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HIGH-INTENSITY, PULSED, OPTICALLY PUMPED POLARIZED PROTON AND H- ION SOURCE *

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ABSTRACT

The polarization of protons by the pick-up polarized electrons from optically pumped sodium atoms in a strong magnetic field has been studied experimentally. The proton polarization 65±3% has been achieved with charge exchange in a field of 15 kG. The results of the development of the source of polarized protons and H- ions for accelerators which is based on a new polarization method are discussed. A pulsed intensity of polarized protons of about 1 mA and H- current of about 0.06 mA have been obtained by charge exchange in a xenon gas cell.

1. Introduction

A Source of polarized protons and H- ions based on the method of polarization through the capture of polarized electrons has been developed for the Moscow Meson Factory. This approach, first proposed by Zavoiskii [1], has recently attracted a lot of interest since the use of advanced dye lasers for optical orientation of electron spins in a charge exchange target makes it possible to increase considerably the polarization [2].

We have studied experimentally the electron polarization of sodium atoms by means of a pulsed dye laser. A 90±5% degree of polarization has been achieved at a target thickness of $3 \cdot 10^{13}$ atoms/cm^2. Similar results have been obtained at KEK by using two 1W single frequency CW dye lasers [4].

Electron capture by 5 keV protons is most likely to result in producing the hydrogen atoms in 2S and 2P states. To avoid depolarization due to spin-orbital interaction, the charge exchange should proceed in a strong magnetic field of 10-20 kG [5,6]. Changing the charge state of a beam at the input and output of the solenoid is known to lead to increasing the beam divergence caused by fringing fields.

For instance, with a beam radius R=0.5 cm and a magnetic field B=1T, the normalized emittance increment is determined as follows:

$$\Delta\varepsilon_n \simeq 1.6\ \pi\ BR^2\ \mathrm{cm \cdot mrad} \simeq 0.4\ \pi\ \mathrm{cm \cdot mrad}$$

Such emittance growth may cause substantial losses of polarized current in the source and during acceleration of the beam. To prevent the emittance degradation the proton source as well as the sodium cell should be placed in the same solenoid [7,8]. We have developed an optically pumped proton and H- source in which the difficulty of the emittance growth has been overcome and the proton polarization at different magnetic fields has been measured [8,9].

* see editors notes on page

2. Polarization scheme

A schematic layout of the polarized proton source and proton polarimeter is shown in Fig. 1. An intense beam of neutral hydrogen atoms and an auxiliary ionizing helium cell (5) are the main special features of the installation.

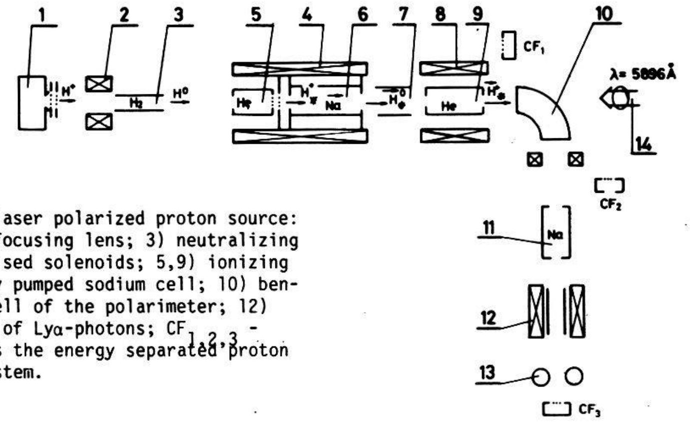

Fig. 1 Schematic lay-out of the laser polarized proton source: 1) source of protons; 2) focusing lens; 3) neutralizing cell (H_2, xenon); 4,8) pulsed solenoids; 5,9) ionizing helium-cells; 6) optically pumped sodium cell; 10) bending magnet; 11) sodium cell of the polarimeter; 12) spin filter; 13) detector of Lyα-photons; $CF_{1,2,3}$ - Faraday cyclinders; H^+_*) is the energy separated proton beam after retardation system.

Both the helium cell and the sodium vapor target (6) are put into the same magnetic field of the solenoid (4). The ionization cross-sections of hydrogen atoms are very close for different gases. Helium is the best choice due to its small neutralization cross-section at atomic energies less than 10 keV, see Fig. 2.

