Report to the government on the results of ATOMKI (Institute for Nuclear Research) in 2023

Contents

Discovery of the oxygen nucleus with mass number 28

According to the shell model, a fundamental model of nuclear physics, the protons and neutrons in the nucleus are located at discrete energy levels, which are grouped into shells similar to the electron shells in the atom. In accordance with the laws of quantum physics, only a certain number of neutrons or protons can be placed in these shells. If all the shells in a nucleus are completely filled, i.e. closed, then the nucleus has a particularly stable structure, which is usually associated with a spherical shape. The proton or neutron numbers 2, 8, 20, 28, 50 and 82 belonging to the closed shells of stable nuclei are called magic numbers, after the Hungarian Nobel laureate physicist Jenő Wigner. The nucleus having this number of protons or neutrons is called a magic nucleus and having noble gas-like characteristics. If both of the numbers of protons and neutrons are magic, then the nucleus is double magic. Such nuclei play a distinguished role in the development and testing of theoretical nuclear models, and their experimental identification is one of the primary goals of recent nuclear physics research.

Oxygen is the eighth element of the periodic table, its nucleus contains 8 protons on closed proton shells. Different oxygen isotopes have different numbers of neutrons in addition to the 8 protons. The most common isotope of oxygen in Nature is ^{16}O, which contains 8 neutrons in addition to the 8 protons, so it has closed proton and closed neutron shells, making it double magic and extremely stable. The researchers of the **Experimental Nuclear Physics Group** of the HUN-REN Institute for Nuclear Research (HUN-REN ATOMKI) in Debrecen have been involved in experiments studying oxygen isotopes with radioactive ion beams for more than two decades in order to identify further double magic nuclei. Their contribution includes designing and building the detectors and the readout electronics, performing simulation to test their operation, assembling the measurement setup and performing the experiments. The latest generation of particle accelerators makes possible to produce extremely neutron rich oxygen isotopes at or even beyond the neutron dripline, and to study their structure under special conditions. At the particle accelerator complex of RIKEN, Japan the researchers of the Experimental Nuclear Physics Group of HUN-REN Atomki in an international collaboration have managed to produce the nucleus ^{28}O containing 8 protons and 20 neutrons (Figure 1), which has been expected to be double magic. ^{28}O is one of the nuclei having the largest neutron/proton ratios (20/8 = 2.5) still feasible to produce experimentally. After the interpretation of the experimental results, the surprising conclusion has been drawn that the ^{28}O nucleus, contrary to expectations, is not double magic and does not exhibit a noble gas-like structure. This unexpected result points to the need for further refinement of theoretical models for nuclei with extremely high neutron content. The results were published in Nature, the most prestigious scientific journal in the world.

