STATUS OF EFFORTS ON FUNDAMENTAL AND APPLIED STUDIES WITH TRITIUM AT RFNC-VNIIEF

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Overview of efforts in the field of fundamental and applied physics with tritium carried out with participation of RFNC-VNIIEF in 2007-2013 is made. New physical results of studying of muon-catalyzed fusion and neutron-excess nuclei are presented; project of a new experiment on searching for a magnetic moment of neutrino using a tritium source and helium detector is discussed. Description of a tritium support testbed for a plasma focus-type neutron source with intensity of 10^{13} s^{-1} is given. Results of studies in the area of interaction of hydrogen isotopes with structural materials are summarized.

I. INTRODUCTION

In Ref. 1 we overview efforts carried out with participation of RFNC-VNIIEF in 1995-2007 in the field of fundamental and applied physics with application of tritium and tritium-based technologies. This paper presents an overview of efforts completed after 2007, describes the present status and our plans for future studies. It also discusses new results of studies in the fields of fundamental science[2-7] and applied research.[8-12]

II. MUON SCINCE

TRITON facility which enables to handle tritium with activity up to 10 kCi in open laboratories in order to study the processes of muon-catalyzed fusion in various hydrogen isotope (HI) mixtures was designed as a collaborative effort of RFNC-VNIIEF and the Laboratory on nuclear problems (LNP) of Joint Institute of Nuclear Research (JINR, Dubna) in 1995/96 (Ref. 13). Systematic studies of muon-catalyzed fusion in a wide range of varied parameters were performed at this facility within a decade.[14] The results showed that it is impossible to develop a power reactor based on muon-catalyzed fusion. However, the progress of theoretical and experimental research of muon-catalyzed fusion allows using this phenomenon to study many-body interactions.

In 2010 we completed study of the reactions of radiative capture $d+d\rightarrow {}^4He+\gamma$ from the state J=1 of muonic molecule ddμ (Ref. 2). An experiment to study reaction $pt\mu \rightarrow {}^4He\mu + e^+e^- + 18.79$ MeV (Ref. 3) is scheduled for 2013.

With this aim VNIIEF developed a liquid-tritium target with capacity of 50 cm^3 (Fig. 1) where a 1% tritium in protium will be studied at muon beam in JINR LNP. TRITON facility will be used for ensuring radiation safety of target experiments (Ref. 13).

Unfortunately, efforts in this direction are curtailed and disposition of TRITON facility is planned for 2014-2015.

III. STUDIES OF CHARACTERISTICS OF NEUTRON-EXCESS NUCLEI

Development of unique equipment for handling tritium in undedicated laboratories[15, 16] which enables to generate a singly –in-the-world (to date) tritium nuclei beam at JINR LNP U-400M cyclotron as well as usage of radiation-safe tritium targets ensured unique feasibility for studying structures of atomic nuclei located at the boundary of stability relative to spontaneous neutron emission.

Series of experiments carried out with the above set of equipment enabled the first studies of the spectra of states of ultra neutron-excess hydrogen and helium nuclei with mass numbers 4 – 5 (Refs. 17-20) and 8 – 10 (Refs. 4, 5, 21, 22), respectively, and determination of properties of these nuclei which is very significant for pursuing the theory of few-nucleon nuclear systems. Properties of ground and excited states of a number of nuclei ^4H ^5H, ^9He, ^{10}He, located beyond the limit of neutron stability were reliably ascertained for the first time; new important data which define the structure of nucleus ^8He which, according to current assumptions, has in its structure ^4He core and halo formed by four neutrons were obtained.

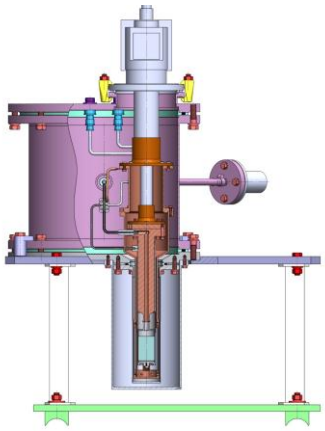

Fig. 1. Liquid-tritium target.

