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PRODUCTION AND USE OF "MEGAVOLT" NEUTRON BEAMS WITH $\Delta E_n/E_n \sim 5.10^{-4}$

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The neutrons of megavolt energies,
the high-monoenergetic neutron beams,
the foilless gas target.

A method of producing MeV neutron beams with a small neutron energy spread in the beam is described. This method uses a combination of unique properties of modern electrostatic accelerators (ESA) and a foilless gas target. The latter allows us to realize continuous and easily controllable reproduction of targets with a low energy "thickness" on the basis of differential pumping out of the target working medium vapour by freezing it out in refrigerators with the help of liquid nitrogen.

A technique of the measurement with the MeV neutron beam of nuclear total cross sections with a resolution up to $\Delta E_n/E_n \sim 5\cdot10^{-4}$ and differential cross sections of elastic scattering with $\Delta E_n/E_n \sim 2\cdot10^{-3}$, which uses the $^{12}C(d,n)$ reaction, has been developed.

By analyzing the properties of neutron fields generated by a deuton beam in the gas target it has been found that presently any further considerable improvement of the energy resolution in neutron experiments is restricted by the characteristics of the ESA used.

1. Introduction.

Beams of neutrons with some known average energy and minimal energy spread ("monoenergetic" ones) in the energy range of the order of MeV are indispensable for a detailed study of neutron-nucleus interaction. Apparently, the best scheme for obtaining such beams is the classical one, i.e. the generation of neutrons in an appropriate nuclear reaction induced by a beam of charged particles from an electrostatic accelerator (ESA). Here the energy of generated neutrons depending on the reaction chosen can be smoothly adjusted by variation of both the charged particle energy and emission angle of used neutrons with the ESA charged particle beam. In this scheme the formation of the neutron beam with the aid of collimation allows us to separate neutrons with the required energy and to attenuate the neutron background effectively.

In the scheme under discussion the spread of neutron energies in the beam irradiating some sample (or detector) of finite dimensions is immediately connected with the characteristics of the nuclear reaction chosen and, in principle, depends on the energy spread of the accelerator beam particles, the angular divergence of this beam, the neutron-generating target energy "thickness", the relative linear angle θ at which the irradiated sample (or detector) is observed from the target centre[*], the target temperature. Until lately, as a rule, the decisive factor was the target energy "thickness". Its great value prevented the unique advantages of ESA from being realized in neutron experiments.

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[*] θ is the angle in the reaction plane expressed in the respective linear dimensions of the sample (detector), target and the distance between them.

Indeed, using the ESA one can obtain beams of charged particles having some known average energy, small energy spread and small angular divergence. Thus, the average energy of such a beam can be maintained at some constant value for a long time with the error of not more than 10^{-4} at the angular divergence of the order of a few tenths of a degree. However, no less than 10^{-2} of the ESA beam energy is lost in the target itself if conventional targets are used for the neutron generation. The main difficulties in decreasing the thickness of the hard targets is due to the fact that, as a result of the target material dissipation by the charged particle beam, the target life time turns out to be short and that there arises the problem of the control of the target fitness. The change of the thickness of the target in dissipation is liable to great fluctuations bringing about a considerable uncertainty both in the energy spread and the average energy of the neutron beam.* It requires the development of some technology of producing targets, which are homogeneous in their thickness and are easy to be reproduced, as well as that of their quick replasement and monitoring of the target thickness during experiment.** A non-stop and easy to control reproduction of the target working medium carried out in so-called gas targets would be ideal. However, thin foils separating the target working medium from the ESA vacuum system not only set severe restrictions on the currents of charged particles permissible for the target*** but also increase

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* The requirements upon the reproduction of these values are very severe in the neutron experiment in which the use of the high energy resolution is imposed by the character of the energy dependence of the cross section under investigation.

** The attempts at a partial realisation of such a program are illustrated by the work /1/.

*** At the decrease of the target thickness the only way to increase the neutron yield up to the level sufficient for the experiment performance is, under other equal conditions, to increase the ESA beam current on the target. But, as a rule, the gas target foiles are broken by currents being more than 10 μA.

the energy spread as well as the angular divergence of the ESA beam so appreciably that such gas targets cannot compete with thin hard ones.

However, there is a less popular gas target scheme. In that scheme the working volume of the target is connected with the ESA ion drift tube through a system of diaphragms. This system allows us to obtain (without the foils), using the differential pumping out, a gas pressure differential inside the target set-up from the working pressure in the target volume to that characteristic of the ESA vacuum system. So we achieve the absence of any considerable effective thicknesses of matter on the beam path which can increase the energy and angular spread of the ESA beam before it hits the target working medium.

