DIVISION OF HIGH ENERGY PHYSICS

The most important scientific results for 2019

Measurements of the transverse momentum p_{ll} $(l = e, \mu)$ and of the angular variable $\varphi*$ distributions of Z-boson decay to lepton pairs with the ATLAS detector

A. Ezhilov, O. Fedin, M. Levchenko, V. Maleev, Y. Naryshkin, D. Pudzha, V. Solovyev,– High Energy Physics Division, NRC "Kurchatov Institute" - PNPI

The new precision measurements of the transverse momentum p_{ll} $(l = e, \mu)$ and of the angular variable $\varphi*$ was done in ATLAS experiment. These measurements allow to compare the results with the theoretical predictions probing different levels of perturbative QCD.

The analysis is performed using 36.1 fb^{-1} data of the proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV collected by the ATLAS experiment at the LHC in 2015 and 2016. Measurements are performed using the selected Z-boson candidates decaying to the electron-pair and muon-pair final states near Z-pole mass region (66-116 GeV) in all rapidity range. All measurements of the p_T and $\varphi*$ distributions are affected by the detector acceptance and events selections. The differential distributions within fiducial volume are corrected to detector effects and bin-to-bin migrations using Bayesian unfolding method.

Measurements of the $Z/\gamma* \rightarrow ee$ and $Z/\gamma* \rightarrow \mu\mu$ cross-sections, differential (Fig.1) and integrated, have been performed. The cross-section results from the individual channels were combined using the χ^2 minimization using the best linear unbiased estimator prescription. The fiducial cross-section measurements are compared with fixed-order perturbative QCD predictions. The combination is performed on the Born particle level, resulting an integrated combined cross-section $\sigma_{fid}(pp \rightarrow Z/\gamma* \rightarrow ll)$=736.2 ± 0.2 (stat) ± 6.4 (syst) ± 14.7 (lumi) pb.[1]

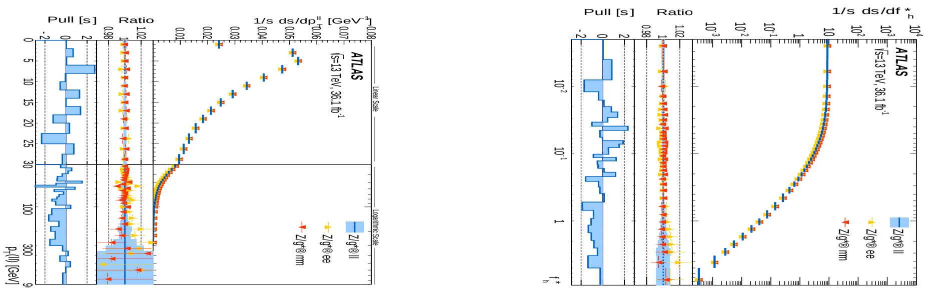


Fig. 1. The measured normalized cross-section as a function of p_T (left) and $\varphi*$ (right) for the electron and muon channels and the combined result as well as their ratio with the total uncertainties (blue band). The pull distribution between electron and muon channels, defined as the difference between the two channels divided by the combined uncorrelated uncertainty, is also shown.

[1] ATLAS Collaboration, A. Ezhilov, M. Levchenko, V. Maleev, Y. Naryshkin, D. Pudzha, V. Solovyev, O. Fedin: arXiv:1912.02844

μSR study of the dynamics of internal magnetic correlations in *Tb(Bi)MnO₃* multiferroic in magnetically ordered and paramagnetic states

S.I. Vorob'ev, A.L. Getalov, E.N. Komarov, S.A. Kotov, G.V. Shcherbakov – High Energy Physics Division, NRC "Kurchatov Institute" - PNPI
E.I. Golovenchits, V.A. Sanina – Ioffe Physical–Technical Institute Russian Academy of Sciences

A comparative *μSR* study of the dynamics of internal magnetic correlations in $Tb_{0.95}Bi_{0.05}MnO_3$ multiferroic in the temperature range of 10–290 K has been studied.

The *μSR* study of the $Tb_{0.95}Bi_{0.05}MnO_3$ multiferroic has revealed a number of features that were not observed in the study of other multiferroic manganites, including $TbMnO_3$.

Separation into two phases with different relaxations of the polarization of muons in the basic matrix of the crystal and the phase separation regions has been detected for the first time both in a magnetically disordered state at $T < T_N = 40$ K and in a paramagnetic state in a transverse magnetic field of 290 *G* in a temperature range of 80–150 K. A muon ferromagnetic complex (Mn^{3+}–Mu–Mn^{4+}), where the hyperfine interaction in a muonium depolarizes a muon in a time less than 10^{-8} *s*, is formed at $T < 40$ K in phase separation regions containing pairs of Mn^{3+} and Mn^{4+} ions, as well as electrons that recharge them. In the matrix of the original crystal containing only Mn^{3+} ions, a muonium is formed with a broken hyperfine bond. In this case, muons are depolarized at a high rate because of their interactions with the local magnetic fields of a cycloid.

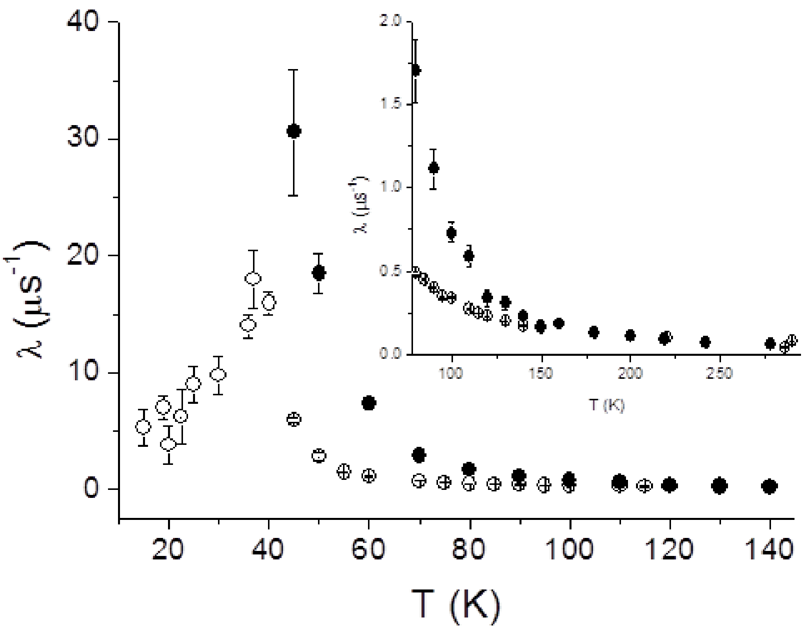


Fig. Temperature dependence of the relaxation rates of the muon polarization (open circles) λ_s in zero magnetic field and (closed circles) λ_F in a magnetic field of $H = 290$ *G*.

At temperatures of 80–150 K, one phase in the phase separation regions constitutes approximately 50% and is characterized by long relaxation times about 10 μs (described by the Gaussian relaxation function). The other phase is formed by Mn^{3+}–Mn^{3+} correlations in the short-range magnetic order regions in the matrix of the original crystal, which are weakly sensitive to a magnetic field of 290 *G*.

[1] S.I. Vorob'ev, A.L. Getalov, E.I. Golovenchits, E.N. Komarov, S.A. Kotov, V.A. Sanina, and G.V. Shcherbakov. JETP Letters, 2019, Vol. ***110****, No. 2, pp. 133 – 139.*
[2] A.L. Getalov, S.I. Vorob'ev, E.N. Komarov, S.A. Kotov, and G.V. Shcherbakov. MNK2018 program for processing data from the μSR experiment. Certificate of state registration of computer programs № 2019663498 of 10.17.2019.

