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PHYSICS AND TECHNOLOGY OF SUPERTHIN INTERNAL TARGETS IN STORAGE RINGS

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PHYSICS AND TECHNOLOGY OF SUPERTHIN INTERNAL TARGETS IN STORAGE RINGS

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ABSTRACT

The new generation of accelerators for coincidence electronuclear investigations is discussed. The luminosity and beam parameters are are calculated for an electron storage ring with an internal target operating in the superthin regime. The advantages and disadvantages in comparison with conventional operation using an external beam and target are described. The intermediate results for 2-GeV electron scattering on polarized internal deuterium target are given (joint Novosibirsk-Argonne experiment).

I. INTRODUCTION.

In the last decade, much attention has been focussed on the creation of devices for electronuclear experiments where coincidence of the scattered electron with the reaction products defines the complete kinematic configuration. This allows some additional parameters characterising the interaction under study to be obtained. At data processing these additional parameters (the kind of secondary particles, their energy and angular distribution, separated longitudional and transversal form factors polarized degrees of freedom) give us qualitatively new possibilities of analyzing and interpreting the results obtained. Unlike inclusive experiments, there arises an attractive possibility to unfold the information into appropriate physical channels which either are subject to a natural physical explanation, or put simplier and single-valued physical problems. These experiments have already offered a lot of interesting information [1-6]. The new possibilities of these experiments allow one to call them the experiments of a new generation.

Naturally, setting up the new generation experiments require the new experimental equipment, in particular, new accelerators which must have a high duty factor, high intensity and attractive kinematic beam parameters (energy and angular distribution, transversal beam dimensions). The energy range of the electronuclear physics is from hundreds of MeV to about 10 GeV, since a wide range of momentum transfers (from fractions of fm-1 for nuclear matter research as a whole to dozens fm-1 for quark degrees of freedom effects research) and a wide range of transferred energies (from a few units and dozens MeV when excitating nuclear resonance to hundreds MeV for studying particles produced in nuclear matter and deep inelastic processes) are required. In accordance with the large physical research programm some of the devices are being modernized and new ones are being designed and constructed [7]. Mainly, three versions of accelerators are used :

i) A continuous microtron or a continuous linear accelerator with recirculation.

ii) A high-intensity pulsed linear accelerator coupled with a stretcher-ring.

iii) A pulsed accelerator coupled with a storage ring in the mode of using a superthin internal target.

The first version is commonly used now. The first electron stretcher at an energy up to 130 MeV was put into operation in Tochoku [8]. At present, a 300 MeV stretcher operates in Saskatoon. The third version seems to be promising. The idea of using of electron storage rings for experiments on internal targets in the superthin regime has been proposed and developed in the Novosibirsk Institute of Nuclear Physics [9-11]. The first experiments were carried out on the storage ring VEP-1 at the end of the sixties. In the recent years this technique has been used successfully for setting up electronuclear experiments in a wide energy range (from 100 up to 400 MeV at the VEPP-2 [2,12,13], 2 GeV at the VEPP-3 [14]). A beam of tagged bremsstrahlung gamma-quanta, generated by a superthin argon internal target, was obtained at the electron storage ring ADONE in Frascati [15].

II. AN INTERNAL TARGET.

There is a natural necessity to decrease the thickness of the target used when increasing the accuracy of the extracted beam experiment. On the other hand, an increase of the statistical accuracy requires an increase of the luminosity of the experiment, i.e. the product of the target thickness and the beam intensity. There appears a paradoxial situation when experiments require more and more power to be applied to beam acceleration, meanwhile a smaller and smaller fraction is used. Most of the accelerated particles irradiate the enviroment and generate background, and some efforts should be taken to suppress them. The desire of multiple use of beam particles on the target until the divergence of their parameters from the average ones becomes too large seem to be natural. Here, at the stage of returning the particles to the target it is possible to compensate for the average energy losses (we call this operating regime the thin target regime) and, due to dissipative processes, to suppress the stochastic heating of longitudinal and transversel degrees of freedom of the beam (superthin target regime, STR). This dissipative process is synchrotron radiation in electron storage rings, or electron/stochastic cooling in ion storage rings.

