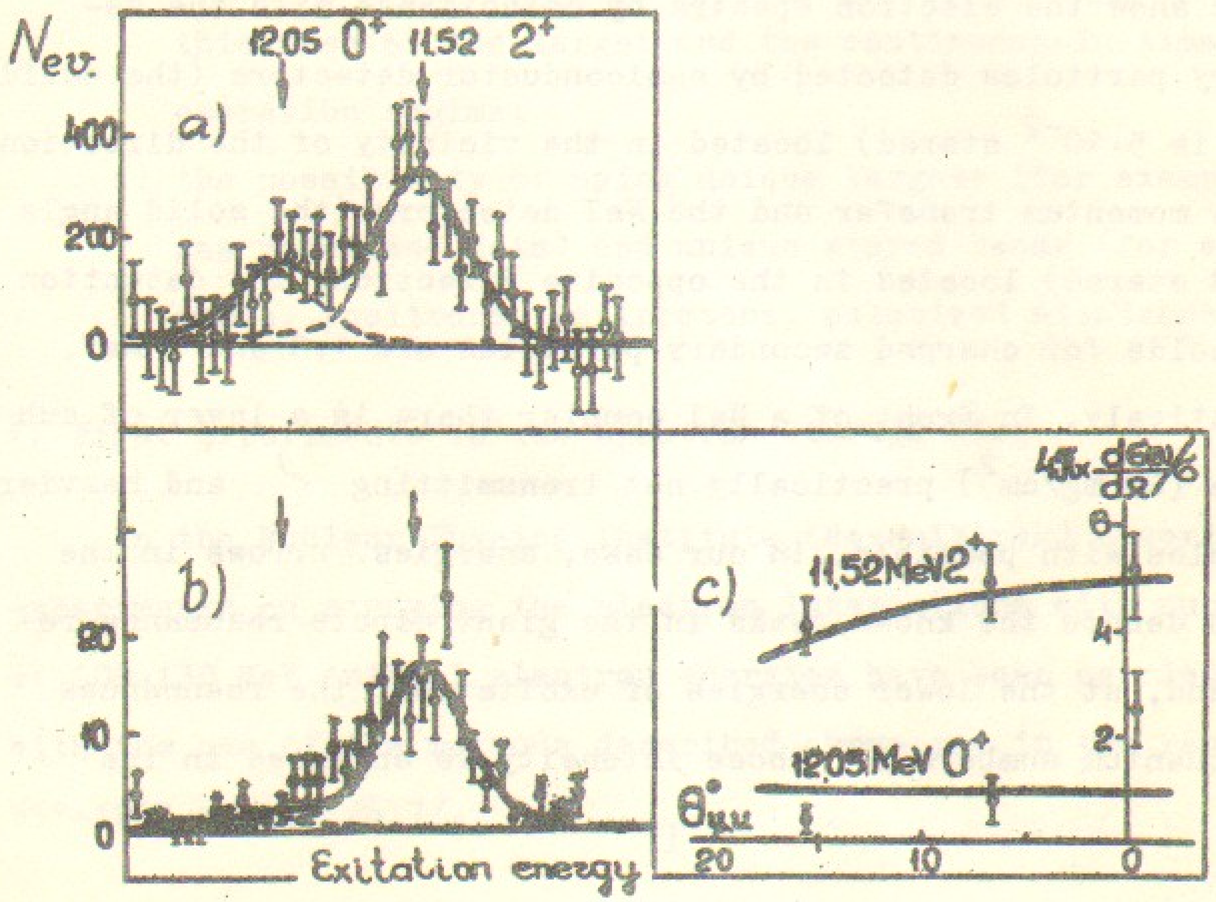


Fig. 4.



spectrum of Fig.3b due to the angular distribution. As an illustration, the simplest analysis of the intensities and the angular distribution of the α-particles emitted from the 11.52 and 12.08 MeV levels makes it possible to find their formfactors and quantum numbers (2^+ and 0^+, see Fig.4) /4/.