Nuclear-matter distributions in the proton-rich nuclei ^{7}Be and ^{8}B from intermediate-energy proton elastic scattering in inverse kinematics

G.D. Alkhazov, A.V. Dobrovolsky, A.G. Inglessi, A.V. Khanzadeev, G.A. Korolev, G.E. Petrov, L.O. Sergeev, A.A. Vorobyev, V.I. Yatsura –
High energy physics division, NRC «Kurchatov institute» – PNPI

In order to study the spatial matter distributions in the proton-rich exotic nuclei ^{7}Be and ^{8}B, absolute differential cross sections for elastic p^7Be and p^8B small-angle scattering were measured in inverse kinematics at an energy of 0.7 GeV/u. The experiment was performed at the GSI Darmstadt. The main part of the experimental set-up was the ionization chamber IKAR, filled with pure hydrogen at a pressure of 10 bar, which served simultaneously as a gas target and a recoil proton detector. The active target IKAR was developed at PNPI and was originally used in experiments on small-angle hadron elastic scattering. The recoil protons were registered in IKAR in coincidence with the scattered beam particles. An analysis of the shape of the measured differential cross sections makes it possible to determine the nuclear matter distributions and radii of the nuclear core and halo.

The measured cross sections were analysed using the Glauber multiple scattering theory and applying four parameterizations of phenomenological nuclear density distributions labeled as SF (symmetrized Fermi), GH (gaussian-halo), GG (gaussian-gaussian) and GO (gaussian-oscillator). The root-mean-square (rms) nuclear matter radii $R_m = 2.42(4)$ fm for ^{7}Be and $R_m = 2.58(6)$ fm for ^{8}B were determined, the value deduced for ^{7}Be being larger than the matter radii obtained in previous experiments. The deduced nuclear matter density distributions are shown in the Fig. According to the present work [1], ^{7}Be is a rather compact nucleus, whereas the radial density distribution deduced for ^{8}B clearly indicates a proton halo structure with the rms halo radius $R_h = 4.24(25)$ fm. In the analysis, the rms radius of the ^{8}B proton distribution was also determined to be $R_p = 2.76(9)$ fm. This value is in agreement with theoretical calculations.

Note that the obtained results for ^{8}B and ^{7}Be are important for nuclear astrophysics because these nuclei play an essential role in the solar neutrino production.

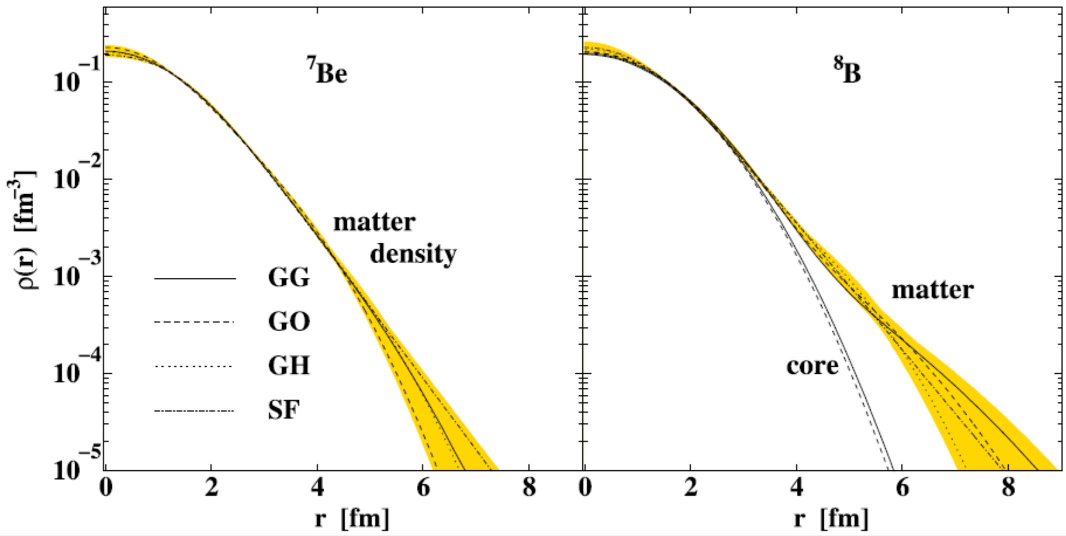


Fig. Nuclear matter density distributions in ^{7}Be and ^{8}B deduced from the measured cross sections using different parameterizations (GG, GO, GH and SF) of the density distributions.

[1] A.V. Dobrovolsky, G.A. Korolev, A.G. Inglessi et al., Nucl. Phys. A, 2019, Vol. ***989****, pp. 40 – 58.*

Observation of *CP* violation in D^0 meson decays

LHCb collaboration,
G.D. Alkhazov, N.F. Bondar, A.D. Chubykin, A.A. Dzyuba, A.G. Inglessi, K.A. Ivshin, S.N. Kotryakhova, O.E. Maev, D.A. Maisuzenko, N.R. Sagidova, A.A. Vorobyev, N.I. Voropaev – High energy physics division NRC «Kurchatov institute» – PNPI

Searches for new sources of *CP* violation are very important for understanding of the Universe evolution during the first seconds after the Big Bang. A difference between particles and antiparticles, which manifests itself in noninvariance of the fundamental interactions under the combined action of charge conjugation (*C*) and parity (*P*) transformations, is one of the necessary conditions proposed by A.D. Sakharov for the dynamical generation of the baryon asymmetry of the Universe. In the Standard Model (SM) of particle physics, *CP* violation occurs in the quark sector. This effect relates to an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa quark-mixing matrix. Before 2019, only processes connected with the transformation of the down-type quarks (*d*, *s*, *b*) were known as *CP* violating. The charm quark belongs to the up-type quark family. The SM predicts very tiny (typically of the order of 10^{-3}–10^{-4}) effects of *CP* violation for charm hadrons.

In 2019, the LHCb collaboration reported about an observation of *CP* violation in D^0 meson decays [1]. In order to establish the effect, one has to find a different probability of the decay of D^0 and anti-D^0 mesons for a particular decay channel. The initial numbers of particles and antiparticles are taken into account using so called tagging procedures. In the LHCb analysis, two tagging methods have been used. The first method uses a strong decay of D^* mesons, where the charge of the π-meson fixes the flavour of the D^0 meson. The second method uses so-called semimuonic decays of *b*-hadrons, where the electric charge of the muon determines the tag-decision. The *CP*-even decays $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ are used to cancel out the detection asymmetry effects. The difference between these rates eliminates an influence of the D^0 production asymmetry, as well as asymmetries of the tagger-particles detection. A non-zero value of the ΔA_{CP} observable is an indication that the *CP* symmetry is broken.

LHCb has measured $\Delta A_{\mathrm{CP}}^{\mathrm{exp}}$ to be $(-15.4 \pm 2.9) \times 10^{-4}$, where the statistical and systematic uncertainties are combined. Thus, the effect of *CP* violation has been observed with the significance above 5.3 standard deviations. This is the first observation of CP violation in the decay of charm hadrons.

*[1] LHCb Collaboration, Phys. Rev. Lett., 2019, Vol. **122**, p. 211803.*

Observation of three new pentaquark states

LHCb collaboration,
G.D. Alkhazov, N.F. Bondar, A.D. Chubykin, A.A. Dzyuba, A.G. Inglessi, K.A. Ivshin, S.N. Kotryakhova, O.E. Maev, D.A. Maisuzenko, N.R. Sagidova, A.A. Vorobyev, N.I. Voropaev – High energy physics division NRC «Kurchatov institute» – PNPI

Due to confinement, quarks and antiquarks can form only colour-singlet hadron states. Two widespread types of hadrons are baryons (three valence quarks) and mesons (quark-antiquark states). Some other combinations are theoretically not forbidden, for example tetraquarks (two quarks and two antiquarks) and pentaquarks (four quarks and one antiquark). A great success of the LHCb collaboration was a discovery of heavy pentaquarks in 2015 [1]. These particles contain a pair of heavy quarks (charm and anticharm). They were discovered in $\Lambda_b^0 \to pK^- J/\psi$ decays. The results of both model-dependent and model-independent data analyses indicated an intermediate resonance $P_c^+ \to J/\psi\ p$.