What gain can be obtained from the multiple utilization of particles on the target? One can simply calculate it for an

electron storage ring at energies higher than 200-300 MeV, when the bremsstrahlung is the main process determining the electron-target interaction. Here is the simplified version of the formula [16]. It overestimates the cross section for large Z (e.g., for Z=90 the overestimation reaches 10%):

$$d\sigma/dh\nu=4*\alpha*r_e^2/h\nu*Z*(Z+1)*L*(4/3-4/3*y+y^2) \qquad (1)$$

here α- the fine structure constant, r_e- classical electron radius, $h\nu$- bremsstrahlung photon energy, $y=h\nu/E$, E- initial electron energy, $L=\ln(184.15*Z^{-1/3})$, Z- target nuclei charge. Let us consider every particle to remain in the process until it loses an energy, higher than that allowable for an electron in an autofocusing radiofrequency field (ΔE_m). One can calculate the total target thickness X(cm-2), where each particle passes through before its loss, from the expression $X*\int_{\Delta E_m}^{E} d\sigma=1$. It turns out to equal:

$$X=Xo/[4/3*\ln(E/\Delta E_m)-5/6] \qquad (2)$$

where $Xo=1/(4*\alpha*r_e^2*Z*(Z+1)*L)$ (cm-2) - is the radiation length unit. If in eq.(2) the allowable energy spread is taken equal to 1% then the effective target thickness will be equal to 0.2*Xo. Note the dependence of the autofocusing parameters proved to be logarithmic, i.e. very weak. Thus, taking into consideration that the target thickness used is no usually more than 0.001*Xo, the efficiency of particle utilization is two orders higher than in the usual case. Naturally, the effective target thickness is independent of the real thickness, because as it decreases, the number of intersections of the target by electrons increases proportionally, and the product of the number of intersections by the thickness will remain the same.

III. BEAMS PARAMETERS IN A ELECTRON STORAGE RING WITH AN INTERNAL TARGET.

A more accurate calculation of the luminosity of the experiment in a storage ring with an internal target than that we have discussed above must take into account all processes limiting the electron lifetime. Electron scattering on target nuclei and their electrons, in addition to bremsstrahlung, are the main processes. In the first case, electrons are lost due to large-angle scattering, wheras in the second case energy loss is the cause [11]. Moreover, the particles can be lost because of different kinds of high current effects (the interaction of intense bunch of particles with the cavity or parasitic resonators in vacuum chamber, Tushek effect, etc.). One can show that the luminosity of a storage ring with an internal target without taking into account the high current effects will be equal to:

$$L=n/\sum\sigma_i \quad (cm^{-2}\cdot s^{-1}) \qquad (3)$$

where $n(s^{-1})$ is the intensity of the electrons injected to a storage ring, $\sum\sigma_i$ - is the sum of the cross-sections of the processes determining the particles lifetime. If in eq.(3) one takes into account only the bremsstrahlung, it becomes equivalent to the above discussion about the effective target thickness. As in the consideration presented above, the luminosity of the facility does not depend, in principle, on the target thickness. However, as the thickness decreases, the particle lifetime and, hence, the stored current, grows, such that a limit with respect to high current effects may appear. Now, we will discuss the actual time cycling of the facility. It is determined by the following time-parameters :(i) period of revolution To; (ii) damping time of oscillations Td; (iii) beam particle lifetime Tl; (iv) injection period of electrons Ti.

The condition Tl>>Td>>To necessary for realization of STR is achieved easily by chosing the target thickness which defines the lifetime of the beam. But, if Tl>Ti, the electron current in the storage ring increases up to the level corresponding to the rated luminosity. If the equilibrium current (its value is (no/To)*(Tl/Ti) electrons per second, where no is the number of electrons per injection pulse) is too large, some of the electrons will be lost as a result of the high current effects and, correspondingly, the luminosity will fall. The minimal average current is obtained for Tl=Ti (at a level of n /To) and the achievable luminosity in accordance with (3) is approximately $n*10^{25}/Z^2$ $(cm^{-2}*s^{-1})$ or $10^{40}/Z^2$ at a 200 μA injection rate. Fig.1 shows the typical time cycle for such a case.