The lesser popularity of such a scheme is mainly due to the technical difficulties of its realization: high-capacity vacuum pumps are required including large-sized mechanical forevacuum ones; there exists the problem of the working gas contamination in passing through the pumps and, respectively, the problem of this gas regeneration for the reuse, etc.; it is necessary to have special personnel trained to operate the target. In neutron experiments, which are long-term by the nature, these difficulties turn into considerable obstacles.

We have decided to use as a working medium of the target some chemical compounds whose vapour guarantees an acceptable yield of neutrons and is well-frozen by liquid nitrogen. As for the high-capacity vacuum pumps, we have replaced them with cryogen traps. By using appropriate organic compounds (for example, acetone) or heavy water and a beam of accelerated deutons in the $^{12}C(d,n)$ and $D(d,n)$ reactions, it is possible to obtain neutrons in a wide energy range on the ESA-2.5 used by us. Such a target allows us to make use of the maximal currents obtained with the aid of the ESA. A set-up of the gas target designed employing the above-mentioned principle is described below.

2. Construction of Gas Target.

The gas target scheme is presented in fig. 1. The target working volume is formed by a thin-walled tube, 9 mm in diameter. To allow the passage of a beam of deutons going perpendicular to the tube axis, two openings are cut in this tube. The shape and dimensions of the openings are detrmined by those of the deuton beam cross section near the target.

The working medium (acetone, heavy water) is in a thermostatically controlled tank. The supply of the vapour from the tank into the tube from which the vapour flows freely through the openings is regulated by a throttle valve. An oil pressure gauge is used to measure pressure immediately in the target tube and the pressure monitoring is effected.

The differential pumping out of the working medium vapour is performed by three stages separated from each other by a system of diaphragms D1-D4 allowing the deuton beam to pass. The inner working surface of refrigerators is made sufficiently developed and makes it possible to freeze out more than 5 l of matter at moderate overall dimensions of the refrigerators (each refrigerator capacity as to liquid nitrogen is 4 to 5 l). The heaviest load is on the first pumping out stage, therefore, provision is made in it for two refrigerators used alternately. Having filled one refrigerator it is possible to change over to the other without shutting down the set-up. The target is closed-circuited with the working medium conservation in the refrigerators: having heated up the refrigerator, we by-pass the working medium using the pressure of its vapour into the tank for further work.

A high-vacuum pumping-out preventing the BSA vacuum system and the ion drift tube after the target from contamination by the target working medium vapour and removing the products of the target medium decay by the beam from the refrigerators is performed by three diffusion pumps with a capacity of about 100 l/s.* In the ion drift tube between the BSA and gas target there is a furnace heated up to ~600° used for cracking the working medium vapour; a high-vacuum gas-discharge pump with a capacity of about 100 l/s is additionally connected near the furnace on the side of the accelerator.

During operation with the working medium vapour in the target liquid nitrogen is poured in the refrigerators and traps as the need arises on the basis of the forevacuum data in the set-up, i.e. once in 2 - 4 hours. The time of the set-up operation until one refrigerator of the first stage is filled is inversely proportional to the working pressure in the target and amounts to 8 hours in operation with the maximal pressure in the target at which it is possible to carry out the measurements and which equals ~10 mm Hg. The consumption of nitrogen under such conditions does not exceed 100 l per 24 hours.

The target has turned out to be very easy to operate and can function 21 - 22 hours a day (2 - 3 hours are needed to start the set-up, to pour nitrogen into it, to by-pass the working medium from the refigerator to the tank, etc.). The set-up is usually operated and maintained by a physicist carring out experiments. The target parameters are stable in time and well-reproduced; the target energy "thickness" can be changed practically instantly and a number of

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*The whole set-up made of the refrgerators, traps, high-vacuum pumps and valves with the tubing system is arranged very compactly and in all it takes up the volume of ~1 m^3.

check ("background") measurements can be performed at any moment of the experiments by breaking off the supply of the working medium vapour to the target.

The problem of the deuton beam passage through the gas target is closely connected with that of the neutron background and is considered below.