Y. Kondo et al., (100 authors): *First Observation of ^{28}O*, Nature **620**, 7976 (2023) 965.

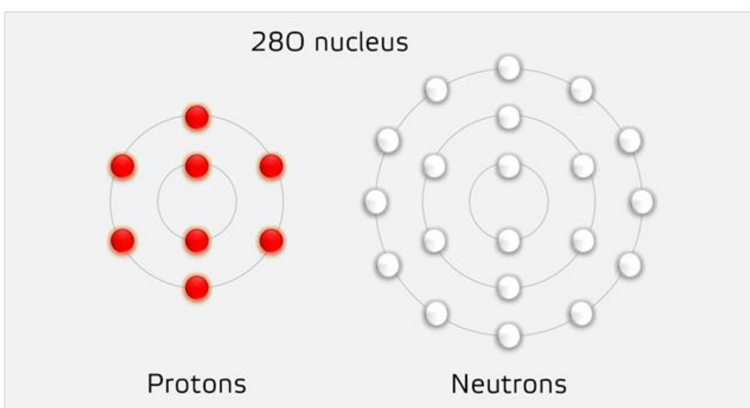


Figure 1: Structure of the ^{28}O nucleus

Comprehensive study of the proton-capture cross section of ^{12}C

The energy production of our Sun and the stars similar to our Sun takes place through the hydrogen burning. During the process, four protons combine to form a helium nucleus, and the binding energy difference is released. Depending on the star's mass and composition, hydrogen burning can take place through the proton-proton (p-p) chains or via the carbon-nitrogen-oxygen (CNO) cycles. The first step of the CNO cycle is that a carbon (^{12}C) nucleus containing six protons and the same number of neutrons captures a proton and transforms into a nitrogen (^{13}N) nucleus consisting of seven protons and six neutrons. The resulting nitrogen nucleus is unstable to beta decay, and with a half-life of about 10 minutes, it turns into a carbon (^{13}C) nucleus consisting of six protons and seven neutrons. The decay is accompanied by neutrino emission. Today, with detectors using state-of-the-art technology, the yield of these key neutrinos is already known with an accuracy of a few percent. If we knew with comparable accuracy the probability of the proton capture of the ^{12}C nucleus (i.e. its cross-section) in the energy range corresponding to the Sun's temperature, we could precisely determine the composition of the Sun using data from neutrino detectors. In the interior of our Sun, however, the energy of the interacting protons and the ^{12}C nuclei is significantly lower than the Coulomb repulsion between them, so the capture process can only take place through the quantum mechanical tunnel effect with extremely low probability.

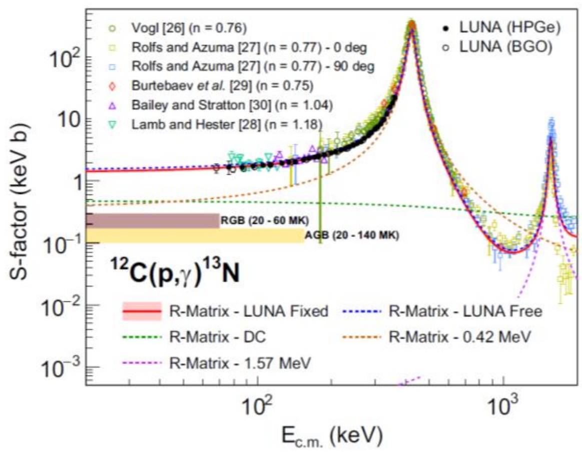


Figure 1: The probability of proton capture of the ^{12}C nucleus (in astrophysical S-factor units) as a function of the energy of the interacting nuclei.

Due to the astrophysical importance of the reaction, the members of the LUNA (Laboratory for Underground Nuclear Astrophysics = Underground laboratory for nuclear astrophysics) collaboration decided to determine the partial cross sections in the relevant energy region by measuring the yield of the gamma radiation. The targets for the experiment were prepared by the members of the **Nuclear Astrophysics Group** of the HUN-REN Nuclear Research Institute (ATOMKI). Furthermore, the properties of the targets were also determined using ion beam analytical techniques at ATOMKI. The determination of the exact parameters of the resonances, as well as the measurement of the total reaction cross-sections, were carried out with the Tandetron accelerator by the members of the Nuclear Astrophysics Group.

As a result of all these works, it was possible for the first time to measure the proton capture cross section of the ^{12}C nucleus in the astrophysically relevant energy range. The uncertainty of the derived reaction rate values is only 4-6% compared to the uncertainty of more than 30% of available data calculated based on higher energy measurements. The results are shown in Figure 1. The new experimental data are important steps towards a more precise determination of the composition of our Sun, and explain the reason for the $^{12}C/^{13}C$ ratio of molecular nebulae being different from our Solar System [1].