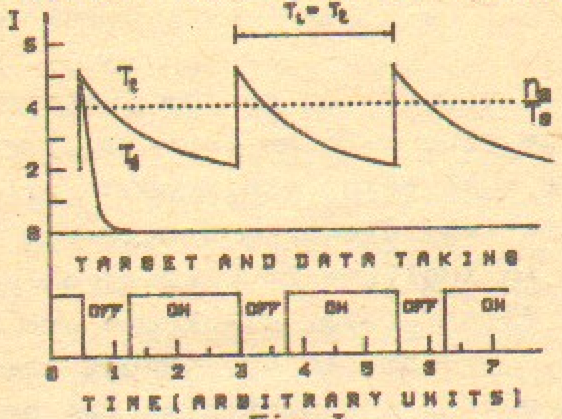

Fig.I

During the electron injection time and the period required for damping the particle oscillations (on Fig.1 this time is 3*Td), the target source is switched off and the detection systems are blocked. The duty-factor is determined by the injection period Ti. When we reach top luminosity and use the short injection period (on the order of the damping time Td) the condition Tl>>Td is not fulfilled. In this case, the luminosity will be lost (there is no possibility to use each pulse from the injector) or, the damping time must be reduced by, for example, the wiggler magnet.

The beam parameters (the energy and angular spreads) are determined by the balance of the damping effect, the beam-heating due to interaction with the target, and the fluctuations from synchrotron radiation losses. The resulting value corresponds to the equilibrium between the rate of increase and the damping of the square amplitude of the appropriate degree of freedom. The effective beam parameter is calculated as the variance of the appropriate amplitude of oscillation during one half the damping time. It is also necessary to take into account that noncoherent set of harmonic oscillations is described by mean square which is twice smaller the appropriate square oscillation amplitudes.

The energy spread of the electrons is determined mainly by three processes :

i) Quantum fluctuation of the synchrotron radiation. A full calculation of this effect requires knowledge of the ring magnetic structure. For estimation an approximate expression may be used [17]:

$$\sigma_{\frac{\Delta E}{E}}=\gamma*\sqrt{55*\sqrt{3}/192*\lambda_e/R(cm)} \qquad (4)$$

where γ - is Lorentz factor, λ_e- is Compton length of electron, R- is the orbital radius in bending magnet. After inserting the constants, we obtain: $\sigma_{\frac{\Delta E}{E}}=4.4*10^{-6}*\gamma/\sqrt{R(cm)}$.

ii) Bremsstrahlung fluctuations on the target:

$$<\Delta E^2>=X*\int_0^{\Delta E_m}E^2*(4/3-4/3*y+y^2)*dE/E \qquad (5)$$

where X-is the target thickness passed in one half of the damping time for radial-phase oscillations. At the upper limit of the target thickness (in this case there is biggest possible energy spread corresponding in Fig.1 to Tl=10*Td), where $\frac{\Delta E_m}{E}=10^{-2}$, we obtain: $\sigma_{\frac{\Delta E}{E}}\simeq6*10^{-4}$.

iii) Fluctuation of the ionization energy losses. This effect dominantes the damping energy spread when the electron energy is small (less then 200 Mev) and the target atomic number also small.

Radial angular spread in the electron beam is accumulated from the angular original spread, the spread of energy and the multiple scattering on the target nucleus. Vertical angular spread is determined by scattering on the target and the coupling of vertical and radial betatron oscillations which repump energy from radial oscillation to vertical one. By using approximate expression for multiple scattering [18] one obtains the maximum angular spread in the beam:

$$\langle\theta^2\rangle^{1/2}=1.5/\gamma \qquad (6)$$

Recount for correspondens cross section of the beam should be done with taking in account beta-function in the target location and in the point of beam size measurement.

IV. AN INTERNAL TARGET IN A STORAGE RING.

For reaching maximum luminosity it is necessary to fulfil several requirements. Clearly from expression (3) the luminosity is determined by the injection rate of electrons to the ring. The relationship for the various times controlling the particle motion must be fulfiled (life time, damping time). For realization one the optimal mode storage ring operation, as shown in Fig.1, it is necessary, first, that the injection energy be equal to the experimental energy such that time is not spent on accelerating particles in the storage ring. Second, the target thickness must provide both requirements of STR: Tl>>Td and Tl=Ti. The corresponding target thickness is directly proportional to the orbit length Π and inversely proportional to Ti and Z*(Z+1)*L:

$$Xs=2.8*10^{15}*\Pi(cm)/(L*Z*(Z+1)*Ti) \qquad (7)$$

From this expression it is clear that for obtaining top luminosity obtaining the required target thickness is up to 10^{18} cm-2, depending on machine parameters and Z of the target. Now, internal targets for storage ring are operational at Novosibirsk [19,20], Frascatti [21], Indiana [22].