3. Background Conditions.

The success of neutron experiments depends, as a rule, on a relative value and stability of the neutron background. When the source of the background neutrons is the reaction on the target working medium itself, this problem is solved conventionally /2,3/. However, in our case when the total yield of neutrons from the target is relatively low the use of the deuton beam results in considerable complications: the beam generates neutrons practically on all the parts of the set-up, with which the beam gets in contact, with the intensity which may cinsiderably exceed that of the neutron generation in the target itself. Even when the construction materials are specially chosen, it is practically impossible to get rid of the background neutrons from the D(d,n) reaction on deuterium, which is "stuffed" into the surface layers of the constructions by the deuton beam itself, and, in particular, from the $^{12}C(d,n)$ reaction on the films of carbon-containing materials in the same parts of the construction. In this situation it is difficult to guarantee the background stability and the most practical solution of this problem is to decrease the part played by undesired sources of background neutrons to the minimum. Here it is also important that these undesired neutron sources are separated in space from the target working volume since this circumstance allows us, having reduced the neutron yield from these sources as much as possible, to decrease the background neutron flux at the place of installation of the detectors by means of the respective neutron shielding using conventional techniques so that the background turns out to be negligible or low enough to allow us to confine ourselves to a relatively rough account of its fluctuations.

The attenuation of the background sources of neutrons is made directly: the parts of the construction are shaped so that the beam, if possible, could go through the set-up without touching its parts, at least in the vicinity of the target itself.

It is clear from fig. 1 that the diaphragms D1 - D4 of the target pumping-out system and the edges of the target tube openings belong to the construction parts on the surface of which neutrons may be generated near the target working volume. Their dimensions and distance to the working volume are dependent on the possibilities of the pumping-out system and cannot be made arbitrarily large. Therefore, it is necessary by limiting the cross section of deuton beam to let it pass through the set-up without getting in contact with the component parts of the construction.

A scheme of the system of the deuton beam shaping and transportation is given in fig. 2. The beam cross-sectional size in a cross-over, which is in the region of the slit device of the beam energy stabilization system (at the outlet of the analysing magnet), is a fortiori less than 2 mm, while the root-mean-square angular divergence does not exceed 0.2°. To transmit the image of the beam cross-over into the target working volume use is made of two quadrupole magnetic lenses (QML)* with the magnification of 1:1 each. The reten-

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* Symmetrical triplets whose mechanical part is manufactured with a high precision are used as the QML. During the mechanical assembly the geometrical axes of the QML and gas target set-up are aligned. Among the advantages of such QML is the simplicity of the readjustment in going over from one energy of the beam to another.

tion of the beam initial parameters, i.e. the dimensions and the angular divergence, and its passage through the set-up practically without losses can most easily be effected (with the respective selection of sizes and location of the limiting diaphragms) by letting the beam pass along the geometrical axis of the set-up. To limit the beam, use is made of three diaphragms positioned along this axis, which simultaneously serve as the beam position indicators (BPI)*.

The diameter of the BPI-1 opening equals 2 mm. In principle, by decreasing this size, it is possible to limit the beam cross section as, due to its position outside the experimental hall behind a brick wall 1 m thick, the BPI-1 turns out to be considerably withdrawn from the source of useful neutrons and the collimator inlet aperture and to be shielded. Respectively, by using an appropriate diaphragm near the QML-1, it is possible to decrease the angular divergence of the beam.

The information on the current distribution over the BPI plates is used for adjusting the QML-1 and QML-2. At a correct adjustment, the QML-1 yields an intermediate image of the beam crossover at the place of the BPI-1 location. Then this image is projected by the QML-2 immediately in the target working volume. The BPI-2 and BPI-3 arranged symmetrically on both the sides of the target tube at a distance of about 125 mm each allow us to judge the correctness of the beam passage and the degree of the beam focusing immediately in the target tube area. The diameter of the BPI-2 and BPI-3 openings which

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The BPI is a diaphragm formed by four plates insulated from each other and from the construction parts. Each plate covers an angle of a little more than 90°. The currents getting on the plates of all the BPI and on some parts of the target construction (the target tube, the pumping-out system diaphragms) and on the collector (the final beam stopper) are constantly controlled by means of multichannel detector.

equals 3.8 mm is so selected that at a normal operation the beam cannot touch either the edges of the D1 - D4 diaphragms, or those of the target tube being 4.5 mm in diameter.

At the end of the ion drift tube the deuton beam hits the beam stop collector which catches no less than 99.5% of the beam current passed through the slit device, i.e. up to 120 μA, under the set-up normal operation.