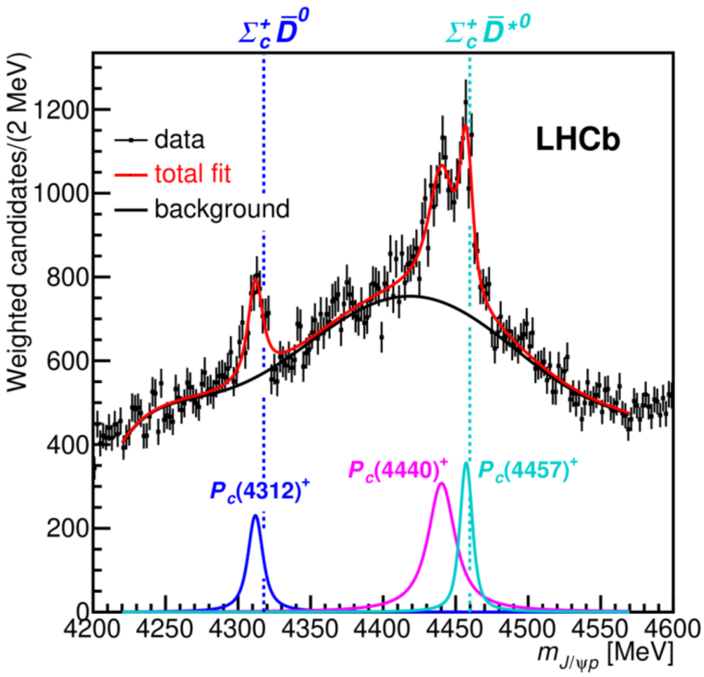


Fig. Mass spectrum of the $J/\psi\ p$ system for selected events. Blue, magenta and cyan lines show contributions from new pentaquark states. Vertical dotted lines show thresholds for other possible open charm decay channels.

In 2019, LHCb published a new data analysis on a search of pentaquark states with hidden charm in the $\Lambda_b^0 \to pK^- J/\psi$ decay channel [2]. A dataset collected between 2015 and 2019 was used. The collected statistics was increased by a factor of ten due to higher integrated luminosity, higher Λ_b^0 production cross section at 13 TeV and also due to improved selection algorithms.

Three narrow peaks have been observed in the $J/\psi\ p$ mass spectrum (see the Fig.). They correspond to three new narrow resonances named $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$. Masses, widths, as well as partial contributions of these resonances into the Λ_b^0 decay have been determined by using a one-dimensional approximation of the $J/\psi\ p$ mass spectrum. The discovered particles have masses right below the thresholds for the open charm decay channels $\Sigma_c^+ \overline{D}^0$ and $\Sigma_c^+ \overline{D}^{*0}$. This allows us to interpret these resonances as loosly bound broad molecular baryon-meson states. However, they can also be interpreted as strongly bound compact hadronic clusters (so-called hadrocharmonium).

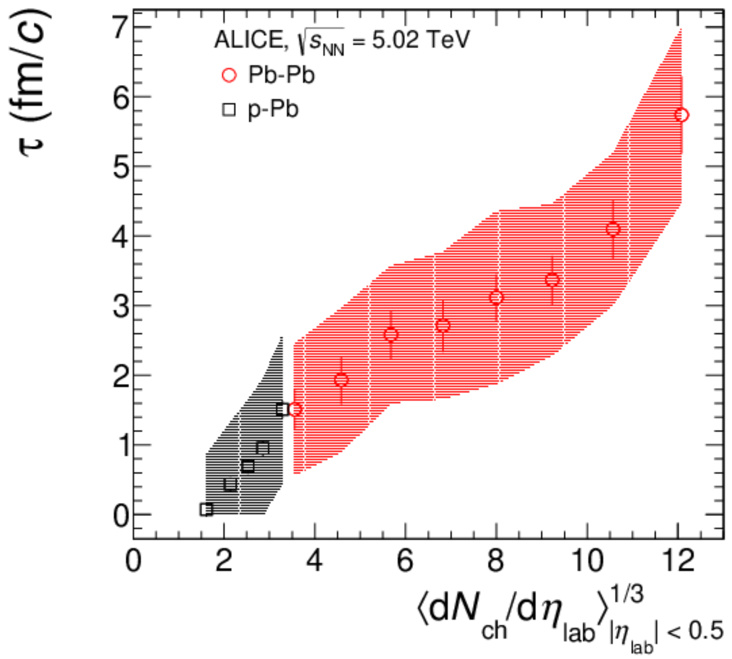
*[1] LHCb Collaboration, Phys. Rev. Lett., 2015, Vol. **115**, p. 072001.*
*[2] LHCb Collaboration, Phys. Rev. Lett., 2019, Vol. **122**, p. 222001.*

Chronometry of evolution of the dense hadronic medium in central collisions of ultrarelativistic heavy ions at the LHC

V. Ivanov, E. Kryshen, A. Khanzadeev, M. Malaev, V. Nikulin, V. Ryabov, Yu. Ryabov, V. Samsonov, M. Zhalov (PNPI, ALICE Collaboration)

One of key parameters for the description of evolution of a high-temperature quark-gluon plasma (QGP) formed in the interaction zone of central collisions of ultrarelativistic nuclei is the lifetime of the hadronic medium, τ_A, which is produced in the process of hadronization of the QGP. An estimate of this characteristic can be obtained by comparing yields of such hadronic resonances with different lifetimes as ρ mesons, Kaons, ϕ mesons, and pions in central and peripheral nuclear collisions. With a dominant contribution of the PNPI group, such an analysis has been carried out in collisions of lead nuclei at $\sqrt{s_{NN}}$ equal to 2.76 and 5.02 TeV [1,2] in the ALICE experiment.

The figure (e-Print: arXiv:1910.14419 **[nucl-ex]**) shows the obtained lifetime of the hadronic medium in nucleus-nucleus and proton-nucleus collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of the multiplicity of produced charged hadrons. One can see that at high multiplicities, which are characteristic of events with formation of the QGP, the lifetime of hadronic medium reaches the values as high as 6 fm/c, which are comparable to the QGP lifetime.



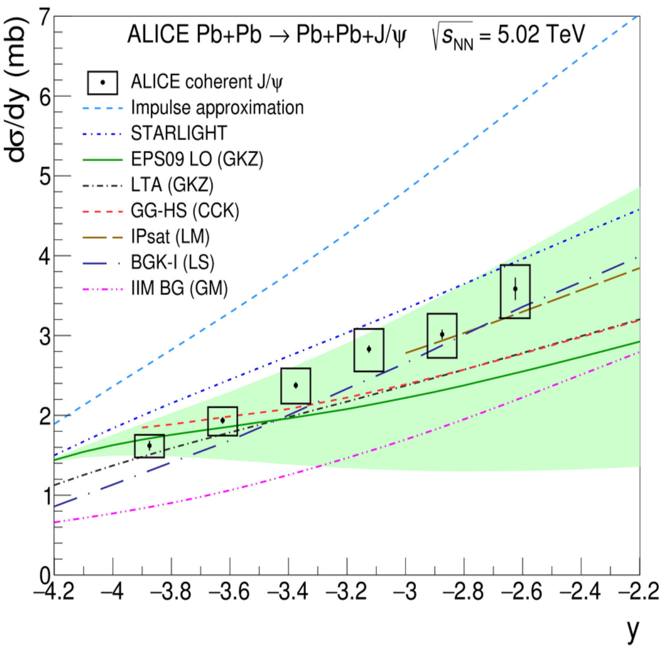
[1]. Production of the ρ(770) meson in pp and PbPb collisions at √sNN =2.76 TeV ALICE Collab., Phys.Rev. C99 (2019) no.6, 064901

