Final report for the OTKA project entitled “Correlations in nuclei; varieties and interrelations”
No: K106035

The most important results of the project are summarized briefly below with references cited in the list of publications.

The following unique spectrometers have been designed and constructed or characterized in Debrecen for our experimental investigations.

1. The properties of the large volume cylindrical 3.5 x 8 inches (89 mm x 203 mm) $LaBr_3$:Ce scintillation gamma-ray detectors coupled to the Hamamatsu R10233-100SEL photomultiplier tube were investigated in Debrecen. These crystals are among the largest one’s ever produced and still need to be fully characterized to determine how these detectors can be utilized and in which applications. We tested the detectors using monochromatic gamma-ray sources and in-beam reactions producing gamma rays up to 22.6 MeV. The detector absolute full energy efficiency was measured and simulation was performed up to gamma-rays of 30 MeV [5].
2. A neutron spectrometer, the European Low-Energy Neutron Spectrometer (ELENS), has been constructed in Debrecen to study exotic nuclei in inverse kinematics experiments. The spectrometer, consisting of plastic scintillator bars, can be used in the neutron energy range of 100 keV to 10 MeV. The neutron energy is determined by the Time-of-Flight technique, while the position of the neutron detection is deduced from the time difference information from photomultipliers attached to both ends of each bar. A novel wrapping technique has been developed for the plastic scintillators. The array has > 25% detection efficiency for neutrons around 500 keV kinetic energy, and an angular resolution of less than 1 degree [23].
3. An electron-positron pair spectrometer has been designed and constructed for the simultaneous measurement of energy- and angular correlations of $e^+ e^-$ pairs. Experimental results are obtained over a wide angular range for high-energy transitions in ^{16}O, ^{12}C and ^{8}Be. A comparison with GEANT simulations demonstrates that angular correlations between 50 and 180 degrees of the $e^+ e^-$ pairs can be determined with sufficient resolution and efficiency [38].
4. An array of Parallel Plate Avalanche Counters (PPAC) for the detection of heavy ions has been developed. The new device, consists of four individual detectors and covers 60% of 4π. It was designed to be used in conjunction with the SiRi array of silicon telescopes for light charged particles and fits into the CACTUS array of 28 large-volume NaI scintillation detectors at the Oslo Cyclotron Laboratory. The low-pressure gas-filled PPACs are sensitive for the detection of fission fragments, but are insensitive to scattered beam particles of light ions or light-ion ejectiles. The new setup is particularly well suited to study the competition of fission and γ decay as a function of excitation energy [24,25].

The most important experimental results are as follows:

1. One of our experimental results obtained with an electron-positron pair spectrometer constructed in MTA Atomki, created a large international interest. At the end of January 2016 we published our experimental results in Phys. Rev. Lett. on the existence of a new, light boson, which is 34 times heavier than the electron. Shortly after, a group of US theoretical physicists showed that the data didn’t conflict with any previous experiments and concluded that it could

be evidence for a fifth fundamental force. It followed an article in Nature stating “A laboratory experiment in MTA Atomki has spotted an anomaly in radioactive decay that could be the signature of a previously unknown fifth fundamental force of nature”, which created a boom in the media. We have actually measured the e^+e^- angular correlation in internal pair creation (IPC) for the M1 transitions depopulating the 17.6 and 18.15 MeV states in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the 18.15 MeV transition with a confidence level of $>5\sigma$. Such a peak-like deviation between the experimental and theoretical angular correlations can be described by assuming the creation and subsequent decay of a new boson with mass of 16.70 MeV/c2 [12,33,38].