All the parts of the construction which may get in contact with the deuton beam are made of stainless steel or copper. The collector heated by the beam current is made of tantalum. Despite the fact that during all the time of the operation the collector's temperature is high thus preventing the deuterium "stuffed" by the beam from being accumulated, the collector still generates the background neutrons with a relatively high intensity (apparently, on impurities and, possibly, on carbides). Therefore, the collector is withdrawn from the target working volume to the maximal distance allowed by the experimental hall and is surrounded by blocks of paraffin with borax whose thickness in the direction of the measuring room reaches 1 m.

The BPIs also belong to the number of the surfaces irradiated by deutons during the normal operation and catch up to 0.5% of the beam current. During the system adjustment carried out without the gas in the target summary (over the plates) currents on all the BPIs together amount to no more than 0.15% of the beam current. However, when the gas is supplied to the target, the current on the BPI-3 increases and at the maximal pressure in the target it reaches 0.4% of the beam current and it is impossible to decrease it by readjusting the system. That increase of the current on the BPI-3 is, apparently, due to a multiple small angle scattering of the beam particles by the target gas.

The elimination of the deuton beam impact on diaphragms D2, D3 and the edges of the target tube apertures allows us to get rid of the most dangerous undesired sources of neutrons. However, the deuton beam gets in contact with the BPI-2 and BPI-3 surfaces but their remoteness from the collimator axis of the neutron working beam and constant control of the currents on the plates of these BPIs reduce the part played by these sources of the background neutron down to a harmless level.

The generation of neutrons on the surfaces being near the target working volume takes place mainly due to the $^{12}C(d,n)$ reaction on the films of carbon-containing compounds. These compounds appear and are accumulated there in the process of operation as a result of the deuton beam effect on the target working medium. The rate of formation of such deposits depends on the properties of a compound used as a working gas and at the use of the acetone vapour this process goes relatively slowly, so that it is enough to perform a routine cleaning once a week at the target continuous operation in order to keep the contribution made by these neutron sources to the general background at some permissible level. The situation is different when the benzene vapour is used as the target working medium: under the action of the deuton beam the benzene combines into hard compounds which quickly and irregularly cover all the inner surfaces of the gas target construction and hang like festoons between them (in particular, on the edges of the target tube openings). Therefore, the use of the benzene vapour resulting under other equal conditions in the neutron yield being 30 - 40% higher than that of the acetone vapour has turned out to be inconvenient during long-term measurements (for details, see ref. /4/).

A considerable general decrease of the neutron background is achieved by means of a conventional neutron experiment technique of the shielding of recording equipment. In the case under consideration we have a room isolated in the experimental hall to perform measurements on a well-collimated beam of neutrons from the target working volume. This room is formed by blocks of paraffin with borax. Use is made of a double-V-shaped collimator of the neutron working beam whose axis is directed horisontally and forms the angle $\theta_{lab} = 30^0$ with the deuton beam; the collimating channel dimensions can easily be changed by replacing the respective insert in the collimator body (the set-up scheme is given in fig. 3). From the inside the walls are covered with lead sheets reducing the γ-background level so that the use of the neutron scintillation counters with stilbene crystals and the "n - γ separation" pulse gating circiut allows us to neglect the detector background produced by γ-quanta.

As a result, in spite of the relatively insignificant amount of the useful neutrons yield from the target using the acetone vapour, i.e. $\sim 2.10^4$ neutrons per second, per μA of the deuton current at the target "thickness" of 1 keV* in the direction of the collimator axis, the background conditions have turned out to be quite acceptable for the performance of long-term measurements of the neutron cross sections. Maximum permissible instabilities of the ESA operation have been investigated in the experiment and it has been found that there exists a certain upper limit of each BPI current at which no sufficient deviation of the beam from the normal position is not yet present and, respectively, no significant change of the neutron background takes place in the measurement room. These limits depending, apparently, on the character of the experiment to be performed, as well, restrict the permissible instabilities in the ESA

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* In calculating the losses of the deuton beam energy in the target gas, i.e. the target "thickness", use was made of the data from ref. /5/.

operation. To get rid of the effect of such erratic instabilities on the experiment result, provision is made for a follow-up system blocking the accumulation of the data from the detectors in case the maximum permissible value of the beam current is exceeded on any BPI or on other elements of the target construction dangerous as to the background.

For the monitoring two sensors are used: a semiconductor detector of protons from the concurrent reaction of $^{12}C(d,p)$ installed in the target tube bend and a scintillation detector of the same type as those used to measure the cross sections, which detects neutrons emitted from the target at the angle $\theta_{lab} = 90^{0}$ (the detector is positioned at the outlet of the special narrow V-shaped collimator and is safely protected by the blocks of paraffin with borax and lead). The agreement between the readings of these monitors is one of the criteria of the set-up normal operation. To perform an additional monitoring and to measure the background with a blank target, use is made of an integrator of the beam current reaching the collector (for some details concerning the recording equipment, see ref. /6/).