[2]. Evidence of rescattering effect in Pb-Pb collisions at the LHC through production of K(892) and ϕ(1020) mesons, ALICE Collab., e-Print: arXiv:1910.14419 [nucl-ex]

Exclusive photoproduction of J/Ψ on nuclei in ultraperipheral collisions at $\sqrt{s_{NN}}$=5.02 TeV

V. Ivanov, E. Kryshen, A. Khanzadeev, M. Malaev, V. Nikulin, V. Ryabov, Yu. Ryabov, V. Samsonov, M. Zhalov, V. Guzey (PNPI, ALICE Collaboration)

The soft gluon density in nuclei $G_A(x,\mu^2)$ is a key parameter characterizing properties of high-temperature quark-gluon matter formed in central collisions of ultra-relativistic nuclei. A promising way to study the small-x gluon distributions in nuclei is offered by the measurement and analysis of quarkonium photoproduction in ultraperipheral collisions (UPCs) of heavy ions at the Large Hadron Collider. The ALICE collaboration measured exclusive photoproduction of J/Ψ and Ψ(2S) vector mesons in Pb-Pb UPCs at $\sqrt{s_{NN}}$=5.02 TeV in the -4<y<-2.5 rapidity interval [1], see the figure. The measured values agree with a reasonable accuracy with the theoretical predictions of the PNPI group (the curve labeled GKZ in the figure).



Using the ratio of the nucleus and nucleon cross sections, the analysis of this data allowed one practically model-independently to determine the factor of nuclear shadowing $R_g \approx 0.8 - 0.9$ for 0.03< x<0.07 at $\mu^2 \approx 3.0$ GeV^2. Besides, the measured ratio of the Ψ(2S) and J/Ψ photoproduction cross sections in this region of x is approximately equal to R = 0.150±0.018(stat.)±0.021(syst.), which is close to the predictions of [2] and practically coincides with the respective cross section ratio for the proton target measured at HERA. Hence, one can conclude that the magnitudes of nuclear shadowing do not significantly differ in these two cases.

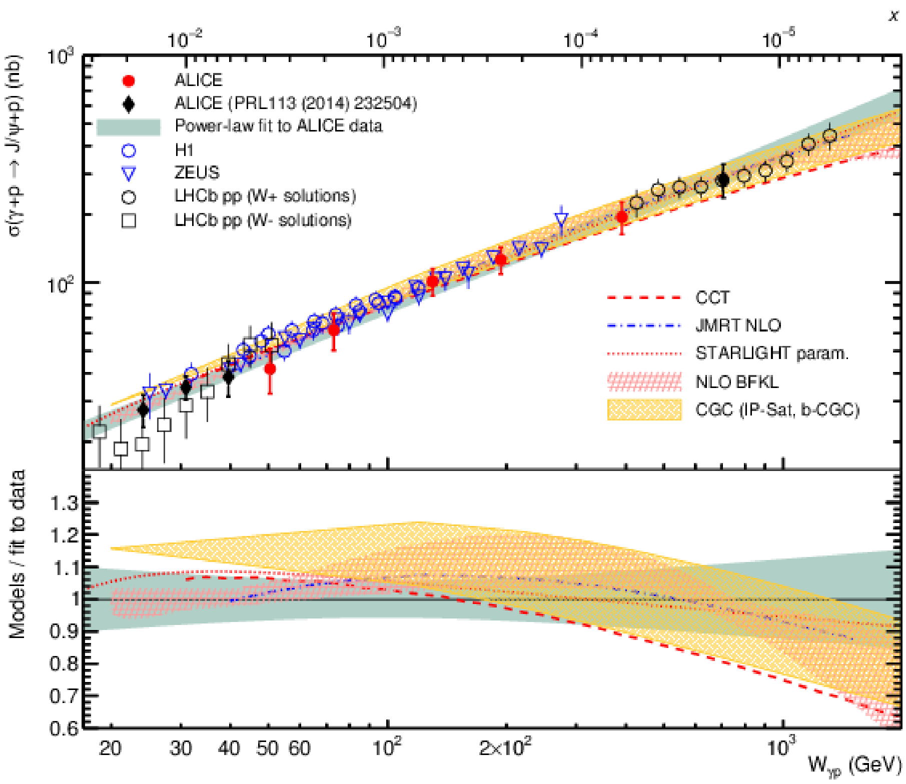
[1] **Coherent J/ Ψ photoproduction at forward rapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02\ TeV$** Collaboration ALICE **Phys.Lett. B758 (2019) 134926.**

[2] **Coherent photoproduction of vector mesons in ultraperipheral heavy ion collisions:Update for run 2 at the CERN Large Hadron Collider,** V.Guzey, E.Kryshen, M.Zhalov (PNPI NRCKI) **Phys.Rev. C93 (2016) 055206**

Photoproduction of J/Ψ mesons in ultraperipheral proton-nucleus scattering at the Large Hadron Collider

V. Ivanov, E. Kryshen, A. Khanzadeev, M. Malaev, V. Nikulin, V. Ryabov, Yu. Ryabov, V. Samsonov, M. Zhalov, V. Guzey (PNPI, ALICE Collaboration)

Ultraperipheral collisions (UPCs) in proton-nucleus scattering, where the nucleus serves as an intensive source of quasi-real photons and the proton plays the role of the target, give an opportunity to study photon-nucleus interactions at unprecedently high energies at the LHC. Taking advantage of unique capabilities of the ALICE detector and with a significant participation of the PNPI group, the cross section of J/Ψ photoproduction on the proton in the interval of photon-proton energies from 50 GeV to 500 GeV has been determined using the analysis of the data collected in 2019 [1] (red filled circles in the figure below taken from [1]). In the framework of perturbative QCD, the cross section of this process is determined by the gluon density in the proton. The figure presents the comparison of the obtained cross section with the results of theoretical calculations employing the next-to-leading order BFKL approximation and the approach of Color Glass Condensate (CGC) with the gluon density saturation. It allows one not only significantly reduce the uncertainty in the small-x gluon density in the nucleon, but also advances our understanding of fundamental properties of the physics of strong interactions.



[1] **Energy dependence of exclusive J/ψ photoproduction off protons in ultra-peripheral p–Pb collisions at √sNN=5.02 TeV,** ALICE Collab.
Eur.Phys.J. C79 (2019) no.5, 402

Loss reduction in the system of slow extraction of 400 GeV/c proton beam from the SPS accelerator at CERN by channeling a part of the beam with a bent crystal.

Yu.M. Ivanov, Yu.A. Gavrikov, B.L. Gorshkov, A.S. Denisov, M.A. Koznov,L.G. Malyarenko

Together with the researchers of NRC KI - IHEP and CERN, an experiment was prepared and performed on the use of a bent crystal to reduce losses on the electrodes of the electrostatic septum during beam extraction from the SPS accelerator. The relevance of the work is associated with an increase in the intensity of the extracted beam for the SHiP project to search for dark matter.

The proposed solution to the problem is to deflect a narrow region of the beam with a curved crystal and thus create a “shadow” in the area of the septum wire electrodes (Fig. 1).