[1] J. Skowronski *et al.*, (46 szerző): *Proton-Capture Rates on Carbon Isotopes and Their Impact on the Astrophysical $^{12}C/^{13}C$ Ratio,* Phys. Rev. Lett. **131**, 162701 (2023)

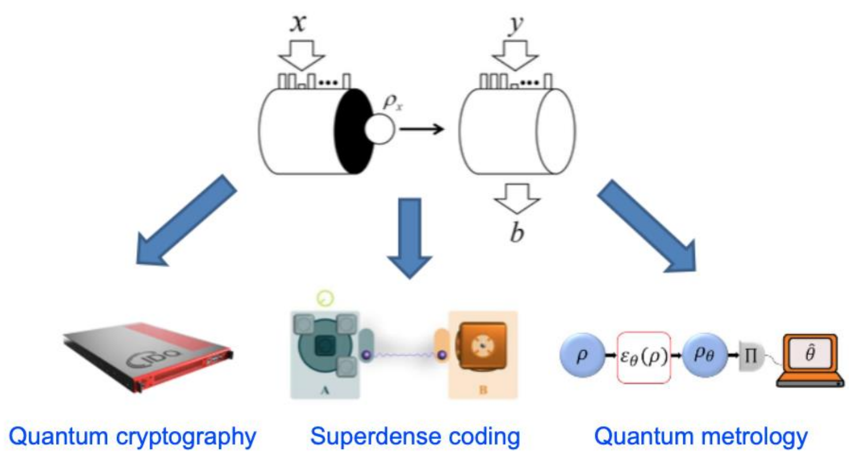
[2] **Gy. Gyürky** *et al.*,(6 szerző): *Cross section measurement of the $^{12}C(p,\gamma)^{13}N$ reaction with activation in a wide energy range*, Eur. Phys. J. A **59** 59 (2023)

[3] **L. Csedreki** et al., (3 szerző): *Precise resonance parameter measurement in the $^{12}C(p,\gamma)^{13}N$ astrophysically important reaction,* Nuclear Physics A **1037** 122705 (2023)

Certification of quantum states and measurements in prepare-and-measure scenarios

Quantum devices already available or expected in the future are much more efficient at performing certain tasks than traditional ones, and they promise to solve problems that cannot be solved with classical methods, or only in a very long time. A justified requirement of the user of the device can be the ability to make sure that the device operates as expected, even if it has been supplied by an untrusted party. It is often possible to work out verification methods making this possible while knowing nothing or very little about the details of the operation of the device. A statistical analysis of the response of the device to some input values may be enough, possibly using additionally some weak assumption about the device. In quantum physical experiments it is a typical arrangement when a particle is emitted by a source in a state depending on its setting (preparation), and then a measurement is performed on it according to the setting of the measuring instrument. This so-called prepare-and-measure (PM) arrangement is part of several protocols of quantum information science serving as bases of quantum devices, such as quantum key distribution for cryptography, superdense coding, generation of truly random numbers, or quantum metrology (see figure). Scientists of the Institute have investigated several aspects of the PM scenario, including questions concerning verification, and they have achieved internationally significant results. Quite a few papers have already appeared, and there are some being prepared. The paper that appeared recently in Physical Review Letters have been made in collaboration with colleagues working in Austria and in Spain. The work makes it possible to verify in the framework of the PM scenario any set of pure states of any multi-level system, provided the dimensionality of the the states is known. Earlier papers have been restricted to either two-dimensional (two-level) system, that is qubits, or to very special sets. The authors constructed an expression, which can be calculated from the results of appropriate measurements performed on the set of states to be verified, and whose value is maximized for those states. Whenever the value takes this maximum value for an unknown set of states of proper dimensionality, it is true that the absolute values of the pairwise overlaps of these states are the same as those of the reference states for each pair. For two-dimensional systems from this it follows that the unknown set is the same as the desired one up to some global symmetry transformation, and this is enough for the verification. If the dimensionality is more than two, unfortunately this is not true generally. However, it has been proven that with a generalization of Wigner's theorem to finite sets the verification can still be performed by extending the set of states with a number of properly chosen additional states. A further important result of the paper is that the possibility of verifying any arbitrary set of states enables one to verify generalized measurements, too. The theoretical methods introduced in the paper may be useful for the certification of future quantum devices.