2. We have developed a novel method to determine the neutron-skin thickness of nuclei by measuring the charge-exchange anti-analog giant dipole resonance (AGDR).Calculations performed using the relativistic proton-neutron quasiparticle random-phase approximation (pn-RQRPA) reproduce the isotopic trend of the excitation energies of the AGDR, as well as that of the spin-flip giant dipole resonances (IVSGDR), in comparison to available data for the even-even isotopes $^{112-124}$Sn. It is shown that the excitation energies of the AGDR, obtained using a set of density-dependent effective interactions which span a range of the symmetry energy at saturation density, supplemented with the experimental values, provide a stringent constraint on value of the neutron-skin thickness. For ^{124}Sn and ^{208}Pb, in particular, our results agrees nicely with the previous experimental results [4,9,10-14,34].
3. We were involved in many other giant resonance studies performed at the Research Center for Nuclear Physics (RCNP), Osaka. We have performed high-resolution studies of Gamow-Teller excitations in the ^{40,42,44,48}Ca(^{3}He,t)^{40,42,44,48}Sc reactions. We observed for the first time a "low-energy super-Gamow-Teller state in ^{42}Sc, and also soft spin-dipole resonances in ^{40}Ca. Our experimental results are important for nuclear astrophysics as well [18-22,32].
4. The neutron-skin thickness was studied in different experiments performed at GSI, and at RIKEN using our newly built ELENS European Low Energy Neutron Spectrometer. The ^{208}Pb(p,nγp)^{207}Pb reaction was also studied at a very low beam energy of 30 MeV to excite the anti-analog of the giant dipole resonance (AGDR) and to measure its gamma-decay to the isobaric analog state in coincidence with proton decay of IAS. The analysis of the data is in progress [39].
5. The fission probability of ^{232}Pa was measured as a function of the excitation energy in order to search for hyperdeformed (HD) transmission resonances using the (d,pf) transfer reaction on a radioactive ^{231}Pa target. The experiment was performed at the Tandem accelerator of the Maier-Leibnitz Laboratory (MLL) at Garching using the ^{231}Pa(d,pf) reaction at a bombarding energy of E_d=12 MeV and with an energy resolution of ΔE=5.5 keV. Two groups of transmission resonances have been observed at excitation energies of E^*=5.7 and 5.9 MeV. The fine structure of the resonance group at E^*=5.7 MeV could be interpreted as overlapping rotational bands with a rotational parameter characteristic to a HD nuclear shape ($\hbar^2/2\Theta=2.10\pm0.15$ keV). The fission barrier parameters of ^{232}Pa have been determined by fitting TALYS 1.2 nuclear reaction code calculations to the overall structure of the fission probability. From the average level spacing of the J=4 states, the excitation energy of the ground state of the third minimum has been deduced to be $E_{III}=5.05-0.10+0.40$ MeV [1,2].
6. The fission probability of ^{238}Np was measured as a function of the excitation energy in the energy range of E = 5.4 –6.2 MeV in order to search for hyperdeformed rotational bands using the (d,pf) transfer reaction on a radioactive ^{237}Np target. The experiment was performed at the Tandem accelerator of the Maier-Leibnitz Laboratory at Garching employing the ^{237}Np(d,pf)

reaction at a bombarding energy of E_d = 12 MeV. Overlapping resonances have been observed at excitation energies around E = 5.5 MeV. These resonances could be ordered into a hyperdeformed rotational band by the preliminary analysis of the high-resolution excitation energy spectrum. The existence of a third minimum in the fission barrier of ^{238}Np is also supported by nuclear reaction code (TALYS1.4) calculations which was used to describe the experimental data [29].

7. The photofission cross section of ^{238}U was measured at sub-barrier energies as a function of the γ-ray energy using a monochromatic, high-brilliance, Compton-backscattered γ-ray beam. The experiment was performed at the High Intensity γ-ray Source (HIγS) facility at the Duke University (USA) at beam energies between E_γ=4.7 MeV and 6.0 MeV and with ~3% energy resolution. Indications of transmission resonances have been observed at γ-ray beam energies of E_γ=5.1 MeV and 5.6 MeV with moderate amplitudes. The triple-humped fission barrier parameters of ^{238}U have been determined by fitting empire-3.1 nuclear reaction code calculations to the experimental photofission cross section [3,6,7].
8. In our photo-fission project, we have initiated a development of two detector arrays to be used and installed at ELI-NP:
   i) an array based on the Thick Gaseous Electron Multiplier technology for the measurement of the cross section of photo-fission processes and for the determination of angular distribution of the fission fragments, and
   ii) a five-folded Frisch-gridded ionization chamber equipped with double-sided silicon strip detectors (DSSD) for the efficient and high resolution measurement of the mass and kinetic energy distributions of the fission fragments and ternary particles.

   The efficient operation of the prototype THGEM unit has been demonstrated very recently by using a ^{252}Cf fission source as well as the power of a Bragg chamber with digital signal processing techniques. Based on our novel detector designs, revolutionary concepts, and the infrastructural potential at MTA Atomki, a Technical Design Report is under evaluation for the photofission project of ELI-NP. A cooperation agreement has already been signed between MTA Atomki and ELI-NP as a result of this work [35].

