^{6}He+^{64}Zn around the Coulomb barrier

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Effects on the fusion cross-section are predicted by theoretical models in reaction induced by halo nuclei below and around the Coulomb barrier [e.g. 1]. Different models disagree about the role played by the break-up of the loosely bound halo nucleon. The reaction studied experimentally so far are not yet sufficient to clarify this physics[2-4]. No data for fusion evaporation reactions induced by halo nuclei on medium mass targets below the barrier are available so far owing to the low beam current, small cross-section and low evaporation residue (E.R.) energies. Moreover indirect E.R. detection, via on-line or off-line gamma spectroscopy, would also be very difficult due to the combination of low E.R. yield with low detector efficiency.

The reaction ^{6}He+^{64}Zn was investigated in order to study the effect of the ^{6}He structure on the fusion cross section around the Coulomb barrier. An excitation function for fusion reaction was performed by using the activation thecnique. The E.R. produced by fusion decay by Electron Capture (E.C.) so they are detected and identified by measuring the X-ray emitted after E.C. decay using a Si-Li detector. The clear advantage of the off-line X-ray technique is the 100% intrinsic detection efficiency and the low background for X-ray detection. We clearly identified five E.R. previously predicted by statistical model calculations (^{68}Ge, ^{66,67,68}Ga and ^{65}Zn) with half-lifes ranging from 1 hour to 300 days. Different isotopes of the same element which cannot be distinguished by atomic X-ray spectroscopy can be identified following the activity curve as a function of time. An activation run using a ^{4}He beam was performed in order to check the absolute normalisation by comparing our results with previously measured excitation function for ^{4}He+^{64}Zn using radiochemical method [5]. Along with the fusion excitation function, elastic scattering and transfer reactions were measured. The contribution of the transfer channel has been clearly identified for the first time in such kind of studies.

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Analysis of the ^{6}He(p,p'), ^{10,11}C(p,p') and ^{6}He(^{12}C,^{12}C) data at 40 A.MeV

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We have studied angular distributions of cross sections of elastic scattering of light exotic nuclei on targets of protons and carbon. Our aim was to know whether the weak binding of exotic nuclei should appreciably enhance the polarization potential, which includes the couplings to the continuum and break-up effects. We have also wanted to determine whether the models and the effective NN interactions, proved to be well adapted to the stable nuclei, had to be put into question when going far from the valley of stability.

Data for ^{6}He, ^{10,11}Be at 40 A.MeV on p and ^{12}C were measured at GANIL where the SISSI (Superconducting Intense Source for Secondary Ions) and the SPEG (Energy Loss Spectrometer at GANIL) devices have performed the production of the secondary beams and the detection of the scattered particles, respectively. The nucleus-nucleon interaction for the elastic scattering on protons is calculated with the microscopic, complex and parameter-free JLM potential [1]. A complex surface potential, with a repulsive real part, is expected to simulate the surface effects generated by the polarization potential [2]. By taking it into account, we have reproduced successfully a large set of data for the elastic scattering of exotic nuclei on protons at energies from 25 to 100 A.MeV.

In the case of ^{6}He $+^{12}$C elastic scattering, the energy resolution was good enough to separate the elastic scattering from inelastic contributions. The real part of the potential of interaction between the exotic nucleus and ^{12}C was calculated in the framework of the folding model, including new density-dependent NN interactions, recently obtained by D. Khoa and W. Von Oertzen [3]. With the polarization potential, the agreement found with the data is satisfactory.

For (p,p') reactions, the MUST device, a set of Si and Sili telescopes specifically designed to detect recoiling light charged particles, is used to measure angular distributions for elastic and inelastic scattering of radioactive beams on proton. (p,p') scattering data to the first excited state of ^{6}He at 1.8 MeV have been measured over a wide angular range with a 40.9A.MeV ^{6}He beam produced at Ganil. Inelastic scattering on proton, to the first excited state, for ^{10,11}C, were also measured at E_{lab} $\simeq$40 A MeV. The JLM potential is used to calculate the inelastic cross sections. The calculated inelastic (p,p') cross sections are sensitive to M_n/M_p factor, which is the ratio of the radial moments of the transition densities, $M_{p,n} = \int dr r^{l+2} \rho^{tr}_{p,n}$. The extraction of nuclear structure information in terms of the M_n/M_p factor from the angular distributions of cross sections will be explained. We show that the ^{6}He(p,p') analysis is in favour with the halo configuration for this nucleus. The analysis of the ^{10,11}C(p,p') data is consistent with an extended matter radii of these nuclei, and with the alpha clusterization suggested in [4].