The proton yield is up to 80% for helium and 30% for neon [10]. Production of the neutral beam at the first stage and its subsequent ionization in the solenoid is equivalent to placing the proton source in a magnetic field. In this case the input and output beams are neutral and there is no emittance degradation caused by the solenoid fringing fields. This scheme has some important advantages: the difficulties of operating the proton source in a strong magnetic field are removed and the opportunity arises for arbitrary adjusting the value of the magnetic field.

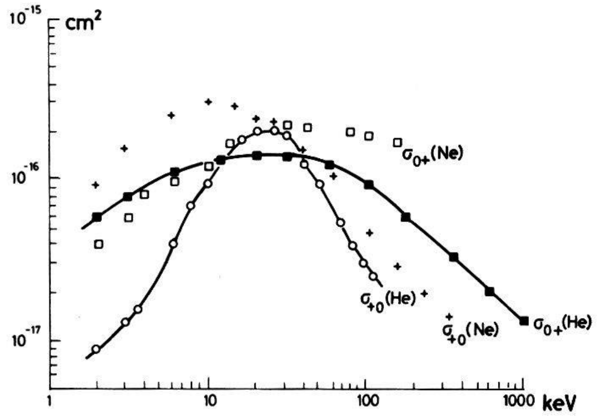

Fig. 2 σ_{0+}-cross-section of ionization of H^0 in helium and neon, σ_{+0}-cross-section of neutralization of H^+ [10].

The protons produced in the cell (5) are retarded by 1 kV voltage applied to it. This allows elimination of an unpolarized component of the proton beam, which is formed by atoms passing through the He-cell without ionization. The unpolarized beam is energy separated and deflected to a diaphragm in a bending magnet.

The protons pick-up polarized electrons from sodium atoms in the target (6). Sodium atoms are optically pumped by circularly polarized emission of a pulsed dye laser. The laser wavelength is tuned to a D_1-transition line 5896Å. The electron pick-up occurs in a strong magnetic field which conserves the high electron spin polarization of hydrogen atoms after their transition to the ground state. The deflecting plates (7) are used to clear the charged particles out of the beam.

A longitudinal component of the magnetic field B_Z varies from 10-20kG to 1.5kG in a gap between the first solenoid (4) and the ionizer solenoid (8). The hydrogen atoms pass the region where B_z-direction is inverted for a time interval much shorter than a period of Larmor precession in the field B_o (B_o is transverse magnetic field at the position where B_z=0). In this case the conditions of a Sona-transition in a zero-crossing magnetic field are completely fullfilled and the electron polarization is transferred to the proton [11].

For the scheme considered these conditions are not so strict as those for the Lamb-shift sources, because a velocity of 6keV atoms is 3.5 times higher than that of 0.5keV ones and the critical field for the ground state is an order of magnitude greater than for the metastable H(2S) state. Thus, the Sona-transition requirements [11] are fully satisfied if $R \lesssim 1$cm, $B' = \partial B/\partial Z \leq 2$ G/cm, and stray field $B_t \lesssim 1$G. The ionization of atoms proceeds in the second helium cell (9).

To provide a high ionization efficiency a target thickness ought to be around $2 \cdot 10^{16}$ at/cm^2. Such a thickness is achieved by pulsed gas filling. In order to keep a high polarization the magnetic field in the ionization region should be not less than 1.5kG. The normalized emittance increment at R=0.7cm is $\Delta\varepsilon_n = 0.08\ \pi$ cm·mrad, which is quite permissible.

In the bending magnet protons with different energies are separated and the beam of polarized protons is transmitted into a proton polarimeter.

3. Some design considerations (see also reference [9])

The proton source consists of a pulsed plasmatron and a four-grid system of beam formation [12]. Protons are focussed by means of a solenoidal lens and neutralized in a hydrogen or xenon gas target (3), see Fig. 1. The beam of hydrogen atoms passes through a polarization system in which the Na-cell has a minimum diameter of 10mm. The diameter of the ionizer cell is 12mm. The distance between the ion source and the bending magnet is about 2m. The equivalent intensity of the atomic beam is measured after ionization in the helium target and amounts to 15mA at an energy of 7keV.

To provide a 10-20kG magnetic field in the charge exchange region, which is necessary to prevent depolarization, a pulsed oil-cooled solenoid is used. The solenoid winding is put into a housing made of two thin stainless steel tubes welded together. The pulse duration is taken to be sufficiently long, about 10^{-3}s, to reduce distortions of the magnetic field induced by eddy currents. The magnetic field energy ranges up to 2kJ per pulse. The power and cooling system of the solenoid restricts the repetition-rate of the source to 1Hz. To provide continuous operation of the source a superconducting solenoid is planned.