For the experiment, crystal deflectors with optimal characteristics of bent silicon crystals

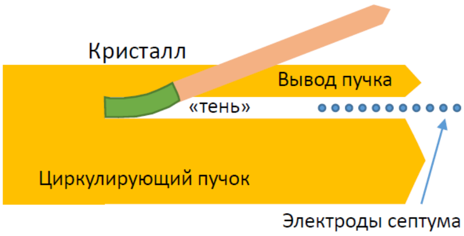


Fig. 1. Experimental design for reducing beam losses at the electrodes of the electrostatic septum of the SPS accelerator by channeling part of the beam with a curved crystal (left). Crystals with anticlastic bending, prepared at the NRC KI - PNPI for the experiment (right).

were developed: the length of the crystals along the beam was 2.0 mm, the width across the beam was 0.8 mm, and the bending angle of atomic (110) planes was 175 microradians (Fig. 1).

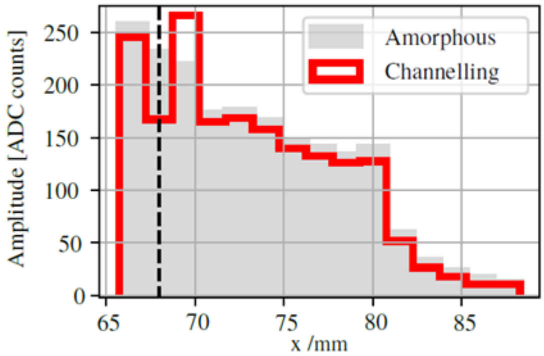


Fig. 2. Data from wire profilometer

An analysis of the experimental data of a wire profilometer located between the crystal and the septum showed that a shadow arises in the channeling mode of the beam with a curved crystal (Fig. 2), which significantly reduces losses. The results are presented at the IPAC2019 Conference [1, 2].

1. L.S. Esposito, P. Bestmann et. al. CRYSTAL FOR SLOW EXTRACTION LOSS-REDUCTION OF THE SPS ELECTROSTATIC SEPTUM, IPAC2019, Melbourne, Australia, doi:10.18429/JACoW-IPAC2019-WEPMP028.

2. F.M. Velotti, P. Bestmann et. al. DEMONSTRATION OF LOSS REDUCTION USING A THIN BENT CRYSTAL TO SHADOW AN ELECTROSTATIC SEPTUM DURING RESONANT SLOW EXTRACTION, IPAC2019, Melbourne, Australia, doi:10.18429/JACoW-IPAC2019-THXXPLM2.

Study of the Higgs boson properties at ATLAS and CMS experiments

L.A. Chtchipounov, O.L. Fedin, V.L. Golovtcov, A.E. Ezhilov, Yu.M. Ivanov, V.T. Kim, E.V. Kuznetsova, M.P. Levchenko, P.M. Levchenko, V.P. Maleev, V.A. Murzin, Yu.G. Naryshkin, V.A. Oreshkin, D. Pudzha , V.A. Schegelsky, I.B. Smirnov, V.M. Solovyev, D.E. Sosnov, V.V. Sulimov, L.V. Uvarov, A.A. Vorobyev - High Energy Physics Division NRC "Kurchatov Institute" – PNPI

After the discovery of Higgs boson of Stamdard model (SM) by ATLAS and CMS experiments at LHC in 2012, one of the most important goals for further research is to study its properties. During 2019 the datasets collected by the ATLAS and CMS experiments for LHC Run 1 (2011-2012) and Run 2 (2015–2018) were analyzed. ATLAS experiment has measured the partial cross section for Higgs boson production in the process of gluon fusion and electroweak vector boson for decay channel H → ττ: $\sigma_{gg\text{->}H}$ x Br = 3.1 ± 1.0(stat.)$\pm^{1.6}_{1.3}$ (syst.) pb and $\sigma_{WW\text{->}H}$ x Br = 0.28 ± 0.09(stat.) $\pm^{0.11}_{0.09}$(syst.) pb, respectively [3]. CMS experiment has measured total Higgs boson production cross section σ_H = 61.1 ± 6.0(stat.) ± 3.7 (syst.) pb and signal strength μ = 1.17 ± 0.10 [3], improving precision by factor two. Also, ATLAS and CMS have improved accuracy in measurement of coupling constants in the main decay channels: *H→ ZZ, WW, γγ, ττ, bb* [3,4]. In the Fig. 1 coupling scale factors k_F and k_V) for fermion and vector channels obtained by CMS [3] are shown.

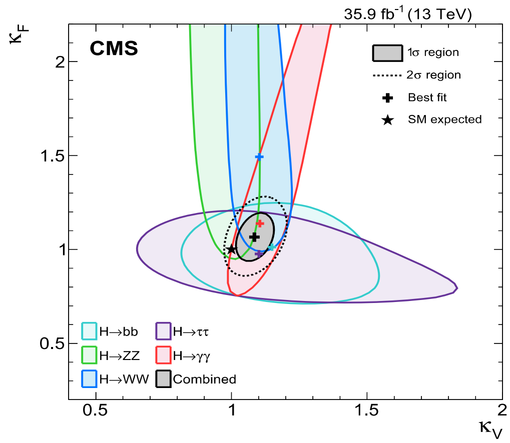


Fig. 1. Coupling strength scale factors kV and kF for different Higgs boson decay channels [3].

PNPI has made the large contribution to the development and construction of Endcap Muon (EMU) detector of the CMS experiment and Transition Radiation Tracker (TRT) for ATLAS detector which plays an important role in the Higgs boson properties study.

[1] *ATLAS Collaboration, M. Aaboud,..., O. Fedin, A. Ezhilov, M. Levchenko, V. Maleev, Yu. Naryshkin, D. Pudzha , V. Schegelsky, V. Solovyev et al.*, Phys.Rev. D **99** (2019) 072001.

[2] *CMS Collaboration, A. Sirunyan, ..., L. Chtchipounov, V. Golovtsov, Yu. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev et al.*, Phys. Lett. B **792** (2019) 369-396.

[3] *CMS Collaboration, A. Sirunyan, ..., L. Chtchipounov, V. Golovtsov, Yu.I vanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov,A. Vorobyev et al.*, Eur. Phys. J. C **79** (2019) 421-396.

[4] ATLAS Collaboration, G. Aid, ..., O. Fedin, A. Ezhilov, M. Levchenko, V. Maleev, Yu. Naryshkin, D. Pudzha , V. Schegelsky, V. Solovyev, et al., CERN-EP-2019-097, Phys. Rev. ***D*** *101 (2020) 012002*

Search for invisible Higgs boson decays with the ATLAS experiment

V. Gratchev, O. Fedin, A. Ezhilov, M. Levchenko, V. Maleev, Yu. Naryshkin, D. Pudzha , V. Schegelsky, V. Solovyev, – High Energy Physics Division, , NRC "Kurchatov Institute" – PNPI
On behalf of the ATLAS collaboration.

A search for a new physics phenomena in an invisible Higgs boson decays is performed in the ATLAS experiment at LHC. The decays called "invisible" as decay products could not be detected by the experimental setup such as light neutralinos, graviscalars in extra-dimension models, Majorons, neutrinos, or dark matter (DM). Signature of this kind of events is the presence of large amount of missing transverse momentum. A searches of H → invisible decays where H is produced according to the Standard Model via vector boson fusion, Z(ℓℓ)H and W/Z(had)H is performed. Based on the data, obtained by ATLAS experiment for Run I (2011-2012) with the energy of proton-proton collision at a center-of-mass $\sqrt{s} = 7\ (8)\ TeV$ and integrated luminosity 4.7 (20.3) fb^{-1}, and with data collected in Run II (2015-2016) with the energy of pp collisions $\sqrt{s} = 13$ and luminosity 36.1 fb^{-1} the upper limits on H → invisible branching ratio have been obtained Fig. 1. By using the combination of different Higgs production mechanisms and data taking periods the observed (expected) exclusion limit on the H → invisible branching ratio is measured: $B_{H\rightarrow invisible}< 0.26\ (0.17^{+0.07}_{-0.05})$ at 95% CL and the upper limit on cross section of Higgs boson decay to a dark matter particles is obtained. Based on the model in which Higgs boson is assumed to be the only mediator between Standard model and dark sector the upper limits for the dark matter - nucleon scattering cross section within mass interval 0-10 GeV was found to be $<(0.9\text{-}3.0)\cdot 10^{-7}$ fb which are much stronger than upper limits obtained from the direct measurements.