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Transfer Reactions with Radioactive Ion Beams at HRIBF *

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It is well-known that the order of single-particle orbitals changes as a function of neutron and proton number. In addition, the presence of deformation fragments the single-particle strengths. It is, therefore, critical to study single-particle transfer reactions on nuclei away from the valley of stability to probe the ordering of single-particle energy levels, single-particle spectroscopic factors, and the fragmentation of these strengths as a probe of deformation.

For nuclei away from the valley of stability such transfer reaction studies can only be performed in inverse kinematics, with a beam of the radioactive species hitting a hydrogenic target, for example. Such studies have been successfully performed at the ATLAS facility at Argonne, where a radioactive ^{56}Ni beam impinged on a thin CD_2 target with the mass/charge of energy-degraded beam-like residues selected by the Fragment Mass Analyzer and reaction protons from the (d,p) reaction were detected in a large, annular Si detector array at back angles in the target chamber. [1]

Two experiments have been approved to study transfer reactions in inverse kinematics using beams of ^{56}Ni and ^{92,94}Sr from HRIBF in which the heavy residues would be analyzed with the Recoil Mass Separator and light residues would be detected with position-sensitive Si detectors in the target chamber of the RMS. The present talk would discuss the experimental challenges as well as the prospects for transfer reactions with radioactive ion beams at HRIBF and in the future at RIA.

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Angular momentum transfer in fragmentation reaction

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Spin oriented ensemble and angular momentum transferred to a nucleus produced by fragmentation reaction process at intermediate energies are good tools to investigate such a process. Spin-aligned and spin-polarised nuclei coming from fragmentation reactions have been studied by several group [1-3]. At relativistic energies, it has been observed that the spin-alignment is related to the linear momentum distribution of outgoing fragments [4]. It was then deduced that the angular momentum transfer, spin-alignment and spin-polarisation are directly linked to the reaction mechanism involved.

Experiments performed recently using the LISE3 spectrometer from GANIL facility have investigated the fragmentation reaction mechanism at intermediate energies. The study of the angular momentum transfer occurred during this process have been performed by looking at the population of well known short-lived isomeric states close as well as far from the projectile. The spin-alignment and spin-polarisation of outgoing fragments have been also studied by using the β-LMR and β-NMR experimental techniques [5]. For the first time, a spin-polarised secondary beam have been produced at GANIL.

Experimental results have been quantitatively reproduced in the framework of kinematical [6] and statistical [7] models of nuclear reactions. The predictive power of models shows the possibility to produce isomeric useful for the study of reaction mechanism involved by isomeric beam, spin-aligned and spin-polarised secondary beams by fragmentation reaction useful for nuclear moment measurements.

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High Energy-Resolution Measures of Cross-Sections at RIBs *on the "Method of Spectra Superposition"* - MSS

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In order to estimate the highest possible energy resolution in excitation function-EF (beam-energy dependent cross-sections) , evolution of the initial beam-particle energy spectrum and distortion of the product-particle energy spectrum both are considered as functions of corresponding basic factors involved step by step in the low-energy elastic scattering just as an example.

The EF-energy-resolution independence on the beam (!) and contribution in the EF-distortion only of factors on the product-particle trajectory both are clearly shown.

During some last years the MSS was proven and successfully used in a number of experiments on low energy nuclear physics [1-4].

High significance and importance of the MSS-approach, as of a background for a large set of new energy-precise experiments especially at the Radioactive and Heavy-ion beams, is stressed promising reach results carried with a lot of new information.

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Confirmations of the New Observed Phenomena of the *"COMBINATIV ISOBAR RESONANCES"* - CIRs