From the theoretical side the main results are as follows:

1. We have discussed the role of the unitary symmetries in particle and nuclear physics [26]. The early ones were invented by Eugene Wigner, and some newer ones followed a similar spirit. In particular, we have pointed out the similarities and differences in the two fields, concerning the space and internal symmetries, both for exact and broken ones. We have found that new unitary symmetries connect different configurations and models of nuclear structure.

2. The multichannel dynamical symmetry (MUSY) connects different clusterizations of the same nucleus, like e.g. the ^{24}Mg+^{4}He and ^{16}O+^{12}C configurations in the ^{28}Si. Therefore, it has a considerable predictive power; e.g. the energy-spectrum of one clusterization may completely determine the other spectrum. Actually, this symmetry was introduced previously by one of the authors (J. Cseh, Phys. Rev C50, 2240, 1994), in an empirical way, based on the relations of the energy-eigenvalues. Our recent work [8] exploits the exact mathematical background and detailed physical content of the MUSY. It turns out that the multichannel symmetry, which connects different clusterizations, is a consequence of a usual dynamical symmetry of an underlying multicluster configuration. E.g. the two-channel symmetry (related to two different

binary clusterizations) is a projection of the dynamical symmetry of an underlying ternary configuration.

3. A proposition was put forward [28] on the common intersection of the nuclear shell, collective and cluster models in terms of a dynamical symmetry with U(3)xU(3)>U(3) basis states and U(3) dynamically symmetric interactions.

The shell structure and clusterization are two fundamental aspects of atomic nuclei. We have studies their coexistence and competition.

4. On the one side we have proposed [15] an improved version of Antisymmetrized Quasi-Cluster Model (AQCM). In this approach a smooth transition can be realized from the alpha-cluster wave function to the j-j coupling shell model wave function. We have applied this method in the study of the ground state of ^{12}C. The optimal AQCM wave function for the ground state of ^{12}C turned out to be an intermediate state between three alpha-cluster and $p_{3/2}$ sub closure configuration of shell model.

5. On the other side we have determined the position of the ^{20}Ne nucleus [30] on the joint phase diagram of the shell and cluster models (constructed beforehand by ourselves). Different theories show that it is very close to the SU(3) intersection of the two models.

6. We have studied the shape isomers of some light nuclei and their possible clusterizations. In particular we have extended our previous structure investigations by some reaction considerations. The possibility to include the cluster emission into the statistical preequilibrium (exciton) model was initiated [31]. A part of this work was presented for the general audience, too [17].

7. From the theoretical side the main result of the project was the invention of two algebraic models for the description of quarteting [27,36]. This is a very important phenomenon in nuclear structure due to the fact that the nucleon-nucleon interaction is attractive and short-ranged. Therefore, the energetically most favored arrangement is to put as many nucleons in a single orbital, as possible. The Pauli-exclusion-principle allows two protons and two neutrons to be in the same state. The four strongly bound nucleons form a quartet. These features are known from the beginning of the nuclear research, therefore, several theoretical approaches have been proposed for the description of quarteting. They can be classified into two categories:
   i) The shell-like quartet models, which know about the microscopic, i.e. shell-model background of the quartets. These models are somewhat asymmetric, inasmuch they treat the spin and isospin degrees of freedom algebraically, but not the space part. As a consequence their application is rather difficult.
   ii) The interacting boson-type quartet models on the other hand are fully based on the elegant and efficient group theoretical methods, thus they are easy to apply. However, the microscopic content of their quartet is not known.
8. Recently we have invented two fully algebraic models for the description of the shell-like quarteting [27,36]. One of them is a phenomenologic model, in which the nucleonic degrees of freedom are not taken into account. The other one is a semi-microscopic approach, which treats the nucleons one-by-one. (The model space of this latter one is a symmetry-governed truncation of the no-core shell model.) The U(3) space symmetry (of the Elliott model) is used for the

description of the excitation spectrum in both cases. The semi-microscopic model seems to be especially promising from the viewpoint of application: it is very flexible due to its phenomenological interactions and algebraic formalism, at the same time however, its relation to the fully microscopic (no-core shell model) theory is well-defined. Due to its transparent symmetry properties the relation of this quartet model to the shell, collective and cluster models is also clear.