A special design of the cell is needed since it is placed inside the pulsed solenoid with 42mm diameter aperture. All parts of the cell are made of thin stainless steel sheets in order to avoid eddy currents effects. To obtain the total vapor thickness of about $3 \cdot 10^{13}$ at/cm^2 in a 200mm long cell, the latter must be heated up to 200^{o}C. About 8g of sodium are stored in the cell; this is enough for 200 hours of continuous operation.

For optical pumping of the sodium atoms, a flashlamp pumped dye laser is used. The laser pulse duration is 20-30µs. The pulse power is some hundred watts. To narrow the bandwidth up to $5 \cdot 10^9$ Hz and to adjust a D_1-transition wavelength a two-component birefringent filter and the 0.5mm Fabry-Perot etalon are put inside the laser resonator. The wavelength is tuned by comparison with the spectrum from a hollow-cathode sodium lamp in a diffraction grating spectrometer. The final adjustment which requires a correction for a wavelength shift due to the magnetic field is made by measuring the count-rate of metastable atoms as a function of the wavelength and polarization.

4. Measurement of sodium electron polarization

For polarization measurements a method of analyzing the hyperfine spin states of metastable hydrogen atoms, which are produced by the pick-up of polarized electrons, has been developed. When protons capture electrons from optically pumped sodium atoms the electron spin polarization is conserved. The spin-states, in which the metastable atoms are formed, and hence the sodium polarization, can be determined by passing the H(2S) beam through a spin filter. For this purpose the magnetic field in the ionizer solenoid (Fig. 1, (8)) equals 570G and is adjusted in the same direction as the field in the sodium cell. In this field the metastable atoms with $m_J=-1/2$ (m_J is the projection of the electron angular moment on the direction of the magnetic field) are quenched to the ground state in a time of about $1.6\cdot10^{-9}$s. The atoms in states with $m_J=+1/2$ pass through the spin-filter without any losses. As is known, this difference in lifetime occurs because of mixing between the $2P_{1/2}$ ($m_J=+1/2$) and $S_{1/2}$ ($m_J=-1/2$) sublevels in a magnetic field of about 570G. This property of the H(2S) states is used in all the Lamb-shift polarized proton sources. The intensity of the H(2S) beam passing through the spin-filter is measured by means of a detector with microchannel plates which are sensitive to the Lyman-α photons produced when quenching the metastable atoms in an electric field. The count-rate equals $\sim10^7$ pulses/sec, which provides a high statistical accuracy of measurement in a pulsed mode of operation with a small duty cycle.

For determining the sodium polarization P_{Na} a count-rate N^+ for right circular and N^- for left circular polarization of pumping light have been measured. In the first case the H(2S) atoms are most likely to be produced with $m_J=+1/2$, the count-rate being maximum. In the second case the count-rate is minimum and N^- is close to N_b; N_b being a background count-rate with a cold sodium cell. Then P_{Na} is derived as follows:

$$P_{Na} = \frac{N^+ - N^-}{N^+ + N^- - 2N_b}$$

The metastable atoms produced in the helium cell are quenched by a retarding electric field, so the background count-rate doesn't exceed $0.01N^+$. This allows the ratio $X=N^+/N^- \approx 30$ to be obtained and results in reducing the statistical error of the polarization measurement, since:

$$\delta P_{Na} \simeq \frac{2\delta x}{(1+x)^2} \simeq \frac{2}{x}\frac{\delta N^-}{N^-} \simeq 1\%$$

The dependence of P_{Na} on sodium cell temperature T°C is presented in Fig. 3. To determine the sodium density $\eta(T)$ we measured the ratio $J(T)/J(T_o)$ where $J(T)$ is the proton current and $J(T_o)$ is the current for the case of a cold cell. This ratio gives us the charge exchange efficiency: $\varepsilon_{Na}=1-J(T)/J(T_o)$ which is unambiguously related to the density.

It is important for the practical use of these results that more than a 90% degree of polarization was achieved at $\varepsilon_{Na}=0.2\div0.3$. When the density increases, the degree of polarization falls apparently due to the pick-up of unpolarized resonance radiation which occurs in spontaneous transitions during optical pumping.