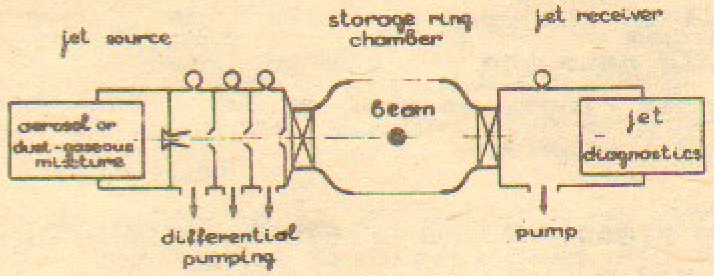

Fig.II

The schematic drowing of a target system for storage ring experiments is shown in Fig.2. Three kinds of target were used in this configuration: supersonic-clusters, dust and aerosols. For the first kind of utilization, the jet is produced by a supersonic nozzle. For some gases (hydrogen, nitrogen, oxygen...) it is precooled, for others it is heated (water vapors). For second kind, a usual nozzle or directing tube is used with a pre-prepared suspension of a carrier gas and target dustlets. The particles of the dust target must be prepared specially to have the required dimension (usually not more 1-2 microns) and a surface free of adsorbed substances. We have used nickel and carbon dust jets. The third method, in contrast with second one, uses aerosole clusters formed from the vapors of target material (e.g., sulfur) trapped and cooled by a flow of carrier gas. Hydrogen or carbon dioxide were used as a carrier gases. The fraction of the carrier gas in the target did not exceed several percent. The main problem in using such a target is maintenance of appropriate vacuum conditions in the experimental section. The requirement for the vacuum in the storage ring operating with an internal target is the thickness of the residual gas integrated along the circumference should be much less target thickness (normalized over atomic number). As a rule this requirement is fulfilled rather easily especially at the machines of a large circumference, but special efforts are needed:

i)A jet must be well enough formed;

ii)Multistage vacuum pumping system of the source and the experimental section must provide requirements above;

iii)A target receiver must trap the main portion of the flow.

Also important is the interaction of the intense electron beam with the target. Target clusters can be melted and vaporized by the beam. As a result, the jet loses its directionality, such that part of the target material does not enter the receiver and the vacuum becomes worse. A fraction of the clusters, during the time of the electron beam crossing, can be ionized, trapped by the beam electrostatic potential, and diffuse around the ring, making the vacuum conditions worse. This effect can be suppressed by using an electrostatic field which either smooths the potential well of the beam or locks ions in the interaction region. One should note the ion charge compensation effects in electron beam storage rings, as well as methods of cleaning, are not sufficiently well studied.

V. ADVANTAGES AND DISADVANTAGES OF EXPERIMENTS WITH AN INTERNAL TARGET IN STORAGE RINGS.

At the present time, the target configurations are rather large and for this reason detector installation in an experimental section is complicated. Another important disadvantage, both structural and psychological, is that the experimental section is an intrinsic part of a complicated device- a storage ring. This makes installation of detector elements and rapid transfer from one experiment to another more difficult. The construction of an experimental section of the storage ring for installation of a target and detector must include adjacent elements of the magnetic system (an example is a detection of secondary particles in the forward and/or backward directions). However, the advantages of the internal target experiments are much more significant.

i)A high efficiency of particle utilization and, as a consequence, the high luminosity is available. The ratio luminosity/background is also high, since all particles are used at the target. In addition, oscillation damping restricts the halo around the beam. As a result, unique background conditions are achievable close to the beam. The luminosity achievable by STR is much higher than in the usual method at equal injection rates. However, up to now, the maximal STR luminosity has not been demonstrated. At the Novosibirsk machine VEPP-2, electronuclear experiments were performed at the luminosity of 10^{32} cm-2·s-1. Luminosity losses were due to the fact the storage ring was not adjusted for the operation with an internal target (small efficiency of electron injection, bad vacuum conditions in the experimental section...). The special purpose storage ring NEP [17], which is now under construction in Novosibirsk will use the same electron injector and its expected luminosity is higher than 10^{34} for a target of Z=8. The tagged photon intensity at Frascati [15] is restricted by the increase of the angular spread of the electrons, due to multiple scattering on a target, in connection with the large distance to the place where photons are utilized.