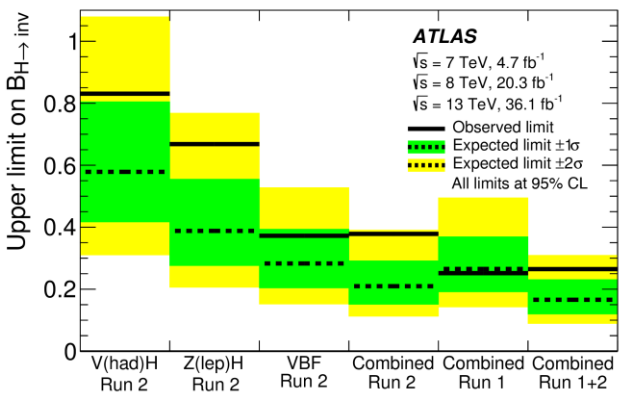


Fig. 1. The observed and expected upper limits on BH→inv at 95% CL from direct searches for invisible decays of the 125 GeV Higgs boson and their statistical combinations in Run 1 and 2.

[1] M. Aaboud, ..., O. Fedin, A. Ezhilov, M. Levchenko, V. Maleev, Yu. Naryshkin, D. Pudzha , V. Schegelsky, V. Solovyev, et.al., ATLAS Collaboration, "Combination of searches for invisible Higgs boson decays with the ATLAS experiment", Phys.Rev.Lett. 122 (2019) no.23, 231801.

High precision measurements of nuclear masses with the PENTATRAP

S.A. Eliseev, Yu.N. Novikov, P.E. Filianin, O.I. Bezrodnova – High Energy Physics Division, NRC "Kurchatov Institute"-PNPI and PENTATRAP-group of MPIK (Heidelberg)

For measurements of very subtle effects that are necessary for solving a number of fundamental questions of modern physics, much greater accuracy in determining physical quantities is required than that provided by existing ion traps. One of these problems is the study of neutrino properties, which was the focus of work in the SHIPTRAP project in previous years performed by the Laboratory of Exotic Nuclides of the PNPI.

In 2018, a new PENTATRAP system consisting of 5 Penning traps was launched at the M. Planck Institute in Heidelberg. The first initial experiments showed that the accuracy of direct mass measurement $\delta M/M$ is 3×10^{-11}, which improves the accuracy 10^{-9} achieved on SHIPTRAP and other similar installations by two orders of magnitude. In 2019, working measurements of the masses of various xenon isotopes were started, intended to be used later for calibration measurements in ultra-precision mass spectrometry.

An experiment to measure the mass difference of ^{187}Re-^{187}Os on PENTATRAP in 2019 resulted in an accuracy of 3 eV, which lays a good base for determining the mass of the antineutrino. Further refinement of this value in the full-scale ECHo collaboration experiment will allow us to consider this pair of nuclides as complementary to the KATRIN tritium experiment. The comparison of the mass difference values obtained on PENTATRAP coincides with the measurements of the decay energies for ^{187}Re using cryogenic microcalorimetry and once again confirms the possibility of determining the neutrino mass using bolometers.

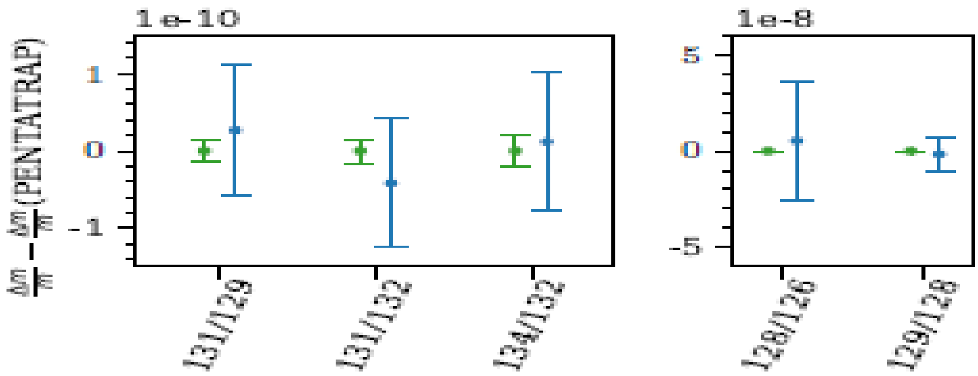
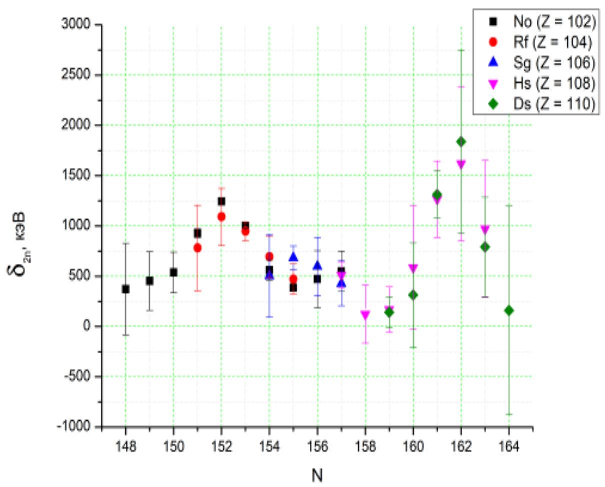


Figure. Comparison of differences in relative errors for a set of xenon isotopes with mass numbers from A=126 to A=132 compared to the literature data (and the most accurate in mass spectrometry), indicating that ultra-precision accuracy has been achieved. On the left of each pair PENTATRAP data are shown.

Mass determination of Superheavy nuclides by the use of SHIPTRAP-installation

S.A. Eliseev, N.S. Martynova, Yu.N. Novikov, P.E. Filianin, S.V. Chenmarev –High Energy Physics Division, NRC "Kurchatov Institute" –PNPI and SHIPTRAP- collaboration

Direct mass measurements of transuranium nuclides is one of the main goal of the SHIPTRAP at the GSI which is the unique installation which can implement this goal. This unit is based on the UNILAC-accelerator which can produce superheavy nuclides in the fusion-reaction. The separation of nuclides under interest can be done by the velocity selector SHIP. During the summer 2018- champaign the masses of transfermium nuclides of No, Lr and Rf have been carried out. The experiment was performed in a modified configuration of the entire system's location in relation to the beam direction using a cryogenic beam deceleration chamber developed with the participation of our group and a new phase mapping method introduced earlier by S. A. Eliseev to determine the resonant frequency. In 2019, data processing and analysis were performed, resulting in specific quantitative results. The mass values directly measured for $^{251-254}$No, $^{254-256}$Lr and ^{257}Rf allowed to obtain the part of the mass landscape of superheavies as far as darmstadtium (Z=110) by using the known alpha-decay chains. This led to a possibility of shell gate determination which are responsible for the stabilizing factor in the superheavy nuclides.



nuclides in dependence on the neutron number. Mass landscape allowed to reach a conclusion that neutron numbers of N=152 and N-162 are semimagic in the superheavy nuclides. It can be seen from the behavior of the shell gap parameters on the figure. These data lead to the conclusion based on the experiment that there are small stability Islands that occur on the approaches to the expected island of superheavy elements.