For investigation of polarization relaxation-time the dependence of polarization on the delay-time between the laser pulse and the registration gate has been measured. A polarization of about 60% has been observed even 40 µs after the end of the light pulse. It obviously shows that polarization is partially conserved during interaction of atoms with the cell walls.

5. Proton polarization measurement

The magnetic field in the cell is less than 0.1G. The solenoid (12) with B=570G serves as a spin-filter which freely transmits atoms in states 1 and 2 and fully quenches atoms in states 3 and 4 down to the ground state, similarly to the sodium polarization measurement. Hence, the detecting system (13) receives only the atoms with $m_J=+1/2$, the corresponding count-rate is: $N=N_1+N_2$ [13].

Variations of the laser emission polarization and, correspondingly, of proton polarization result in the count-rate variations:

Positive polarization: $N^+ = N_o\ (1+P)/4$

No polarization: $N^o = N_o/2$

Negative polarizaton: $N^- = N^o(1-P)/4$

Thus, after two measurements we can derive the polarization of protons as follows:

$$P = \frac{2}{C}\,\frac{N^+ - N^-}{N^+ + N^- - 2N_b}$$

N_b being the count-rate in the case of the cold sodium cell, $C=\cos 161^o=0.947$.

The registraton system for metastable atoms is described in chapter 4. Gating is necessary to synchronize the laser emission and the current pulses. During the measurements one of the gates coincides in time with the laser pulse, the other is shifted and used as a reference, thereby the effect of current fluctuations on the count-rate is supressed. Normalization on the value of current is used as well. Modules of scalers and ADC's are designed in standard CAMAC. The computer-aided measurement system is based on the microcomputer "Electronika-60".

In Fig. 3 the count-rate is plotted versus the sodium cell temperature for a 10 µA proton current, the count-rate increases more than 100 times when heating the cell. The measurement of the proton beam polarization with a statistical accuracy of about 3% takes not more than 200s.

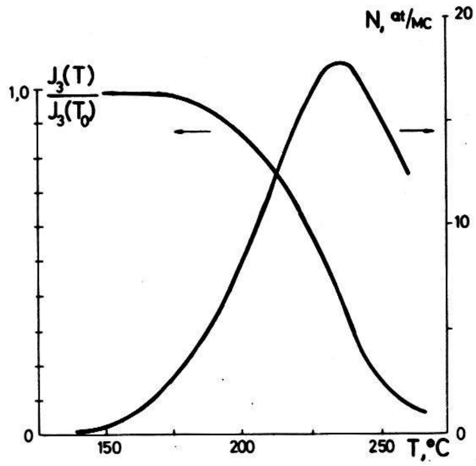

Fig. 3 Dependence of the metastable atmic count-rate N(T) and the proton current through the polarimeter $J_3(T)$ on the temperature of the sodium cell in the polarimeter. $J_3(T)$ is measured by means of CF_3, $J_3(To)$ being the current for the case of a cold cell. The ratio: $N(250^0)/N(To) \simeq 300$.

6. Results (see also reference [15])

6.1 The intensity of the 7keV neutral beam passing through the polarizer was about 15mA as measured by charge exchange in the second helium cell. The efficiency of ionizaton in helium can be easily defined owing to the presence of two cells. The neutral beam is subjected to charge exchange in the first cell, the protons obtained are deflected and the remaining neutrals are measured when being re-ionized in the second cell. The efficiency measured appeared to be around 70%.

6.2 Fig. 4 shows the dependence of the polarized proton current versus the magnetic field strength in the charge exchange region in oriented sodium. The same figure also shows the data taken from ref. [14] illustrating the fact that the divergence growth at the charge exchange in a magnetic field produces a great loss of current. It is seen that here an intensity fall does not occur, unlike a layout with a direct charge exchange [14].

On the contrary, an increase of the value of the magnetic field is accompanied by some increase of the current, which is probably due to an improved compensation of the space charge of the beam. Thus, the main difficulty on the way to developing a new source - the emittance growth at the charge exchange in a strong magnetic field - is overcome.