4. Energy Characteristics of Neutron Beams with $\Delta E_n/E_n \sim 5\cdot 10^{-4}$.

The error in determing the absolute value of the neutron beam average energy should not exceed in a general case the beam energy dispersion, i.e. ~1 keV in our case. We calibrated the neutron beam average energy by measuring, immediately on the neutron beam, the characteristic features of the total cross sections of the elements whose position in the energy scale was clearly established. To this aid we used, in particular, the maximum of σ_t for ^{12}C at $E_n =$ $= (2078.0 \pm 0.3)$ keV /7/. The results of measuring this maximum in the calibration are given in fig. 4d.

On the basis of results of such measurements it is also possible to determine the energy of the ESA deuton beam, i.e. to establish some correlation between the analyzing magnet field and the beam energy. It has rather quickly been found that such a calibration of the ESA energy scale (using one point) is not satisfactory for our purpose: at a variation of the ESA energy by ~ 15% the data of the "carbon" calibration deviated from those of the energy calibration immediately on the neutron beam as to the total cross sections of other elements approximately by 10 keV. It has been found that this effect is due to the imperfection of the analyzing magnet used to measure the ESA beam energy, which is unimportant at the neutron energy resolution of about 10 keV and worse. Therefore, we decided to use a number of reference points for the calibration of the neutron beam energy scale, having chosen for this purpose characteristic and easily identified particular features in the total cross sections of a number of easily available elements whose position in the energy scale of neutrons is well known*.

Fig. 4 presents some peculiarities of the total cross sections of a number of elements which we used to calibrate the energy scale of the neutron working beam. Apparently, it would be more preferable to use narrow minima in σ_t as the reference points; it would be desirable that their steepness resembled that of the minimum in the cross section of ^{208}Pb shown in fig. 4b.

The main reasons for the energy spread of neutrons emitted by the target in the direction of the collimator axis of the neutron

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* In the region of the neutron energies $E_n < 2.0$ MeV the data of the σ_t measurements performed by the time-of-flight method on "white" beams of neutrons /8,9/ may serve this purpose. These beams being absolute as to the neutron energy determination allow us to reach the required accuracy of the energy scale calibration.

working beam were enumerated in the introduction. Let us dwell on the part played by the deuton beam angular divergence and the finite cross-sectional dimensions of the target and of the sample irradiated by the neutron beam (of the detector in the σ_t measurements)[*]. Here the fact that under other constant parameters the energy of neutrons from the neutron reaction considerably depends on the neutron emission angle relative to the deuton beam direction has a great influence. In the $^{12}C(d,n)$ reaction at $E_d = 2.3$ MeV and $\theta_{lab} = 30^\circ$ $dE_n/d\theta$ reaches 4.1 kev/degree, so that the angular divergence of the deuton beam in the target working volume of 0.2° results in the energy spread of neutrons emitted at this angle of 0.82 keV[**]. Due to the same reason, the finite dimensions of the target working volume as well as those of the sample (detector) irradiated by the neutron working beam bring about the respective spread of the energy of neutrons irradiating the sample, too. Since the neutron energy depends only on θ, the increase of the dimensions of samples or detectors over the φ angle does not bring about an additional spread of the energy of neutrons. Therefore, in the experiments, in which provision is made for the measurement of differential cross sections of the neutron-nucleus elastic scattering (without investigating the

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[*] The estimations show that under the above conditions the contribution to the neutron energy spread from the temperature effects on the target is negligible as compared with other sources of the energy spread.

[**] The contribution from the beam angular divergence to the neutron energy spread, which is due only to the beam properties of our ESA, is of primary importance. This contribution rises both absolutely and relatively in the transition to the neutron generation by means of the D(d,n) reaction, as the neutron energy increase falls behind that of the $dE_n/d\theta$ derivative value at $\theta_{lab} = 30^\circ$ (thus, with the use of the deuton beam with the same energy of 2.3 MeV the neutron energy is approximately three times increased, while $dE_n/d\theta$ approximately 7 times).

polarizing power), one can arrange the investigated samples and detectors of scattered neutrons as shown in fig. 3, so that the investigated sample dimension in the θ angle direction is minimal but the number of investigated nuclei on the neutron beam path is still sufficient.