Miguel Navascués, **Károly F. Pál, Tamás Vértesi**, and Mateus Araújo: *Self-Testing in Prepare-and-Measure Scenarios and a Robust Version of Wigner's Theorem*, Phys. Rev. Lett. **131**, 250802 (2023).



Characterization of particulate matter pollution before and during the COVID-19 crisis in a central-eastern European urban environment

Atmospheric particulate matter (APM) pollution is the biggest environmental health risk in Europe. According to the latest data, 97% of the EU's urban population is exposed to concentrations of fine particulate matter ($PM_{2.5}$, particles with diameter less than 2.5 mm) above the latest guidelines of the World Health Organization. Therefore, the reduction of APM exposure is a primary goal of the governments and societies.

Lockdowns and restrictions around the world due to the COVID-19 pandemic provided a precious window to study the changes in urban air quality under conditions of reduced anthropogenic activities.

The objective of this work carried out at the **Heritage Science Group** of the HUN-REN Institute for Nuclear Research (ATOMKI) was to study and understand the variation of APM pollution besides other air quality parameters in the city of Debrecen, Hungary from 2018 to 2022. In order to understand all the processes that influenced the evolution of air pollution, an integrated approach was introduced which combines receptor modelling, trajectory statistical methods and local and regional meteorology taking into account anthropogenic activities.

Concentration, composition, and sources of APM were determined for four lockdown periods with varying levels of restrictions, two transition intervals and two relaxation periods in 2020-22, and they were compared to corresponding baseline values from 2018-19.

The following sources were identified by source apportionment: soil dust, combustion, biomass burning (e.g. domestic heating with wood burning), biogenic emission, traffic, secondary sulphate (aerosol particles formed in the atmosphere from SO_2 gas), sea salt, construction and roadworks. In the heating season, biomass burning and combustion from heating were the main sources of pollution, while in the summer, besides soil dust, secondary aerosols and biogenic emission gave the highest contribution.

From March 2020, the restrictions due to the pandemic influenced strongly the concentration of all air pollutants, a 20-25% reduction in average could be detected in the case APM and of most gaseous pollutants. In the coarse fraction (particles with diameter between 2.5 and 10 mm) the contribution of traffic and soil decreased to the greatest extent. A significant reduction in agricultural activities around the city could also be traced back. In PM2.5 sources related to energy production decreased the most. However, during the closures in the springs of 2020 and 2021, a significant increase in biomass burning from domestic heating was detected, which was caused by the forced staying at home and the colder weather. The shift of traffic-related pollutants from the school year to the summer relaxation periods was also an indication of the changed habits of the urban population.

Another important local source was construction and roadworks. The impact of a large-scale industrial site development could be identified even from a distance of up to 10 km.

It was shown that a large part of APM pollution in Debrecen comes from regional and long-range transport. The main source areas of secondary sulphate aerosols were the western Balkan countries and south-west Romania. Therefore, the change in emission in these countries also had a strong influence on the air pollution level in the city.

Local meteorological parameters, the origin of air masses, and long-range transport processes had a significant influence on the evolution of air pollution, too. The effects of these conditions were similar in magnitude to the changes caused by the closures.

Thanks to the special situation due to the COVID-19 pandemic, it was shown that a significant reduction in traffic and industrial production locally and globally could improve the air quality of Debrecen by 20%. The results of source apportionment indicated that only properly targeted local and regional measures together would provide a reduction of urban air pollution to the required level. The importance of understanding the effects of complex local and global meteorological situations and episodic emissions from distant natural and anthropogenic sources was also demonstrated. All these results point in the direction that air quality improvement policies should be based on source apportionment, which takes into account local, regional, and global influences of meteorological parameters and emission sources.