Another interesting result was a direct measurement of the masses of a number of isomeric states in nobelium and lawrencium

Figure shows the shell model gaps for transfermium and superheavy nuclides in dependence on the neutron number.

Search for heavy vector bosons in the ATLAS experiment

O. Fedin, A. Ezhilov, M. Levchenko, V. Maleev, Yu. Naryshkin, V. Schegelsky, V. Solovyev – High Energy Physics Division, NRC "Kurchatov Institute" - PNPI

A search for heavy (with masses above 1 TeV) charged, W', and neutral, Z', vector bosons was continued in the ATLAS experiment. Presence of such bosons is predicted by many models which extend the Standard Model (SM).

The search for W' and Z' bosons was performed in $W' \to l\nu$ and $Z' \to ll$ decay channels, where l stands for an electron or a muon, and ν stands for a neutrino. A data sample of 139 fb^{-1} of proton-proton collisions at $\sqrt{s}$=13 TeV collected with the ATLAS detector at the Large Hadron Collider during 2015-2018 is used in the search.

The baseline model that is considered in this search is the Sequential Standard Model (SSM). In this model W' and Z' bosons have the same couplings to fermions as the SM W and Z bosons. Furthermore, widths of W' and Z' bosons, Γ, increase linearly with their masses, m, while keeping the ratio Γ/m equal to 3% which corresponds to SM W and Z bosons case.

No significant excess beyond SM expectations was observed in this search. In the absence of any signal from heavy bosons decays upper limits on $pp \to W' \to l\nu$ (fig. 1) and $pp \to Z' \to ll$ cross-sections as functions of W' and Z' bosons masses were set at 95% confidence level (CL). SSM W' and Z' bosons are excluded with masses below 6.0 and 5.1 TeV respectively at 95% CL. The results of this search were published in ref. [1, 2].

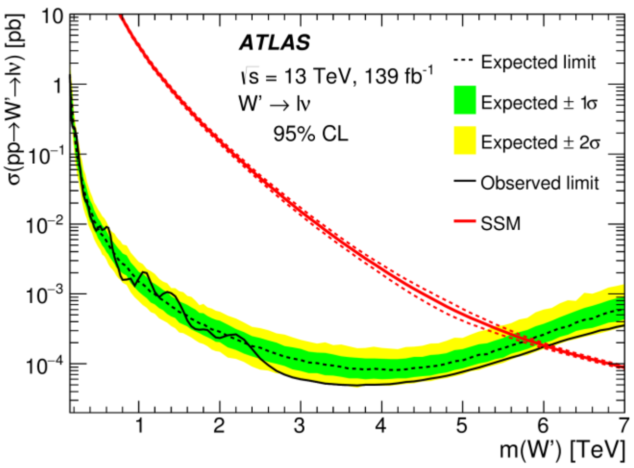


Fig. 1. Observed and expected upper limits at the 95% CL on the $pp \to W' \to l\nu$ cross-section for the combination of the electron and muon channels as a function of SSM W' boson mass. The predicted SSM cross-section with its uncertainty is also shown.

[1] G. Aad, ..., O. Fedin, A. Ezhilov, M. Levchenko, V. Maleev, Yu. Naryshkin, V. Schegelsky, V. Solovyev, et.al., ATLAS Collaboration, Phys. Rev. D, 2019, Vol. ***100****, No. 5, p. 052013*
[2] G. Aad, ..., O. Fedin, A. Ezhilov, M. Levchenko, V. Maleev, Yu. Naryshkin, V. Schegelsky, V. Solovyev, et.al., ATLAS Collaboration, Phys. Lett. B, 2019, Vol. ***796****, pp. 68 – 87.*

Development of mass-separator laser-nuclear facility IRINA

V.N. Panteleev, A.E. Barzakh, L.Kh. Batist, D.V. Fedorov, V.S. Ivanov, S.A. Molkanov, M.D. Seliverstov – High Energy Physics Division, NRC "Kurchatov Institute" - PNPI

Construction of mass-separator laser-nuclear facility IRINA (Investigation of Radioactive Isotopes on Neutrons fAcility) is carried on according to Project "Construction of equipment for the reactor complex PIK"[1]. In Fig.1, the part of the facility, including mass-separator, ion guides, detection systems and PITRAP (the Penning trap system for the precision measurements of nuclear masses) installation is shown. IRINA, installed on the neutron channel of the PIK reactor will make possible the unique experiments on the nuclear structure of exotic isotopes, very far from stability, on solid state physics, the new medical isotope production method developments. This facility will provide with the world highest yields of neutron-rich nuclei. IRINA – is the complex of high-tec equipment, placed in reactor channel and installed in experimental hall of reactor PIK.

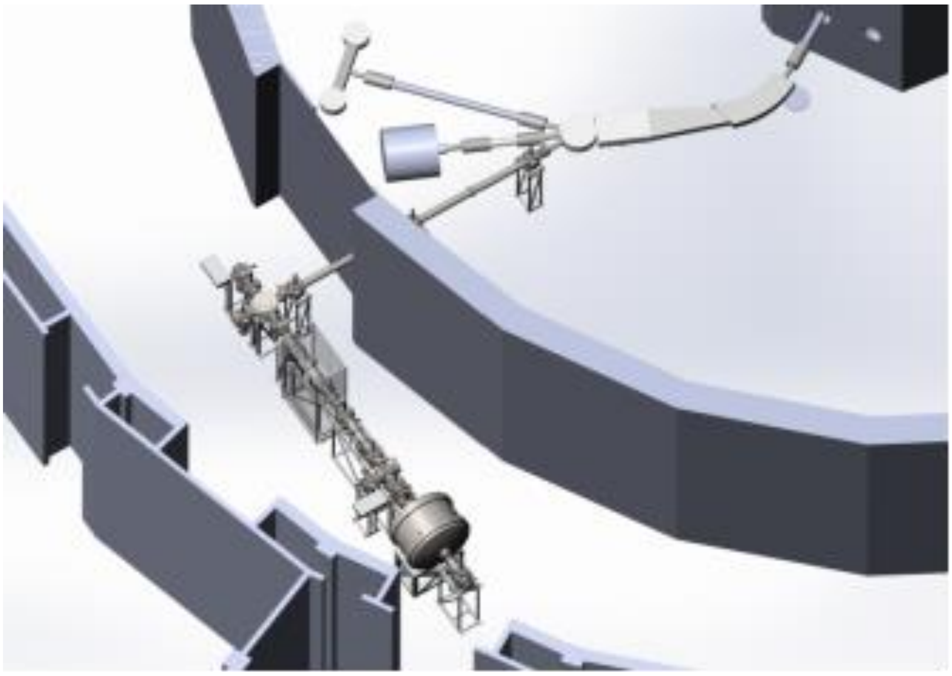


Fig. 1. Scheeme of IRINA.

Recently, the technical proposals for all main parts of IRINA (target-ion source system, mass-separator with ion guides, Penning trap system, laser installation and the special hot cell) have been prepared and discussed with the possible manufactures.

[1]. V.N. Panteleev, et al, "PROJECT IRINA AT THE REACTOR PIK", High Energy Physics Division: Main scientific Activities 2013-2018, Gatchina, 2019, p. 336.

Investigation of the neutron-rich astatine isotopes by in-source spectroscopy at ISOLDE (CERN) facility: sell-effect and inverse odd-even staggering

A.E. Barzakh, D.V. Fedorov, P.L. Molkanov, M.D. Seliverstov — High Energy Physics Division, NRC "KurchatovInstitute" — PNPI

Hyperfine-structure parameters and isotope shifts for the 795-nm atomic transitions in ^{217,218,219}At have been measured at CERN-ISOLDE, using the in-source resonance-ionization spectroscopy technique. Magnetic dipole and electric quadrupole moments, and changes in the nuclear mean-square charge radii ($\delta<r^2>$) have been deduced [1].