Note that the neutron fields, which require an introduction of such a characteristic of the nuclear reaction as $dE_n/d\theta$ into the energy resolution of the experiment during the operation with them, make it possible to speed up the measurement of the total cross sections by placing several detectors at different angles θ_i in the reaction plane (see fig. 5) so as to simultaneously measure the transparencies for several neutron energies. An insignificant differance in the θ_i angles corresponding to different detectors ($\theta_i - \theta_{i-1} < 1^\circ$) allows us to use a common collimator of the neutron beam and one sample for all the detectors*.

5. Conclusion.

The use of the foilless gas target has made neutron experiments with the high energy resolution realizable. Under our concrete conditions with the use of the $^{12}C(d,n)$ reaction a possibility of performing the measurements of nuclear total neutron cross sections with the resolution up to $\Delta E_n/E_n \sim 5\cdot 10^{-4}$ and the differential cross sections of neutron elastic scattering with $\Delta E_n/E_n \sim 2\cdot 10^{-3}$ has been realized.

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*Mutual disturbances being due to the neutron rescattering from one detector to the others can be taken into account in the form of small corrections or reduced to a negligible level by separating the detectors in space. The rate of the collection of the information on σ_t in such a geometry when four detectors are used is the same as the rate on the "white" beam in ref. /9/ (with the equal energy spreads).

Now it is not the difficulties of creating thin easily reproducible targets enduring high currents of the ESA beam but the properties of the ESA itself that impede further bettering of the the insufficient value of the ESA beam current, which does not guarantee the detector count rate acceptable for a neutron experiment realization, either by the increase of the target thickness or by that of the angular dimensions of samples (detectors) or by this and that together, which results in the worsening of the energy resolution. It is precisely the state in which under our conditions are the measurements of the differential cross sections of the neutron elastic scattering by nuclei over a wide range of scattering angles. On the other hand, at a sufficient value of the ESA current it is evidently not justified to make the neutron energy spread in the beam, which is due to the target thickness, considerably less than that due to other sources. It is only by using both the deuton beam, whose angular divergence on the target was halved by changing the system of its passage through the set-up, and the special detector with the small (over θ) angular dimension that we have carried out the measurements of σ_t with the best energy resolution of $\Delta E_n/E_n \sim 4\cdot10^{-4}$ (see fig. 4d). The reduction of the ESA beam angle divergence in such a way seems highly important in using the D(d,n) reaction, though it is accompanied by some current losses in our case. However, this way is unacceptable in measuring the differential cross sections of elastic scattering of neutrons with the energy of ~2 MeV for the measurement of which, strictly speaking, our set-up was designed /10/.

It is obvious that in each experiment while choosing some energy resolution, one has to make a compromise decision being determined by a concrete physical problem defining the experiment geometry and by the parameters of the ESA used. In this connection one may, apparently, conclude that the value of the neutron energy spread of energy resolution in experiments. Thus, one has to compensate for the neutron beams obtained by using the above-described method is practically close to the technical limit determined exclusively by the properties of modern ESA.

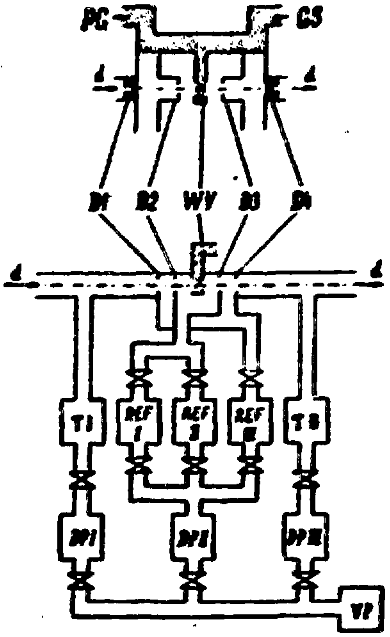

Fig. 1. A scheme of the gas target set-up:
WV is the target working volume; GS, the gas supply; PG, to the pressure gauge; D2 and D3 are the diaphragms separating the first and second pumping out stages; D1 and D4, the diaphragms separating the second and third pumping out stages; Ref. I and Ref. II are the refrigerators of the first pumping out stage; Ref. III is the second pumping out stage refrigerator; TI and TII are the traparefrigerators of the third pumping out stage; DPI, DPII and DPIII are the diffusion pumps; VP, the forevacuum pumps; ⧖, the vacuum valves.