ii)Continuous operation mode and favorable experimental kinematic conditions. One should note that these conditions can

be controlled: one can change the microstucture period of the electron bunches by using higher RF harmonics, the angular spread depends on the characteristics of the magnetic system (beta-function value in the target place); energy resolution can be improved by corrections for the beam energy dependence on the radial coordinate [23].

iii)It is possible to carry out experiments at unique conditions: the small target thickness does not perturb practically the secondary particle parameters, thus experiments are possible with both unique beams (e.g., positrons) or/and unique targets (e.g., polarized atoms jets).

One can note also that the method of driving and utilizing the longitudinal polarization of electrons in storage rings [24,25] has been studied.

VI. STUDIES OF THE ELECTROMAGNETIC DEUTERON STRUCTURE.

As an example of an experiment using a unique target, we discuss separation of the deuteron charge and quadrupole form factors (extraction of so-called T20 parameter). It is a long-standing problem which is very important for the understanding of nucleon-nucleon interactions. The idea is to measure the asymmetry of elastic electron scattering on tensor polarized deuterons. Unfortunately, cryogenic targets cannot be used effectively due to the intense electron beam action [26]. Another possibility is the measurement of the recoil deuteron polarization. Such an experiment was performed by the MIT-Bates group [27]. It has its own drowbacks connected with the polarization measurement by secondary scattering. Adequate is an experiment with a polarized atomic beam [28] as an internal target in an electron storage ring. Unfortunately the target thickness is too small to reach the top luminosity. It is limited by the high current effects: at VEPP-2 it was 1 A, at VEPP-3 it is 0.2 A. The luminosity in this case was determined by the polarized target thickness. For the atomic jet target it was possible to make T20 measurements up to 2-3 fm-1 momentum transfer only. To increase the momentum transfer it is necessary to increase the target thickness. Novosibirsk-Argonne collaboration is pursuing one possibility. It consists [29] of using a storage cell [30] to increase the target density and length. The first stage of the experiment tests the storage cell feasibility under real conditions, and, if possible, to collect information at 3 fm-1 momentum transfer. The storage cell (length 940 mm, 24*46 mm^2 dimensions) was installed in the VEPP-3 experimental straight section. It is covered inside by dri-film to protect the atomic polarization during scattering. In addition, the depolarization may be produced by periodic perturbations by the magnetic field of the electron bunches. To preserve the polarization the storage cell is placed in magnetic field (>300gs). In Fig.3 the deuteron degree of polarization during the run is shown. The degree of polarization is characterized by the elastic electron scattering asymmetry.

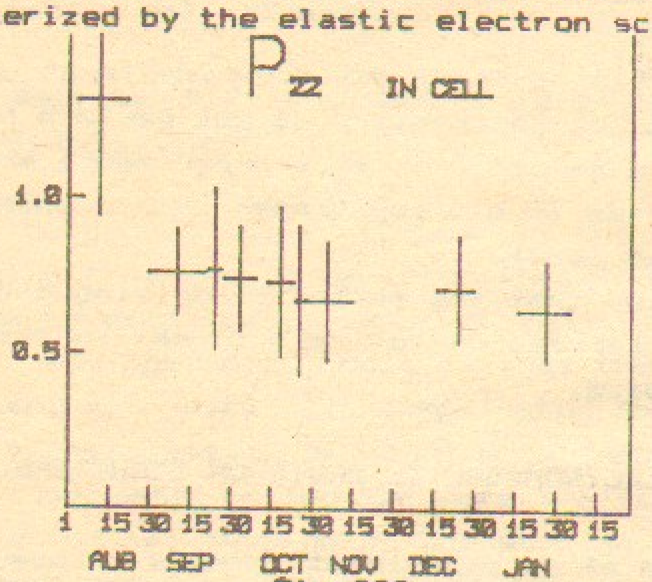

Fig.III

During the run, the cell was crossed by approximately 1 MCl of electron charge (one or two bunch regime, maximum current up to .2 A, bunch length 1 ns). One can see no essential decrease of the deuteron polarization in the storage cell during the run.