Spectra of lower states of ^{8}He and ^{10}He nuclei populated in ^{6}He(t, ^{8}He)p and ^{8}He(t, ^{10}He)p studied at small angles in the system of mass center at ^{6}He and ^{8}He nuclei beams energy ~ 25 MeV/nucleon were obtained.[21, 22] Ground 0^{+} state of ^{8}He and its excited states 2^{+} at excitation energy E* = 3.6–3.9 MeV and (1^{+}) E* = 5.3–5.5 MeV were obtained with cross-sections 200, 100–250 and 90–125 μ_B/av, respectively. Revealed near-threshold anomaly of ^{8}He spectrum was explained by filling of 1^{-} state, i.e. soft dipole excitation mode inherent to ^{8}He nucleus which has a four neutron halo.

Structure and properties of ground resonance state of ^{10}He nucleus was ascertained for the first time: energy of its ^{8}He+n+n disintegration equaling to 2.1 ± 0.2 MeV was determined; shape and width $\Gamma \approx 2$ MeV were determined. Well-defined structures of interference of three ^{10}He nucleus states were found in measured angular correlations of daughter products: ground state with spin-parity 0^{+}, first excited state with spin-parity 1^{-} and energy 4 – 6 MeV and second state with 2^{+} with energy above 6 MeV. The found order of sequence of ^{10}He levels points to sharp decrease of a neutron shell N = 8 in this twice magic nucleus which is mostly peculiar for extremely high proton-neutron asymmetry.

IV. HIGH-INTENSITY PLASMA FOCUS-TYPE NEUTRON SOURCE

Studies of physical phenomena and processes of generation of neutron and x-ray radiation in spherical gas-discharge chambers with plasma focus (PF) have been performed in RFNC-VNIIEF since early 1960s Refs. 23, 24). To date VNIIEF has developed two types of experimental plants based on spherical chambers with PF which include current pulse generators (CPG) with capacitive or inductive energy storage.[6] These facilities cover a wide range of initial energies (from 10^{-1} up to 10^{3} kJ) and provide currents of ~100 kA up to ~2 MA in gas-discharge chambers. Under such conditions spherical chambers generate neutron pulses of ~10-100 ns with integrated neutron yield of $7{\cdot}10^{5}$ up to $3{\cdot}10^{11}$ and energy 2.45 MeV. Maximum yield of $4{\cdot}10^{12}$ DT-neutrons at discharge current of ~1.5 MA was measured in these experiments during feed

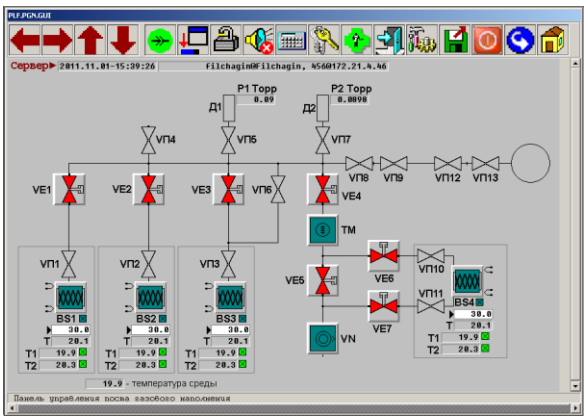

Fig. 2. Layout of MCF-200 gas filling station.

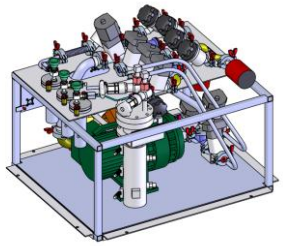

Fig. 3. General view of a gas filling station of MCF-200.

ing of chambers filled with equicomponent D-T mixture from the explosive magnetic generator.[24]

Within recent three years VNIIEF developed a mobile capacitor facility MCF-200 (Ref. 6). The facility constitutes a CPG where energy is stored, current pulse is shaped and transferred to a plasma neutron chamber (PNC).

MCF-200 components except control panel are located in a transportable wagon. It is controlled from a PC-based remote panel (distance up to 100m) and started either by control panel or external device.