This figure demonstrates a relative enhancement of the level 2^+ compared to the level 0^+ (case b corresponds to the coincidence with secondary α-particles). Case c shows the angular distributions of the α-particles from these levels.

An analysis of the experimental data on excited levels which have a possibility of decaying through several channels enables one to verify the assumptions concerning the mechanisms of decaying the excited nuclear states and to test the probability of quasi-elastic knocking out of particles or clusters.

Subtracting, with a high precision, the elastic and inelastic formfactors requires a sufficiently accurate taking into account the radiative corrections /10,7/.

Measurements of the radiative corrections in the elastic electron-proton scattering /10/ (that is shown in Fig.5) confirm the validity of the calculations made by B.Serbo et al. /16/ at least up to the 0.1 inelasticity. Fig.6 shows the spectrum of recoil protons detected by coincidence with the electrons which have lost a fraction of the energy for radiation. Obvious is the possibility of separating the processes with radiation by the electrons of the γ-quantum before and after scattering (two-bump structure of the spectrum).

Apparently, the possibilities of the method are most strickingly illustrated by the planning experiment on measuring the quadrupole formfactor of the deuteron /11/. The fundamental character of the information sought for is beyond question. How-

Fig 5.

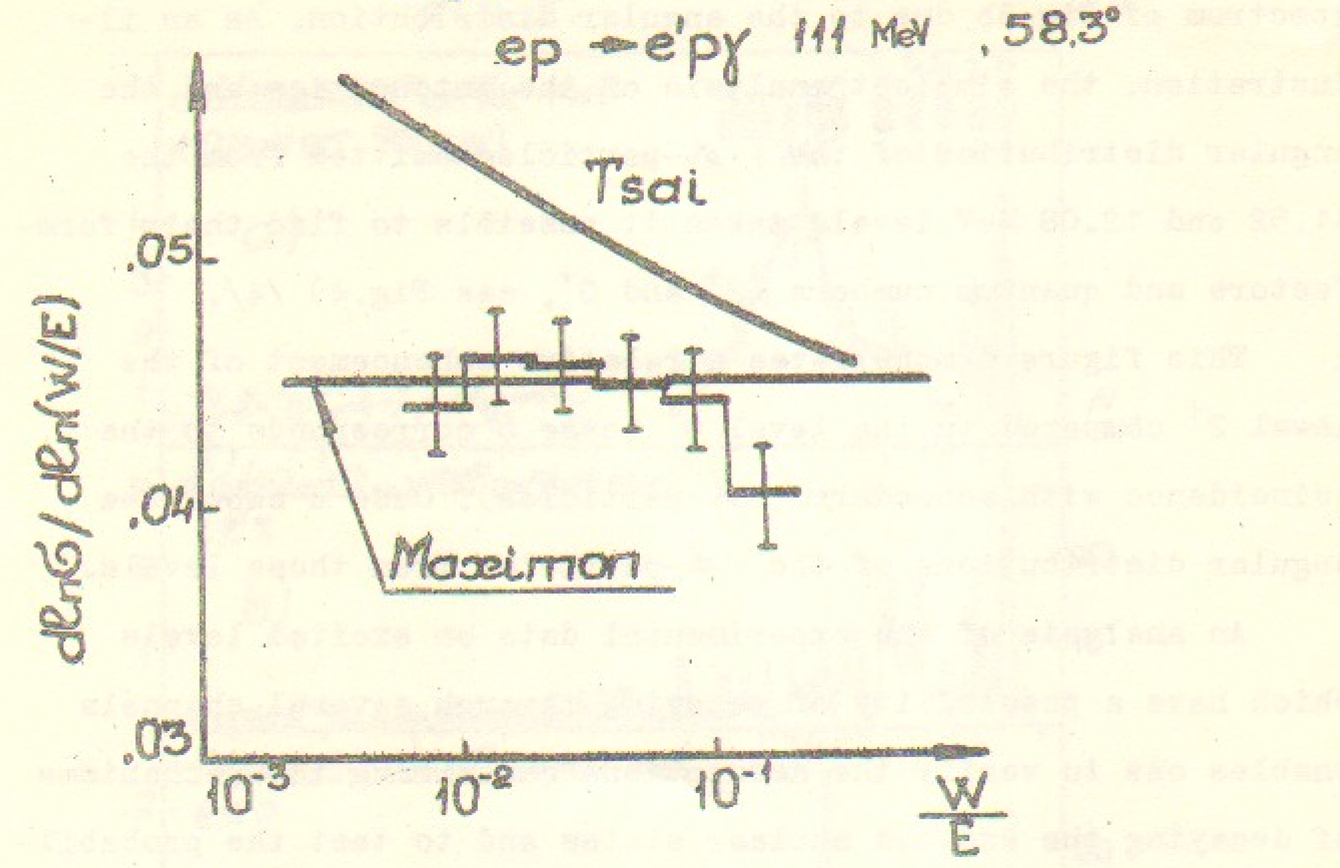
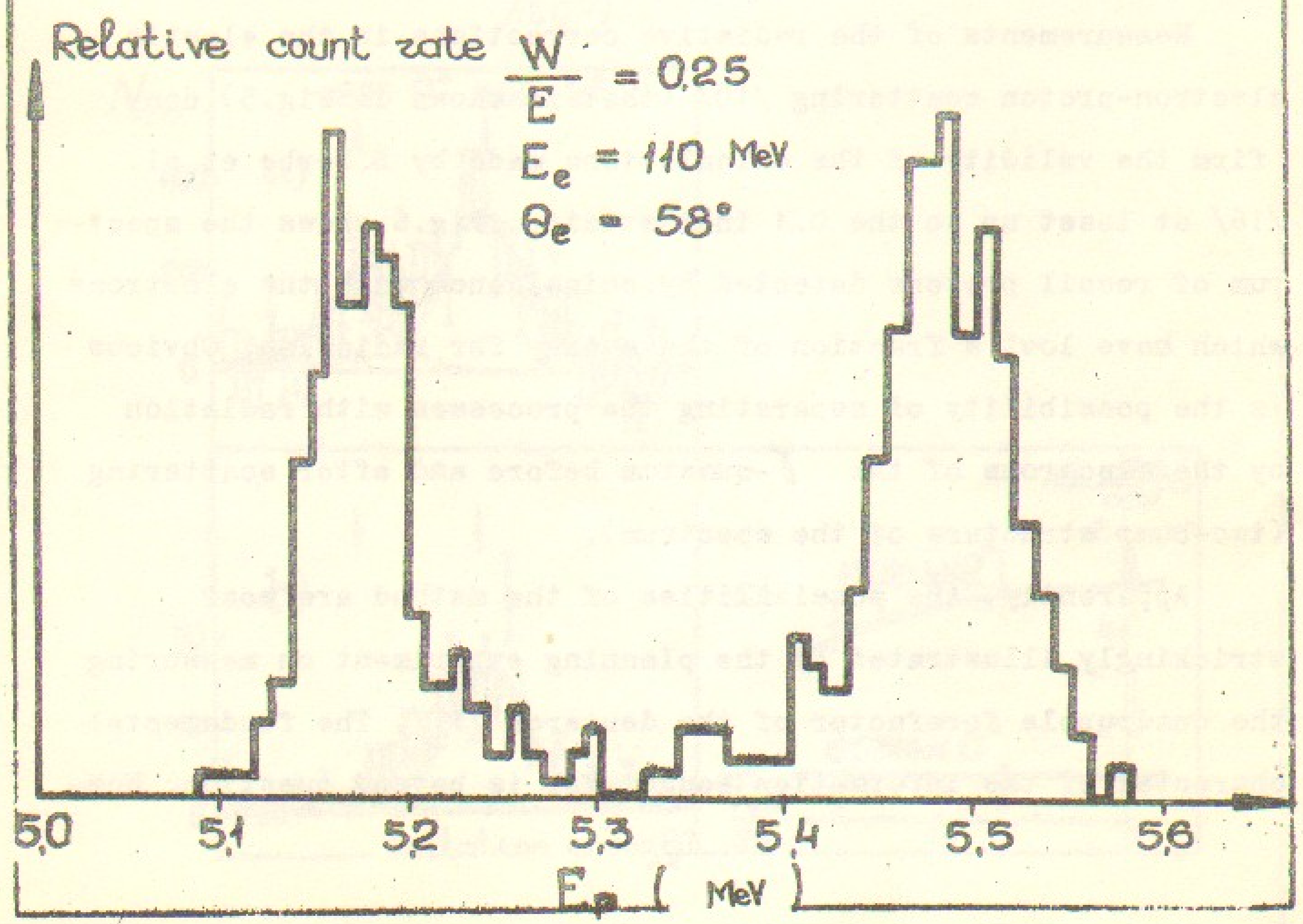