In second stage, we propose to install a movable cell, which will be opened during electron injection and will have small dimensions during event collection to increase luminosity. The third stage provides both the new detector installation, to increase the target length utilized and to extend the secondary particle separation at higher momentum transfer, as well as a laser pumped polarized deuteron source [31] to increase the atom flux. The second stage proposed gain has a factor 4 compared with stage one, whereas, stage three will have an additional proposed gain of a factor 80. These improvements will provide a possibilitiy for measurements at 5 fm-1 momentum transfer. The schedule provides for stage two in April-May 1989 and the fall of the year for stage three. It was mentioned above that the goal of stage one was the testing the feasibility of a storage cell in a ring, but a gain of 3 compared with the free jet was achieved. The expected gain was of 6, the difference is due to incorrect estimation of the jet dimensions.

The intermediate treatment of data, collected before the December 1, is shown in Figs 4 and 5. Fig.4 shows the dependence of T20 value on momentum transfer.

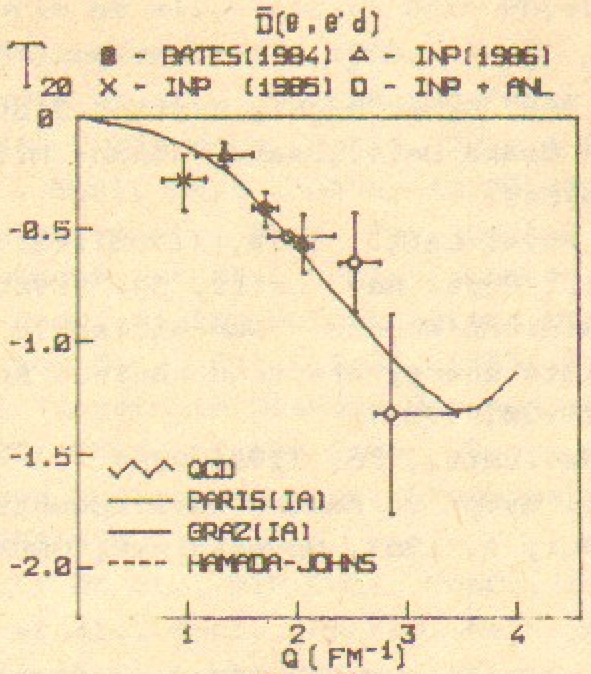

Fig.IV

Fig.5 shows the deuteron photodisintegration asymmetry dependence on energy transfer. In this figure, the curve calculated by H.Arenchovel [32], is also given.

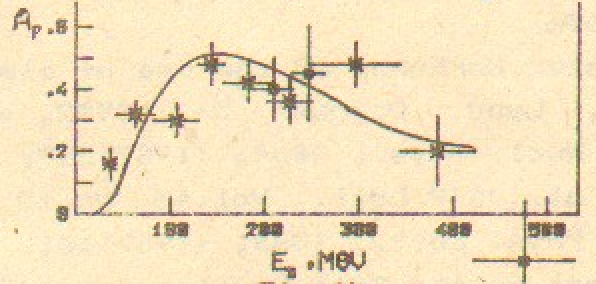

Fig.V

The polarization degree,.74+-.08, is given by the T20 value normalization to theory at the lowest momentum transfer. However, the quantity .40+-.09, obtained from the comparison of the average photodisintegration asymmetry value with the free jet experiment (where the degree of polarization was measured [14]), was used in Fig.5. This difference exceeds the statistical errors. One possible explanation is the background connected with the quasideuteron channel, arising from interaction of electrons with residual gas.

The participants of these experiment are B.A.Lazarenko, S.I.Mishnev, D.M.Nikolenko, S.G.Popov, I.A.Rachek, A.B.Temnych, D.K.Toporkov, E.P.Tsentalovich, Yu.G.Ukraintsev, D.K.Vesnovsky, B.B.Woitsekhovsky (Institute of Nuclear Physics, Novosibirsk, USSR) and R.Holt, E.Kinney, J.Napolitano, L.Young, R.Gilman, R.Kowalczhyk (Argonne National Laboratory, Argonne, USA). The neutron detectors for the photodisintegration measurements were produced in the Leningrad Institute of Nuclear Physics.

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С.Г.Попов

ФИЗИКА И ТЕХНОЛОГИЯ СВЕРХТОНКИХ ВНУТРЕННИХ МИШЕНЕЙ В ЭЛЕКТРОННЫХ НАКОПИТЕЛЯХ

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