During experiment the chamber with PF was predegassed by gas filling station (GFS) up to residual pressure (10^{-1}-10^{-2} Pa) and then filled with deuterium or equicomponent D-T mixture up to working pressure $(1–3){\cdot}10^{3}$ Pa.

GFS layout is shown in Fig. 2 and general view in Fig. 3. Functionally, GFS includes vacuum-pumping and gas filling systems, a control unit and a PC-based control panel. Pumpdown, filling of the chamber with HI and their absorption after experiment are controlled remotely.

Vacuum-pumping system includes a forevacuum pump and a turbomolecular pump (see Fig. 2). Metal-hydride traps with intermetallic compound are used for HI storage, feeding and disposal: BS1- to feed deuterium, BS3 – to feed D-T mixture. Trap BS2 of similar design serves as a backup for absorption of D-T mixture in case of "poisoning" of BS3 trap metal hydride. BS4 trap of a pump-through type serves for more complete absorption of D-T mixture.

At discharge current of ~1.5 MA the chamber generates 75–80 ns neutron pulses at half-maximum and integrated yield of $\sim 1.3{\cdot}10^{13}$ D-T neutrons. A two-peak structure of the neutron pulse is recorded in the experiment (Fig. 4). Contribution of the second peak into integrated yield is ~20-30%, time gap between peaks - 150 ns. Neutron fluence at the chamber casing along its axis is $\sim 9{\cdot}10^{9}$ cm^{-2} in spectral range 0.3–14.5 MeV. Average neutron energy in specified region of spectrum is 11.9 MeV. Fraction of neutrons within energy range of 13.5–14.5 MeV makes up 78.4% of the total spectrum.

V. TRITIUM SOURCE WITH ACTIVITY OF 40 V

V.A. MCI AND HELIUM DETECTOR TO MEASURE MAGNETIC MOMENT OF NEUTRINO

In 2000s VNIIEF was developing a high-intensity artificial source of (anti)neutrino with activity up to 40 MCi

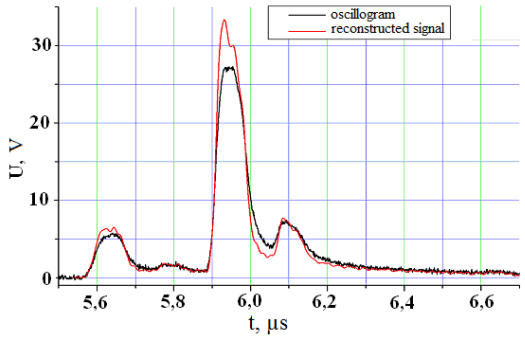

Fig. 4. Neutron pulse structure

(Ref. 25) for the experiment on searching for a neutrino magnetic moment (NMM) of at the level of 10^{-12} Bohr magneton with detectors which record neutrino scattering at the electron with recording threshold ~ 10 eV (Ref. 26). At that time VNIIEF proposed a layout of a tritium source where 4 kg of tritium were placed inside 80 titanium tritide tubular beds (TTB). One TTB contains 50 g of tritium (500 kCi) and is handled in the same manner as a tritium storage bed. Issues related to transportation and handling of such TTB at all stages of its life cycle were worked up.[25] ITEP and JINR were the developers of detectors. But those days an attempt to develop detectors with required characteristics failed.

In 2012 a new proposal sprang up.[7] The idea lies in detecting scattering of neutrino at electrons of atoms of liquid: $e^- + \nu = e^- + \nu$. According to estimates in the field of imparted energy up to 1 KeV, a significant increase of cross-sections as against cross-sections of elastic scattering at free electron is observed in the channel electromagnetic interaction. A tritium (anti)neutrino source is the best candidate for the experiment with such detector. Constraint on laboratory limit of NMM at the level 10^{-12} μ_B (10 times less than existing constraints) can be obtained if detector is filled with 10 kg of helium and activity of an artificial tritium neutrino source is 40MCi.