Fig 6.



ever, attempts to carry out the measurements on a linear accelerator meet with serious difficulties connected with the use of a cryogen polarized target under the action of a powerful electron beam. The use of polarized gas jets, which are being widely developed, in particular for injectors in the accelerators /12/, is adequate to the internal target technique. The calculation shows the possibility of measuring the formfactor up to 10 fm^{-2} momentum tranfer at the VEPP-2M facility. Unfortunately, the thickness of a polarized gas target (10^{12} cm^{-2}, that corresponds to a vacuum of 10^{-5} Torr on the 1 cm length) is small in this experiment. According to the ideology of a super-thin target, at a constant rate of injection this leads to the accumulation of a large equilibrium current. This implies the appearance of specific accelerator mechanisms of electron losses that, according to formula (3), results in decreasing the luminosity. It should be emphasized that the gas jet target possesses such a disadvantage as the necessity of strong efforst to maintain a high vacuum in a storage ring; apart from that jet targets available are limited by a small amount of elements, especially if a purely isotope composition is required. It is quite possible that, in order to increase the density, more promising will be the use of powerful ion beams with an energy decreased in the collision region.

VI. Some Additional Possibilities of Using Internal Targets in Storage Rings

In conclusion, I would like to mention additional applications of the method described above. The first application concerns the production of the so-called "monochromatized", or tagged γ-quanta. The schematical variant of such a device is shown in Fig.7. The magnetic field structure in the storage ring forces the electrons after radiating the bremsstrahlung quanta at the internal target, to be focussed, depending upon the residual energy, onto the plane of location of the counters of secondary electrons. The energy line width can be made close to the energy spread of the electrons in the beam and the total intensity of γ-quanta to be, in practice, equal to the intensity of the electrons injected into the storage ring. Under some conditions the γ-quanta can be polarized /14/.