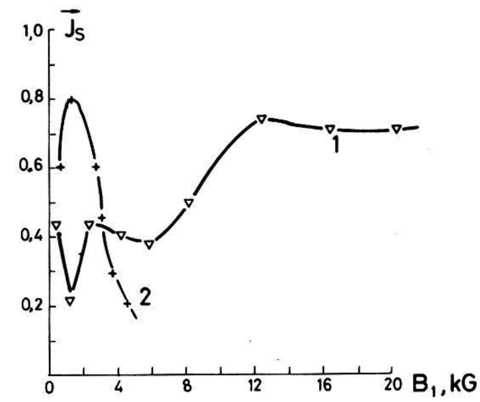

Fig. 4 Current of polarized protons vs the value of the magnetic field B_1 in the optically pumped sodium cell. I) data of this work; 2) data of [14].

6.3 The current of polarized protons was measured by placing the Faraday cup FC_1 just behind the ionizer in the direct beam and by putting FC_2 at the polarimeter exit after a bend and energy separation. The current which passed through the polarimeter was measured in the last Faraday cup FC_3.

The dependence of the polarized proton current in the FC_1 versus sodium cell temperature is presented in Fig. 5. The neutral atoms which pass through the first He-cell without ionization produce a 1.6mA current in the case of the cold sodium cell. While heating the sodium the current of polarized protons is steadily increasing and achieves a maximum value of 5mA.

For measuring the polarization a part of the polarized proton current is bent 90° and directed into the polarimeter. When operating with the retardation system, the value of the background current for the cold sodium cell does not exceed 2% of the maximum polarized current (see Fig. 6). The possibility of removing the background current by retardation allows us to achieve the highest available proton polarization. In the Lamb-shift and intense atomic beam sources the ionization of a non-polarized component gives not less than 10% of the total current and results in a loss of polarization. Energy separation leads to some loss in the intensity. In using a system made in the form of two plane grids the losses ran into ~30-40% of the polarized current.

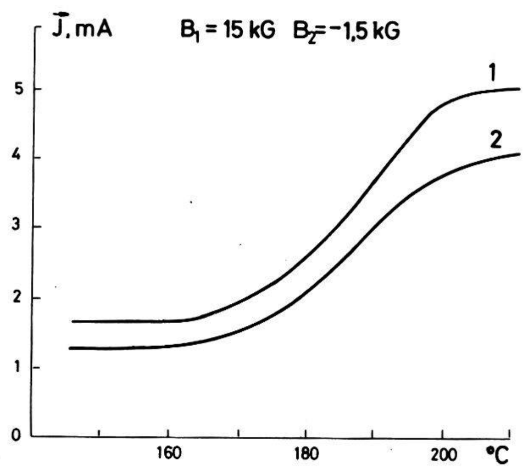

Fig. 5 Dependence of the total current of polarized protons in the direct beam J_1 and in the bent beam J_2 on the temperature of the sodium cell.

In Fig. 6 the results of measuring the proton polarization at a 15kG magnetic field in the charge exchange region are shown. The proton polarization drops with the increase of the sodium vapor density in the cell due to a fall of the sodium vapor polarization.

In our case of high power optical pumping a possible mechanism of polarization is connected with a pick-up of the resonance non-polarized radiation produced during spontaneous transitions. A maximum value of polarization is about 65% and an energy separated polarized proton current in FC_2 (J_s) of 1mA was achieved.

Let us return to Fig. 5. Here at a temperature T_m, corresponding to a maximum value of polarization, the overall intensity of the polarized proton current equals $J_1(T_M)-J_1(T_o)\simeq 2$mA and the polarization is 65%. When the polarized component of the beam has not been separated an overall intensity of about 3mA and ~30% polarization have been obtained.

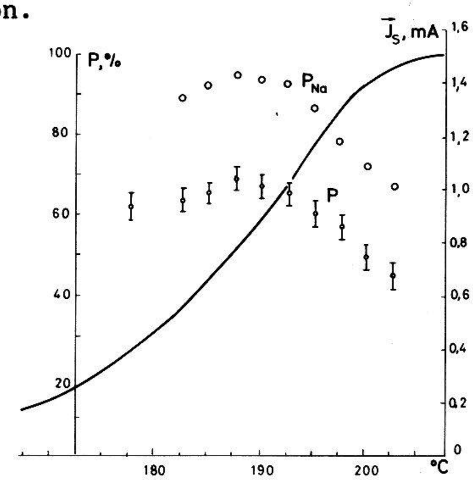

Fig. 6 Dependence of the energy separated polarized proton current J_s, the sodium polarization P_{Na} and proton polarization P on the sodium cell temperature (B_1=15kg - magnetic field strength in optically pumped sodium cell, B_2=-1,5kg - field in the helium ionizer).