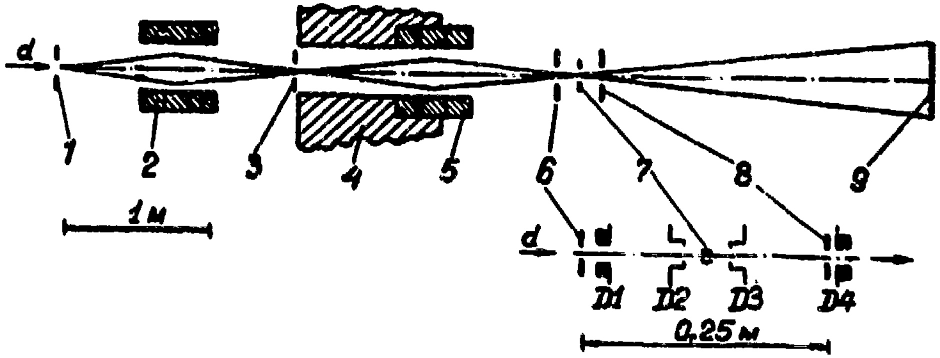

Fig. 2. The ion beam passage in the set-up:
1 - the slit device at the outlet of the ESA analyzing magnet; 2 - the first quadrupole magnetic lens (QML-1); 3 - the first beam position indicator (BPI-1); 4 - the experimental hall wall; 5 - QML-2; 6 - BPI-2; 7 - the gas target working volume; 8 - BPI-3; 9 - the ion beam stop collector. The figure is made to scale only along the beam axis.

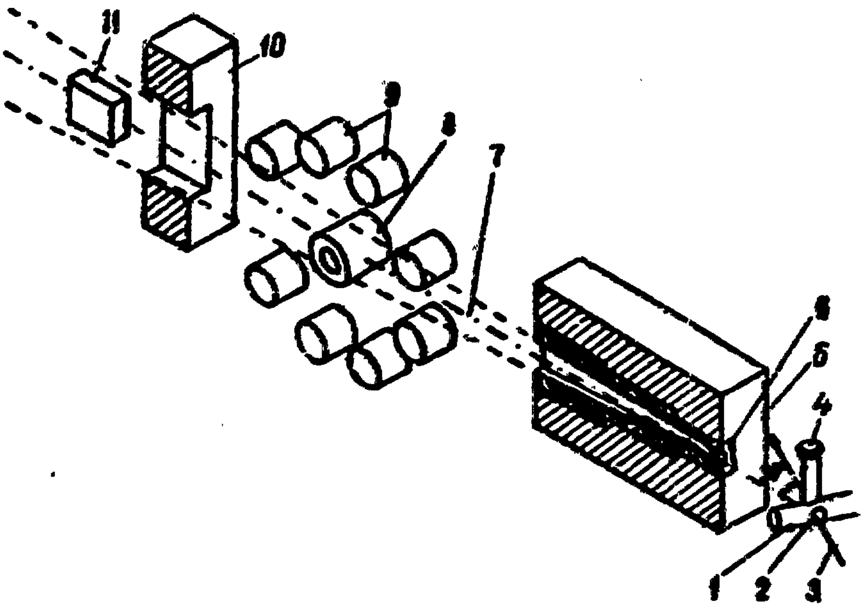

Fig. 3. A scheme of the set-up for measuring neutron cross sections: 1 - the gas target working volume tube; 2 - the aperture for the deuton beam passage; 3 - the deuton beam; 4 - the semiconductor detector - monitor; 5 - the block of the neutron beam collimator (a vertical cross section along the neutron beam axis); 6 - the replaceable insert with the collimator channel; 7 - the collimated neutron beam axis; 8 - the sample for measuring the neutron elastic scattering differential cross sections; 9 - the detectors of elastically scattered neutrons; 10 - the part of the shielding room rear wall with the opening for the neutron beam exit (a sectional view); 11 - - the detector used to measure the sample transparency, beam shape and to adjust the set-up.

