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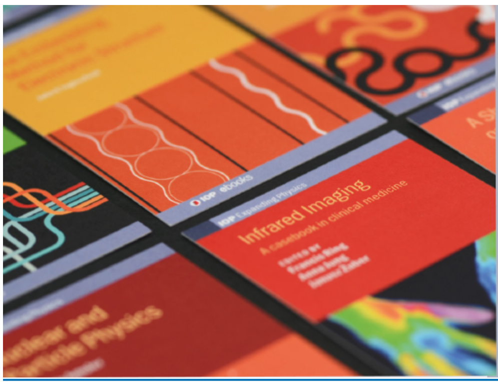

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A view of recent results and perspectives on nuclear structure with MAGNEX at the INFN-LNS laboratory

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Abstract: An intense activity in the field of experimental, as well as theoretical, nuclear structure is ongoing at the INFN-LNS laboratory in Catania. A short overview of the main recent results is reported.

Nuclear structure studies are important research items at the INFN-LNS laboratory in Catania [1]. A characterizing feature is the use of direct quasi-elastic reactions as selective probes of specific degrees of freedom of atomic nuclei. Experimentally, heavy-ion beams are exploited to activate the interesting reactions, accelerated in a broad range of bombarding energies by the 14 MV Tandem van der Graaff and by the K800 Superconducting Cyclotron (CS). Different devices are available for the detection of the charged reaction products, as well as of neutrons and γ-rays. A particular attention is given here to the MAGNEX large acceptance magnetic spectrometer [2-3], which is a dedicated facility for nuclear structure as well as direct reaction mechanism studies. The spectrometer can detect reaction products with high mass, energy and angular resolution in a broad phase space and allows to measure at zero degree. Mass distributions, energy spectra and absolute cross section angular distributions are typically measured, giving access to important quantitative information on the selected nuclear transitions. Here we refer to results achieved in the context of old and new puzzles in nuclear structure, which we have contributed to unveil in recent years.

A campaign of experiments of heavy-ion induced one- and two- neutron transfer reactions was performed by MAGNEX with the aim, among the others, of studying the reaction mechanism and the competition between mean field versus pairing correlations in low lying nuclear states. In most of these experiments, a beam of $^{18}O^{6+}$ ions was accelerated at 84 MeV incident energy and transported to several thin enriched targets from ^{9}Be up to ^{208}Pb. Experiments at higher bombarding energies up to 270 MeV were also performed by using the Cyclotron accelerated $^{18}O^{4+}$ beams. In these experiments the MAGNEX optical axis was centered at forward angles. Neutron-neutron pairing correlations were studied through the (^{18}O,^{16}O) transfer reaction, which has allowed to give a precise determination of nuclear response to two-neutron addition operators. In particular, we have explored several nuclei from light to heavy systems [4-8], finding a clear indication of selectivity of this reaction of two-neutron + core configurations in the residual systems. The weak population of unnatural parity states and the large cross section of two-neutron transfer give a hint of the correlated two-neutron transfer as leading mechanism in the (^{18}O,^{16}O) reaction. This is a direct consequence of the existing two-neutron pair in the ^{18}O ground state wave function emphasized by the weak polarizability of ^{16}O core. An important finding was the observed signatures of the long searched Giant Pairing Vibration [9-10] in ^{14}C and ^{15}C nuclei. The population of several resonances as a distinctive feature of the measured

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energy spectra has also suggested to explore their decay pattern. Coupling MAGNEX with the EDEN array of NE213 liquid scintillators the neutron branching ratios of ^{15}C resonances were measured for the first time [11-13]. Exact finite range Coupled Reaction Channel (CRC) cross-section calculations were performed. The spectroscopic amplitudes were determined by shell-model and Interacting Boson Model (IBM) calculation. In the analyses a quantitative determination of pairing correlation in the wave function is achieved for many of the populated states, giving access to deeper understanding of two-neutron clustering inside nuclear matter. A specific theoretical approach, called Microscopic Cluster Model was also developed to better emphasize this aspect of nuclear structure [14].

