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EXPERIMENTAL APPROACHES TO DOUBLE SHELL-CLOSURES FAR FROM STABILITY

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Production and Identification of μs-Isomers in Fragmentation-like Reactions of a ^{112}Sn Beam

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Abstract: Representative examples of experimental techniques used for the identification and study of nuclei in the close vicinity of double shell-closures are presented. Perspectives for the discovery of new doubly magic nuclei very far from stability using fragmentation or fusion-evaporation reactions including reactions with radioactive secondary beams are discussed.

I. Introduction

Studies of doubly-closed-shell and neighboring nuclei are obviously important for testing and further development of nuclear models. Special attention has been devoted to double magic nuclei far from β-stability line where new effects such as the disappearance of some magic numbers (eg. N=20) or signatures of new closed shells (eg. Z=40, N=40) were observed. Studies concerning nuclei far from stability have additionally an astrophysical context. Reliable predictions of nuclear structure and disintegration rates are crucial for understanding nucleosynthesis under stellar conditions.

II. Classification of Doubly Magic Nuclei (DMN)

Among the doubly-magic nuclei which are predicted to be bound against particle emission, excepting the five stable isotopes (^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca and ^{208}Pb), only three have been identified and studied experimentally - ^{56}Ni, ^{132}Sn and ^{100}Sn (the latter only partially). Four other doubly-magic nuclei very far from stability, namely ^{28}O, ^{70}Ca , ^{78}Ni and ^{176}Sn are predicted by different mass formulae to be bound. At least two unbound doubly-magic systems can be investigated experimentally: ^{10}He - the isotope with the highest neutron to proton ratio among the known nuclei - and ^{48}Ni a candidate direct two-proton emitter. Predictions of different mass formulae[1)] for unobserved (up to April 1995) DMN are summarised in figure 1. The only nucleus which is clearly predicted to be bound is ^{78}Ni. Taking into account the large uncertainties of theoretical predictions very far from stability the existence of ^{28}O, ^{70}Ca , ^{48}Ni and ^{176}Sn can not be presently excluded.

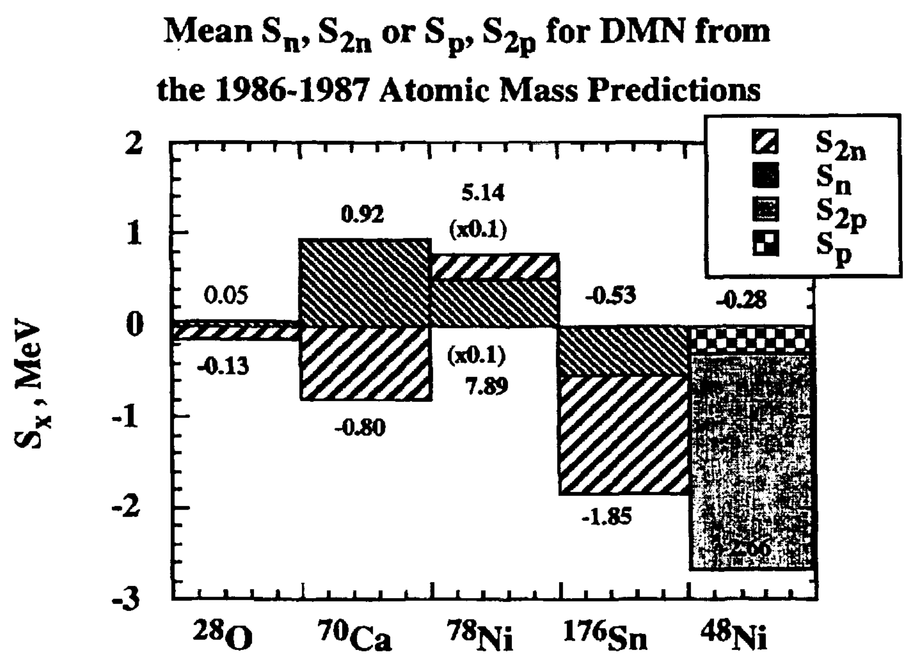


Fig. 1. Predictions of different mass formulae[1)] for unobserved (up to April 1995) DMN.

Studies of DMN close to the proton and neutron drip lines depend on available production rates which are directly related to the reaction cross section and the efficiency of the experimental technique. As a measure of the difficulties in reaching DMN far from stability one may use the difference between isospin of such nuclei (T_z^{DMN}) and the isospin of the closest stable nucleus (T_z^{STABLE}). This difference is plotted in figure 2. for known unstable and hypothetical DMN. From the figure one may conclude that ^{28}O, ^{78}Ni and ^{48}Ni should be identified and studied experimentally (if they are bound!) in the future using existing techniques. The situation seems to be different in the cases of ^{70}Ca and ^{176}Sn - new generation secondary beam factories are necessary for their production.