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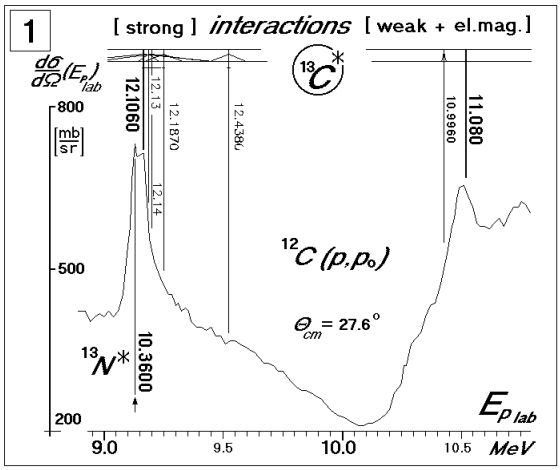
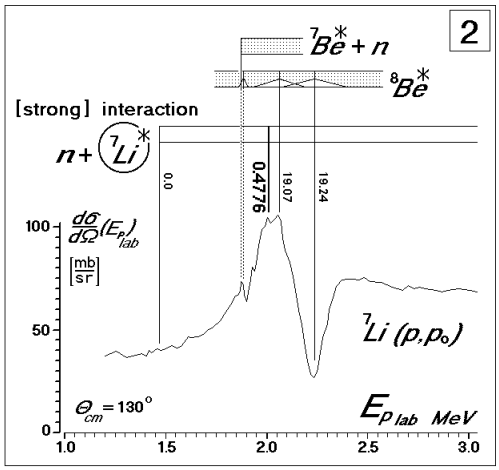
Many years, in the Nuclear Reaction Physics are known Resonances in the *Target-projectile*-system (RTPS) and fluctuations in cross-sections. What are they for certain? Very likely, answer to this can now become the most way to review all content of the Fusion Cycles...
Recently in high energy-resolution measures of Excitation Functions (EFs) at cyclotron using MSS-approach was obtained [1,2] the cross-section curve with 14 well known and large number of the RTPS which were identified only in suggestion that before the final nuclei&particles it take place formation of the isobaric charge-forbidden nuclei with the charge-equilibrium particle(s) inside [2,3]. These phenomena, enlarging number of the energy-accessible combinations of final products, display in $d\sigma(E)/d\Omega$ the respective additional anomalies named CIRs, arising due to the little known projectile-stimulated **soft** π [4,5]. CIR validity is confirmed [3] by the peaks found in [6,7] another EFs (see 1, 2 – lines of the forbidden nuclei $^{13}C^{\star}$ (12.106 MeV and 11.080 MeV) and $^{7}Li^{\star}$ (0.4776 MeV) through the CIR).





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Low Energy Fission of Heavy Exotic Nuclei *

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Results of investigation of shell effects in heavy ion induced low energy fission of transitional, Ac-Th, and super heavy compound nuclei will be discussed. Mass, energy distributions of fission fragments, pre- and post-fission neutron and gamma ray multiplicities from fission fragments will be presented.

Performed analysis of the experimental data for ^{226}Th with the use of a new multicomponent method [1] has shown that alongside the well-known modes, i.e., the symmetric (S) and two asymmetric modes standard-one (S1) and standard-two (S2) [2], a high-energy mode standard-three has manifested itself (S3). The last named mode appears due to the influence of the close-to-sphere neutron shell with N≈50 in the light fission fragment group [3].

In detailed measurements of mean gamma-ray multiplicities from fission fragments of ^{226}Th two components in $M_\gamma(M)$ distribution were established. They were associated with different conditions during formation of fission fragments and it was shown that M_γ is very sensitive to symmetric and asymmetric modes and proprieties of the scission point. Theoretical calculations of the pre-scission shapes of the fissioning nuclei ^{224,226}Th confirm our conclusions.

Future experiments with exotic beams on study of shell effects in low energy fission with will be discussed.

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Systematics on cross sections from fragmentation and fission reactions

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Three reaction mechanisms provide the most promising prospects for the production of secondary beams. Fusion is best suited for the production of nuclei near the proton drip line. Fission specifically populates mid-mass neutron-rich isotopes. Fragmentation and spallation reactions represent rather universal production mechanisms for both neutron-deficient and neutron-rich exotic nuclei, since the fluctuations in the N-over-Z ratio are very important. Due to these large fluctuations, this is the most promising reaction mechanism to reach extremely exotic nuclei over the whole mass range, if sufficiently high primary-beam intensities are available. In particular, it seems to be a unique process for the production of extremely neutron-rich isotopes of elements above the region of fission fragments.

Computer models for understanding reaction mechanisms and predicting the cross sections of fragmentation and fission processes have been developed in our group [e.g. 1,3]. A great amount of experimental data on the production of residual nuclei in reactions at relativistic energies has been obtained in several experiments recently performed at GSI in inverse kinematics [e.g. 2-7]. On the basis of these data, realistic parameters for model calculations can be deduced, and the model predictions can be verified.