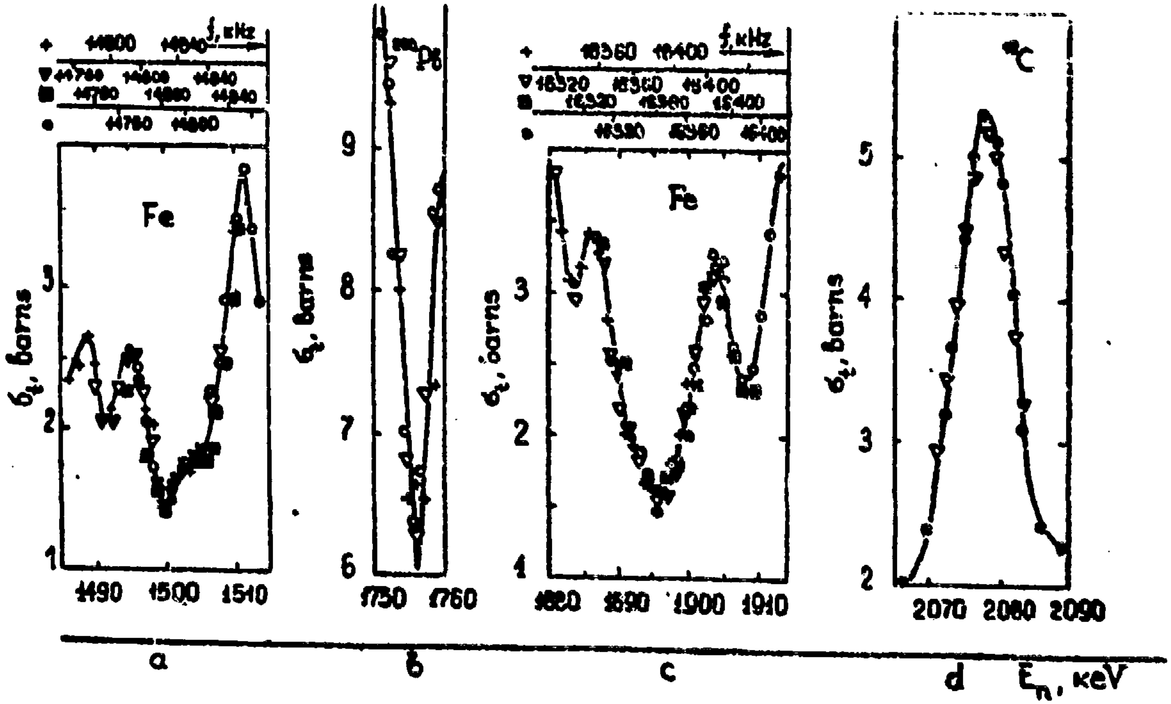

Fig. 4. The data on σ_t obtained in the neutron beam energy scale calibration:
(a), (b) and (c) are obtained in the σ_t measurements performed by several detectors simultaneously at different angles θ_i ($\theta_i - \theta_{i-1} \lesssim 1°$) the energy resolution is $\Delta E_n = 1.3 - 1.4$ keV; f is the NMR frequency in the ESA analyzing magnet characterizing the ESA energy. (d) o stands for $\Delta E_n = 0.9$ keV; ▼, $\Delta E_n = 1.3$ keV.

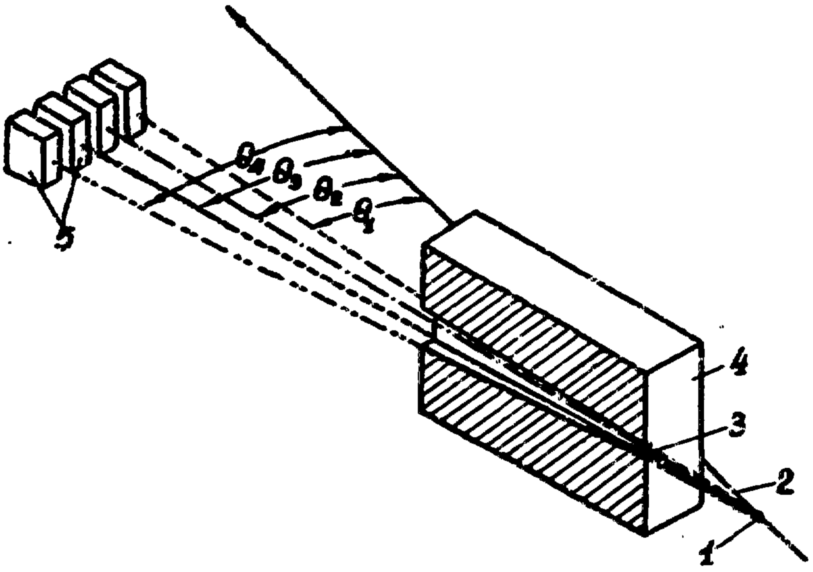

Fig. 5. A scheme of the set-up for measuring σ_t simultaneously by several detectors;
1 - the target; 2 - the accelerated ion beam; 3 - the sample location in measurements; 4 - the neutron beam collimator vertical cross section; 5 - the detectors of neutrons.

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