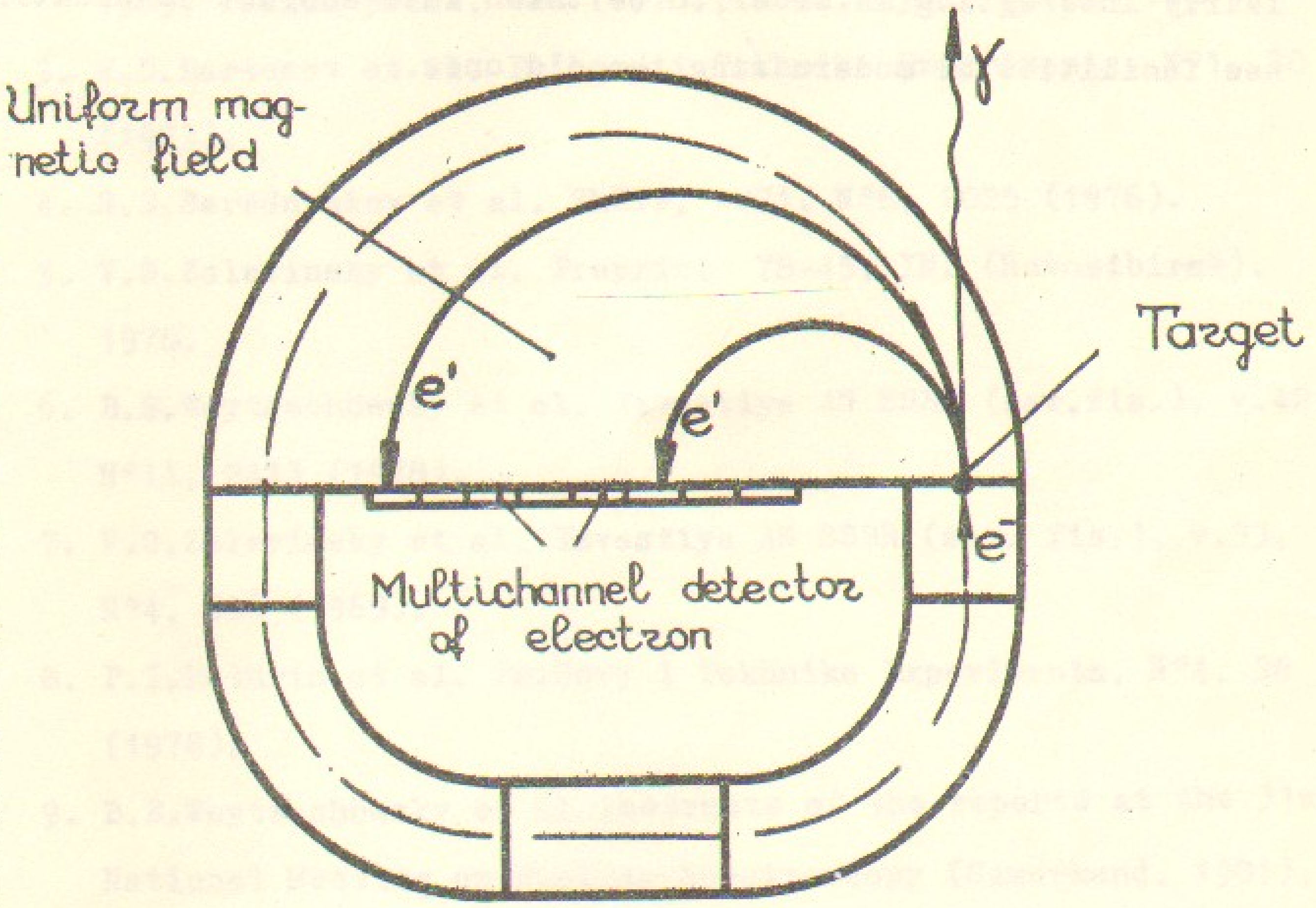
The second application is to use the electron cooling to reach the super-thin target regime in a heavy ion storage ring /15/. The point is that in the conventional experimental setup the target must be very thin because of large ionization losses in the primary beam. If one chooses this thickness to have the ionization losses about 10% of the initial kinetic energy, the estimate gives the thickness by two orders of magnitude less than the effective thickness of the super-thin target in the heavy ion storage ring.

The use of an internal polarized target in colliding proton-antiproton storage ring can give a unique possibility to carry out the studies on polarized colliding proton-antiproton beams /5/.

VII. Conclusion

The first discussions on the possibilities given when placing a thin target in an electron storage ring have been carried out by G.I.Budker when creating the first colliding beam facilities. At that time it was a question of experiments on elastic scattering of electrons from different nuclei. The method has been developed ~~further with participation, from the very begin-~~

Fig 7.



ning, of A.P.Onuchin, G.M.Tumaikin, A.N.Skrinsky, S.T.Belyaev, V.G.Zelevinsky and , in the most recent time, D.M.Nikolenko, D.K.Toporkov, B.B.Woytsechowsky, V.N.Rotaev.

We believe that the possibilities of this methodics are fairly interesting in order to be taken into account in creating new facilities or modernizing the old ones.

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Работа поступила - 2 июня I98I г.

Ответственный за выпуск - С.Г.Попов
Подписано к печати I6.II-I98Iг. МН I5I37
Усл. 0,5 печ.л., 0,4 учетно-изд.л.
Тираж 290 экз. Бесплатно
Заказ № I22.

Отпечатано на ротапринте ИЯФ СО АН СССР