Experimental setup is as follows (Fig. 5) (Ref. 27): detector which is a vessel filled with 10kg of liquid helium is scanned by photoelectronic multipliers which record flashes of light from neutrino scattering at helium

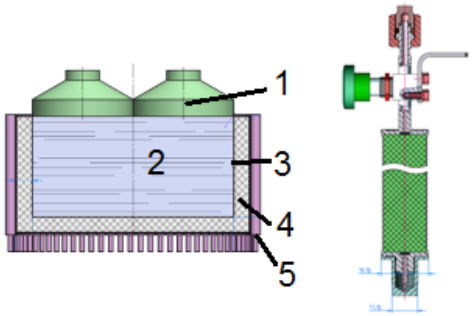

Fig. 5. Setup of experiment for measuring NMM with tritium source and helium detector: 1-photoelectronic multipliers; 2- liquid helium; 3-layer of tetraphenylbutadiene; 4-heat shield; 5-TTB.

electrons. Detector is surrounded at its periphery with tritium tubular beds. At 1-4 kg of tritium average neutrino flux density at detector surface is (1-4)x 10^{14} $cm^{-2}\cdot s^{-1}$.

Optimization of TTB design as applied to specifics of a liquid-helium detector is underway; possibility of conducting experiment in an underground laboratory with low background level (~600 m of water equivalent) is considered.

VI. HYDROGEN AND HELIUM IN STRUCTURAL MATERIALS

As refers to this avenue of RFNC-VNIIEWF activities, in work[1] we confined ourselves only to description of techniques and equipment developed to study properties of structural materials containing radiogenic ^{3}He produced in the matrix of materials by the method of "tritium trick". Since then, we accomplished efforts on studying nickel,[8] stainless steel (SS) (Ref. 9) as well as alloys CrNi40MoCuTiAl (Ref. 10) and CrNi35MoTiAl (Ref. 11).

Basic outcomes of investigation into interaction of Ni containing radiogenic ^{3}He with hydrogen can be summarized as follows.[8] Presence of radiogenic ^{3}He in pure nickel even at the level of 5.6 appm causes disastrous changes: metal mechanical properties are degraded resulting in sharp decrease of its plasticity and increase of brittleness; it also leads to formation of open through porosity resulting in development of molecular flow through the cold sample in permeability tests.

Presence of ^{3}He in SS 12X18H10T (Ref. 9) entails formation of a new high-energy state – traps for hydrogen (Fig. 6). In the range of studied ^{3}He concentrations in SS (up to 160 appm), the quantity of hydrogen captured by SS defects increases monotonically up to concentration 100 appm and then tends to saturation. With increase of ^{3}He concentration up to ~500 appm concentration of ^{3}He platelets also goes up; at that, platelets form two characteristic groups according to their sizes ~8-10 and ~15-30nm. Hydrogen and ^{3}He at concentrations up to 500 appm as well as their joint impact did not significantly affect the ultimate strength of samples made of SS 12Cr18Ni10T in the temperature range 273-873 K. Maxi-

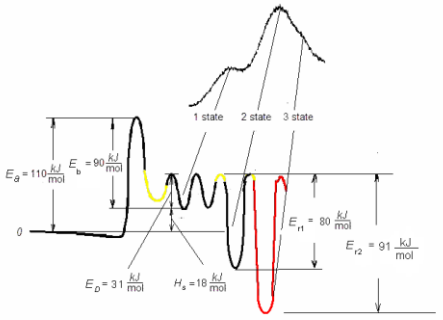

Fig. 6. Energy diagram of interaction of hydrogen with SS 12Cr18Ni10Ti containing 75 appm ^{3}He.

mum change of characteristic σ_u, induced by ^{3}He is observed at ~500 appm ^{3}He and temperature 873 K; compared to initial value, tensile strength decreases by 12-12.5%.

Impact of high-pressure hydrogen (80 MPa) on reference samples insignificantly (~6 %) decreases plastic SS characteristics whereas ^{3}He at 500 appm concentrations gives decrease of plasticity characteristics by 71-73%, and synergetic impact of hydrogen and ^{3}He adds to this tendency (plasticity characteristics decrease by 77 - 80%).