In Fig. 1 the changes in the mean-square charge radii for astatine isotopes near the shell closure at N = 126 are presented. A characteristic increase in the slope of the $\delta<r^2>$ isotopic dependency when crossing the neutron magic number N = 126 is known as the shell effect in radii. The possibility of description of shell-effect in mean-square charge radii is regarded now as one of the main evidences of the nuclear model quality. Further accumulation of the experimental data of this effect is of great importance.

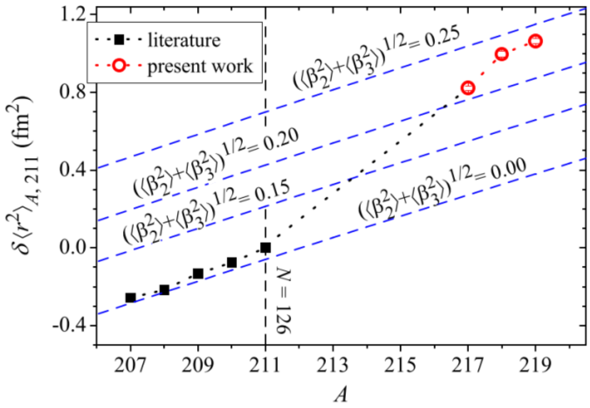


Fig 1. Changes in the mean-square charge radii for astatine isotopes near the shell closure at N = 126.

The odd-even staggering (OES) in radii, when radius of odd-N nucleus differs from the mean value of its even-N neighbors, is quantified by the parameter γ_N:

$$\gamma_N = \frac{2\delta\langle r^2\rangle_{N-1,\,N}}{\langle r^2\rangle_{N-1,\,N+1}},$$

where $\boldsymbol{N}$ — odd number of neutrons. If γ_N = 1, there is no OES, whereas γ < 1 and γ > 1 correspond to normal and inverse OES, respectively. As can be seen on Fig. 2, at 133 < N < 137 there is inverse OES in Fr, Ra and Rn isotopes (γ_N > 1). Our new data for $^{217\text{–}219}$At testify to the retention of this effect for Z = 85 and N = 132–134. It was found previously that inverse OES strongly correlates with the presence of octupole deformation in the corresponding nuclei. Thus, our new data for At isotopes indicate the possible octupole deformation in $^{217\text{–}219}$At. This conclusion is supported by the analysis of magnetic dipole moments of $^{217\text{–}219}$At measured in our experiment. Earlier the $_{85}$At isotopes were expected to lie outside the region of the quadrupole-octupole collectivity, where inverse OES was previously established. Investigation of the octupole deformed nuclei is the one of topical direction of contemporary nuclear physics. These nuclei prove to be a good benchmark to search for T- and P-violation effects beyond Standard model.

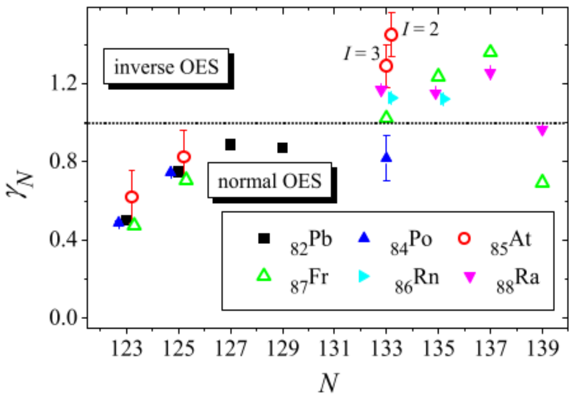


Fig 2. The odd-even staggering parameter in the lead region near the N = 126.

[1] A. E. Barzakh *et al*., Phys. Rev. C **99**, 054317 (2019).

Development of high temperature method for selective production of alpha-emitting radionuclides from the thorium carbide target

V.N. Panteleev, A.E. Barzakh, D.V. Fedorov, V.S. Ivanov, S.A. Molkanov, S.Yu. Orlov, M.D. Seliverstov and Yu.M. Volkov – High Energy Physics Division, NRC "Kurchatov Institute" - PNPI

The use of radionuclides decaying with the emission of alpha particles is a very effective tool for therapy of many kinds of malignant tumors and other diseases at an early stage of their appearance. Alpha-emitters ^{223,224}Ra, ^{225}Ac are widely used for medical purposes. We plan the production of these isotopes by irradiating the high-density thorium-carbide target at RIC-80 facility [1]. Tests of production and selective extraction of ^{224}Ra were carried out at proton beam of the SC-1000 synchrocyclotron. The high-temperature method of the alpha-emitters extraction from the high-density thorium-carbide target has demonstrated high efficiency (~90%) of selective production of ^{212}Pb and ^{224}Ra. Alpha-spectrum of ^{224}Ra, measured at the collector of the mass-separator is presented on Fig. 1. The high-temperature method has a range of advantages as compared to the radiochemical methods: 1) high isotope purity of ^{224}Ra and other radionuclides; 2) the absence of liquid radioactive waste; 3) the extraction process with no target destruction allows the production of different isotopes from the same target; 4) for ^{224}Ra production on mass-separator, one can apply the target, used for production of other nuclides and irradiated by protons for a long period (≥10 days). The optimal temperature for selective extraction of ^{224}Ra on mass-separator was determined. In the target material temperature of 1550 - 1700°C and vacuum of 10^{-5} mbar or better, 80% of the radium atoms can be extracted for about 1 hour.

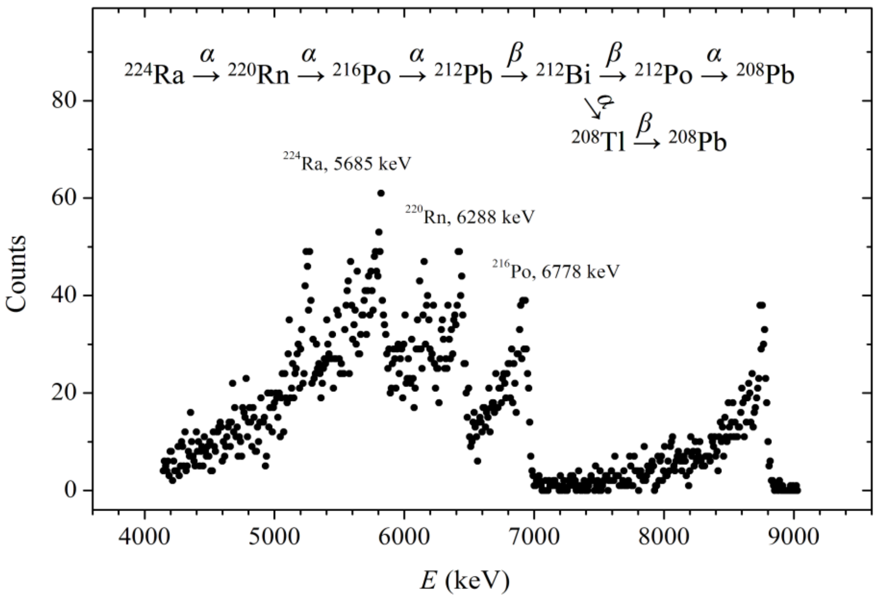


Fig. 1. Alpha-spectrum of ^{224}Ra, measured at cold collector and target material temperature of about 1500°C.

[1]. V.N. Panteleev, et al., Development of high temperature and mass-separation methods for selective production of medical radionuclides, INTERNATIONAL CONFERENCE ON RADIATION APPLICATIONS (RAP 2019) 16–19.09.2019 | 88 ROOMS HOTEL | BELGRADE | SERBIA | www.rap-conference.org