The good actual knowledge of the characteristics of the nuclear reactions allows for choosing conditions optimised to specific needs for the secondary-beam production. Using our experimental data and models it is possible to give rather realistic estimates on the prospects for secondary-beam production in next-generation facilities.

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Investigation of t+t collisions using ACCULINNA beam line and a liquid tritium target

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The use of a tritium target in experiments with radioactive beams seems to be promising for the study of light neutron-drip nuclei. In this respect, favorable are transfer reactions between tritium nuclei and neutron-excess projectiles studied in a projectile energy range of 15–30 MeV/n. Relevant examples could be 2n-transfer reactions ^{3}H+^{3}H$\rightarrow^5$H+p, ^{8}He+^{3}H$\rightarrow^{10}$He+p, etc., or 1p-transfers ^{8}He+^{3}H$\rightarrow^7$H+α, ^{11}Li+^{3}H$\rightarrow^{10}$He+α, etc. Angular distributions obtained for reaction products in these reactions can give useful information about clustering structures in both the exotic projectiles and drip-line reaction products [1,2]. However, the use of a tritium target is even more promising for the study of resonance states of nuclei lying beyond the neutron drip line. Recently, an environmentally safe liquid-tritium target was installed at the radioactive beam line of separator ACCULINNA [3] working with primary beams of U-400M cyclotron. The target cell has a material thickness of 0.4 mm for tritium, beam opening of a diameter of 10 mm and the entrance and exit windows closed with two pairs of 12-μ stainless steel foils. On both sides, these foils are vacuum-tight welded to the cell body providing two small vacuum volumes equipped with a tritium absorber, which prevents the penetration of tritium leaks in the reaction chamber.

Separator ACCULINNA was upgraded to meet conditions imposed by the tritium target and improve precision for the transfer reaction study. The beam line was extended in order to deliver the beam beyond the cyclotron hall to a low-background room where a reaction chamber housing the target and position sensitive ΔE$\times$E Si-telescopes is installed. Neutron wall based on 41 DEMON detectors was placed at a distance of 2.5 m from a target.

A primary beam of 58 MeV tritons was obtained from the U-400M cyclotron and delivered to the tritium target. The separator ion optics was used to select the beam having widths of >0.5 % and >0.5° in the energy and angular distributions. Being delivered to the tritium target the triton beam with an intensity of 1×10^8 s^{-1} was focused in a 4-mm spot. All together, the beam quality, target parameters and performance of detector telescopes, allow one to have a resolution of >300 keV for the widths of ^{5}H resonance states, which could result from the t+t reaction. One resonance state around 1.9 MeV was recently obtained for this nucleus in reaction ^{6}He+p$\rightarrow^5$H+2p [4]. Results of an experiment aimed at the study of transfer reactions occurring in t+t collisions will be presented.

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The Cross-Sections of the Photonuclear Reactions

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The cross-sections of the photonuclear reactions (γ,γ'), (γ,n) and (γ,2n) measured for the 92 nuclear in the region between ^{12}C and ^{238}U. The measurements were performed by the activation method on the bremsstrahlung of the microtron with the boundary energy of 13 and 22Mev.The cross-sections were calculated using the modificated model of the preequilibrium decay. The satisfactory agreement of the experimental and calculated cross-section was observed.

Breakup of Weakly Bound ^{17}F by ^{208}Pb at 170 MeV Bombarding Energy *

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It has been demonstrated that the coupling of nuclear reaction and nuclear structure degrees of freedom of fusing nuclei leads to the enhancement of subbarrier fusion cross section. The advent of radioactive beams stimulates studies of subbarrier fusion with weakly bound nuclei. The large r.m.s. radius associated with these nuclei and the excitation to the soft dipole resonance could reduce the barrier for fusion. However, the influence of the breakup of weakly bound nuclei on subbarrier fusion is still an open question. We have measured the breakup of 170 MeV ^{17}F bombarding a ^{208}Pb target. The breakup fragments were identified by a double sided strip detector and Si surface barrier detector ΔE-E telescope. The angular distribution of the ^{16}O fragments was found to disagree with the dynamical calculation and the coupled discretized-continuum channels (CDCC) calculation. The CDCC calculations underpredict the energy spectra of ^{16}O by a factor of 8. Further experiments at energies closer to the Coulomb barrier for investigating the influence of breakup on fusion and the discrepancy between measurement and calculation will be discussed.

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