Another explored research item is the study of the effect of nuclear structure in the heavy-ion elastic scattering. The coupling of the elastic channel with the other reaction channels was the main topics investigated in a series of experiments at the MAGNEX facility. Above the Coulomb barrier, nuclear internal degrees of freedom are more and more involved in the elastic scattering, which thus gain sensitivity on the details of the nuclear structure of the involved systems. A striking feature is that state of the art Coupled Channel (CC) calculations predict new kind of rainbow-like structures [15]. Experimentally these effects are stronger at large scattering angles, where elastic cross sections are sensibly smaller than inelastic and the channel coupling mechanism can be a dominant source of the elastic flux. However, in this angular region the elastic cross sections become extremely small ($d\sigma/d\omega \sim 100$ nb/sr and less) and experiments are consequently quite challenging. Three experimental campaigns have been set-up to study $^{16}O + ^{27}Al$ scattering at 100 MeV and 280 MeV and $^{16}O + ^{60}Ni$ at 280 MeV. In all the experiments the cross section was accurately measured down to about 100 nb/sr and less [16-17]. The data shows a clear deviation from optical model results and demand challenging CC calculations with state of art optical potentials and nuclear structure models to reproduce the experimental data [18-19]. In particular, it was found that the coupling of the elastic channel with low-lying and even high-lying collective states as giant resonances is essential to reproduce the observed deviation of the experimental cross section angular distributions from Fraunhofer scattering.

Finally, we mention here the intense activity at the LNS for the exploration of nuclear response to isospin by charge exchange reactions. This study started with a systematic exploration of the (^{7}Li, ^{7}Be) charge-exchange reaction at about 8 MeV/*u* was performed in light neutron rich nuclei, showing that at such incident energy this process proceeds with a considerable predominance of the direct one-step mechanism, thus being a useful probe for spectroscopic studies [20-24]. In particular, the $^{19}F(^{7}Li, ^{7}Be)^{19}O$ reaction at 52 MeV incident energy was studied with MAGNEX. More recently the attention has been focused on heavier ion induced reactions such as the (^{18}O,^{18}F) for their connection with the NUMEN project (see below). First results from the $^{40}Ca(^{18}O,^{18}F)^{40}K$, in comparison with state of art (p,n) and (^{3}He,t) data give encouraging indication that this probe can be useful for nuclear structure investigations. Charge exchange reactions have been recently extended to second order by the exploration of (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) Double Charge Exchange (DCE) reactions. Despite the challenging scenario, characterized by very low cross sections (of the order of nb) and the necessity to measure at very forward angles, including zero degrees, these studies are very important for us, due to the possible connections to neutrinoless double beta decay studies.

The NUMEN project [25], which represents a very ambitious perspective for the INFN-LNS laboratory in nuclear science, has started as a natural extension of the charge exchange program at the MAGNEX facility, aims at producing experimentally driven information useful for double beta decay research [26]. NUMEN [27-28] proposes to use heavy-ion induced DCE (HI-DCE) reactions as tools to access quantitative information, relevant for $0\nu\beta\beta$ decay NME. These reactions are characterized by the transfer of two charge units, leaving the mass number unchanged, and can proceed by a sequential nucleon transfer mechanism or by meson exchange. Despite $0\nu\beta\beta$ decays and HI-DCE reactions are mediated by different interactions, they present a number of similarities. Among those, the key aspects are that initial and final nuclear states are the same and the transition operators in both cases present a superposition of isospin, spin-isospin and rank-two tensor components with a relevant available momentum (100 MeV/c or so). In a pioneering experiment, performed at the INFN-LNS laboratory, we studied the DCE reaction $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ at 270 MeV, with the aim to measure the cross section at zero degree [26]. The key elements in the experiment were the high resolution CS beams and the MAGNEX spectrometer. In the "pilot experiment" we have shown that high resolution and statistically significant experimental data can be measured for DCE processes and that precious information towards NME determination could be at our reach. To move towards nuclei candidates for 0νββ decay important experimental limits need to be overcome. As a consequence, the present limits of beam power (~100 W) for the CS accelerator and acceptable rate for the MAGNEX focal plane detector (few kHz) must be sensibly overcome. For a systematic study of the many "hot" cases of ββ decays an upgraded set-up, able to work with at least two orders of magnitude more luminosity than the present, is thus necessary. This goal can be achieved by a substantial change in the technologies implemented in the beam extraction [29], in the control of the beam induced radioactivity, in the detection of the ejectiles [30-33] and in the power dissipation of the thin targets [34]. In addition, the project demands for an enhancement of the maximum accepted magnetic rigidity, preserving the geometry and field uniformity of the magnetic field [35-38] in order to keep the high-precision of the present trajectory reconstruction.

Finally, NUMEN is fostering the development of a specific theory program to allow an accurate extraction of nuclear structure information from the measured cross sections. Relying on the use of the Distorted Wave Born Approximation for the cross section, the theory is focused on the development of microscopic models for DCE reactions, employing several approaches (Quasi-particle Random Phase Approximation, IBM, shell model, among others) for inputs connected to nuclear structure quantities. We are also investigating the possible link between the theoretical description of the 0νββ decay and DCE reactions.

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