Such behavior of material is predictable and fully falls within existing assumptions pertinent to behavior of structural materials containing radiogenic helium when they interact with hydrogen. Therefore, results obtained in Ref. 10 turned out to be quite unexpected. Studies of alloy CrNi40MoCuTiAl with ^{3}He concentrations up to 190 appm showed that at room temperature and in inert environment plastic characteristics of the alloy decrease by 30-34%, whereas at temperature 600 °C the dependence is non-monotonic – in the range of ^{3}He concentrations up to 80 appm plastic properties of material decrease and then start increasing at concentrations up to 190 appm. Such behavior of material requires extra studies. The more so because testing of the alloy CrNi35WTiAl of the same type containing 560 appm ^{3}He within temperature range up to 600 °C did not exhibit any anomalous deviations from present assumptions.[11] At temperature 600 °C tensile strength of the alloy containing 560 appm ^{3}He decreases by 20 and 35% in helium and hydrogen environment, respectively, as against similar tests at room temperature. Changes of conventional yield strength are minor and do not exceed 2% which is within measurement error. In experiments carried out in hydrogen at 600 °C we could not determine $\sigma_{0,2}$ since failure of sample occurred at elastic region.

VII. APPLICATION OF NONPOROUS ALUMINA-BASED CERAMICS FOR TRITIUM DEVICES

One of the main problems in developing devices which operate with tritium-containing media at elevated temperatures is diffusion leakages of tritium. In order to reduce diffusion leakages of tritium different protective coatings are used, additional vacuum-degassed cavities are placed between power and hermetically sealed housings, a heater is placed into an inner cavity of the power housing, etc. which leads to significant overdesigning.

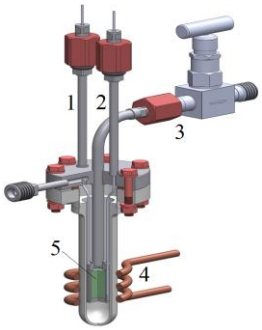

Fig. 7. A prototype of the bed for tritium storage: 1, 2 – impermeable channels for thermocouple insertion (T2, see fig.6); 3 – tritium supply/recovery piping; 4 – inductive heater; 5 – titanium powder.

Application of nonporous Al_2O_3 ceramics as structural material for such types of devices can drastically improve the situation.[12] Comparative studies of permeability of deuterium through chambers manufactured from austenitic stainless steel AISI304 and Al_2O_3 ceramics at temperature 773 K and deuterium pressure of 1200 mbar have shown that the flux of diffusing deuterium from the steel chamber makes up $8\cdot10^{-5}$ cm^3/s; from the ceramic chamber it does not exceed sensitivity of the method of measurement which is $1.5\cdot10^{-7}$ cm^3/s.

This makes feasible direct inductive heating of the object interacting with tritium (Fig.7) (Ref. 12).

VIII. CONCLUSIONS

VNIIEF experts together with colleagues from JINR and ITEP carried out efforts and obtained world-level physical results in the field of research of reactions of radioactive capture d+d→ ^{4}He+γ from the state J=1 of muonic molecule ddμ and in the field of research of characteristics of neutron-excess nuclei of ^{8}He и ^{10}He using equipment and techniques of handling tritium and tritium-containing matters developed at VNIIEF. A mobile plasma focus-type neutron source with record-breaking integrated yield of DT neutrons ~$1.3\cdot10^{13}$ is developed. Preparation of experiments to determine probability of reaction ptμ → ^{4}Heμ + e^+e^- and search for a magnetic moment of neutrino at the level of 10^{-12} Bohr magneton with a detector which uses effect of neutrino scattering at electrons of liquid helium atoms with high-intensity (up to 40 MCi) tritium source is undergoing.

Comprehensive studies of interaction of hydrogen isotopes with nickel and stainless steel 12X18H10T containing ^{3}He performed in the field of applied research; similar work is carried out with high-strength austenitic alloys CrNi40MoCuTiAl and CrNi35MoTiAl; results of studies of applicability of alumina-based ceramics as SM in devices operating in tritium-containing environment at high temperatures and status of efforts on development of structures with their application are presented.

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