The most important result of these measurements is the experimental determination of the overall efficiency of the polarization process, which was estimated as follows: $\varepsilon=J_1/J_o=\varepsilon_{He}^2\cdot\varepsilon_{Na}\simeq 0.7^2\cdot 0.3\simeq 0.15$ where J_o is a current of neutral atoms via the polarization system. Indeed, at J_o=15mA a polarized current of about 2mA has been obtained, which means the absence of losses at the charge exchange in the magnetic field.

6.4 Figure 7 shows the dependence of polarization on the magnetic strength in the region of charge exchange in sodium. It is observed that polarization increases with the increase of a field strength and achieves 65±3% at B_1=15kG. Theoretical calculations [6] show that the lowest boundary for polarization in such a field is 85%. Taking into account that $P_{Na}\simeq 0.9$ and that with ionization in a field of 1.5kG the polarization loss is about 5%, the calculated polarization is determined as: $0.85\cdot 0.9\cdot 0.95\simeq 0.73$, which is close to the experimental data.

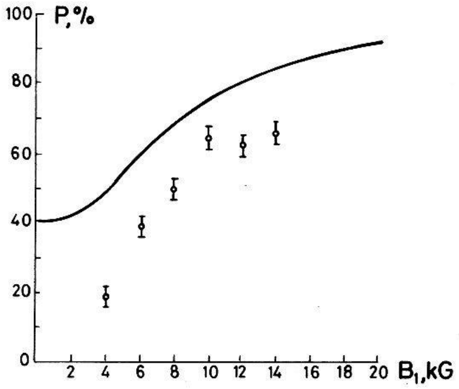

Fig. 7 Polarization vs the value of the magnetic field in the sodium cell.
I) this work; 2) results of calculations [6].

Thus, due to the charge exchange in the strong magnetic field, the depolarization caused by spin-orbital interaction can be considerably reduced. Increasing the magnetic field up to 20-30kG seems to be very promising, since in this case the calculated values of depolarization decreases to 8% and 4% respectively, and proton polarization can range up to 80%. In practice, this can be realized by means of a superconducting solenoid. The increased magnetic field also reduces the probability of changing the value of polarization during spin flipping [6].

7. Summary

In this work the polarization process is experimentally studied in an optically pumped proton source. The dependence of polarization on the value of the magnetic field has for the first time been measured. With charge exchange in a field of 15kG a 65±3% polarization has been obtained. The total current of polarized protons achieved in the direct beam was 2mA. An effective separation is obtained be deflecting the beam with a bending magnet; the fraction of unpolarized component in the beam being not more than 2%. A record high current of polarized protons of 1mA and P=65±3% have been obtained while using the retardation system and 3mA and P=30% for the case without energy separation. The normalized emittance of the beam is evaluated to be about 0.1 π cm·mrad. Optimization of the system for beam separation and output must reduce the losses and make the value of the separated current with a high degree of polarization approach 2mA, as obtained in the direct beam.

The extracted current of polarized H^- ions has ranged up to 60 μA when using xenon instead of helium in the ionizer. It would achieve ~120 μA while using alkali metal vapors.

A further increase in intensity is connected with the improvement of the proton source, a brightness increase and the further development of the system for neutral atoms beam formation.

We assume that a further development of our source would allow us to achieve an intensity for the polarized proton beam as high as 10mA and for the H^- current about 1mA, with an emittance acceptable for high-energy accelerators.

In conclusion we would like to express appreciation to V.G. Roslyakov and V.P. Nizhegorodtsev for their helpful discussions about formation of the intense ion beams; L.P. Vinogradov - for making the most complex units of the source and the laser system; A.I. Berlev - for assistance in electronics; M.A. Prokhvatilov - for developing the computer-aided system of polarization measurements; K.N. Vishnevskii - for valuable assistance in conducting the experiments.

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Editors notes:

In a letter addressed to the editors, Dr. Zelenskii states: "We have made a sodium cell ionizer for production of polarized H^-. The yield of H^- ions from sodium vapor is 2.5 times higher than that from xenon targets."

This paper has been looked at by several specialists at the workshop. They agreed that it should appear in the proceedings with only minor linguistic corrections in order to avoid altering the original meaning. The manuscript of this version has not been sent for control by the authors in order to avoid a delay in the publication.