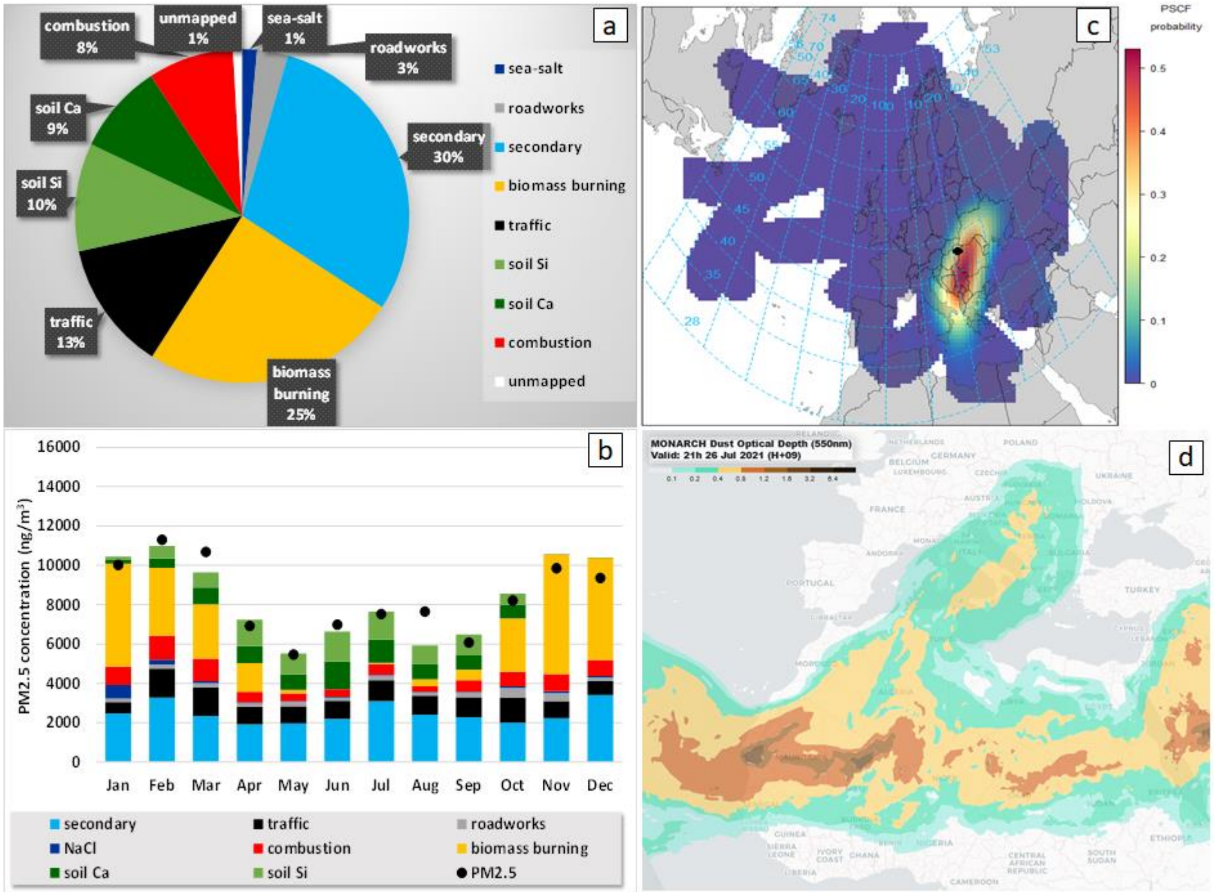


Figure 1: (a) relative contribution sources to PM2.5 in 2020-21.
(b) contribution of sources to PM2.5 by months in 2020-21,
(c) source areas of secondary sulphate pollution in Debrecen
(d) Saharan dust episode in July, 2021 based on aerosol optical depth data.

Zs. Kertész, S. Aljboor, A. Angyal, E. Papp, E. Furu, M. Szarka, S. Bán, Z. Szikszai: *Characterization of urban aerosol pollution before and during the COVID-19 crisis in a central-eastern European urban environment*, Atmospheric Environment **318** Paper: 120267 (2024)