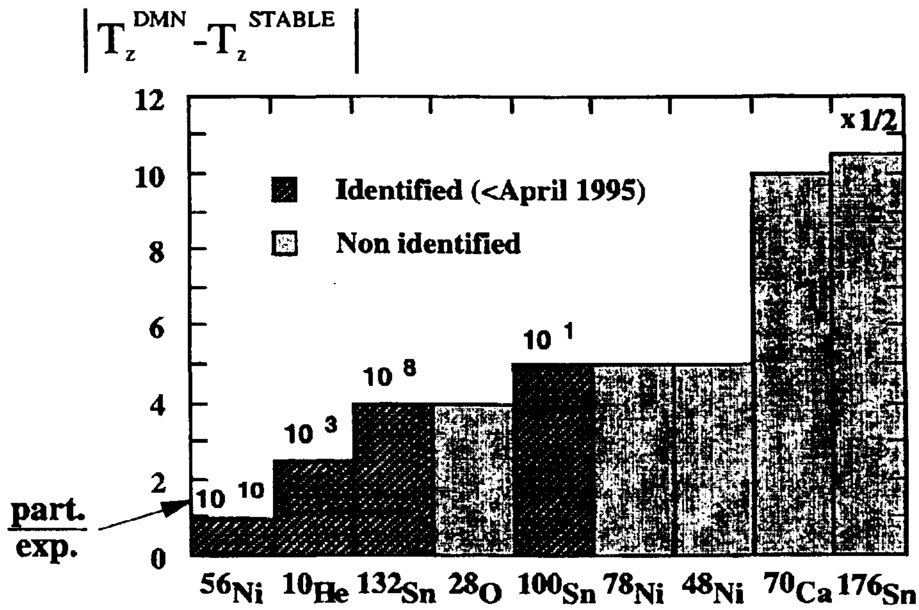


Fig. 2. The difference between isospin of a DMN (T_z^{DMN}) and the isospin of the closest stable nucleus (T_z^{STABLE}). Typical numbers of atoms identified per experiment are given above the bars.

III. Experimental techniques used for the identification and studies of DMN far from stability : representative examples

Rapid developments in experimental techniques for the production, identification and study of nuclei far from stability lead in 1994 to the discovery of the two doubly-magic nuclei ^{10}He and ^{100}Sn. Also in 1994 results of a detailed study of another doubly-magic nucleus ^{132}Sn were published.

The nucleus ^{10}He was observed and studied at RIKEN in reactions induced by a 61 MeV/nucl. secondary ^{11}Li beam (2x10^4 pps) on a CD_2 target[2]. The emitted ^{8}He and one or two neutrons were measured in coincidence using a particle hodoscope and a neutron wall respectively. From their energies and angles of emission the energy of a broad ($\Gamma \leq 1.2$ MeV) resonance state assigned to the ground state of ^{10}He was deduced. A radioactive beam and radioactive target were combined to produce ^{10}He in the double-charge exchange reaction $^{10}Be(^{14}C,^{14}O)^{10}He$ at 24 MeV/nucl. at HMI[3]. A Q3D magnetic spectrometer was used for a precise measurement of the energy and angle of emission of the ^{14}O ions. In this experiment as well as the ground state of ^{10}He, the energies and widths of two excited states of this nucleus were extracted from the data.

The nucleus **^{100}Sn** was produced in fragmentation of relativistic (^{124}Xe at 1095 MeV/nucl.) and intermediate-energy (^{112}Sn at 63 MeV/nucl.) heavy-ion beams and identified using projectile-fragment separator techniques.

In the first experiment performed at GSI[4]) fragments produced in the interactions of a ^{124}Xe beam of $4x10^7$ pps in a 6 g/cm^2 thick Be target were analysed by means of the fragment separator FRS. The ^{100}Sn nucleus was produced and clearly identified using ΔE, time-of-flight and $B\rho$ measurements. Despite the very low production rates for the most exotic nuclei (about 0.6 ions per day in the case of ^{100}Sn), very selective implantation and low background detection of β^+-decay provided for the first measurements of the half-lifves of ^{100}Sn, ^{102}Sn, ^{104}Sb and ^{105}Sb. Details of the experimental technique and results of this experiment are presented at this conference in the contribution of F.Heine et al. [5]).

In the second experiment performed at GANIL a ^{112}Sn beam of 2.4 pnA impinged on a 144 mg/cm^2 ^{nat}Ni target placed between two high-acceptance superconducting solenoids of the SISSI device[6]). The outgoing fragments were separated using the Alpha and LISE3 magnetic spectrometers. The identification of reaction products (A, Z and atomic charge q) was based on the measurements of the time-of-flight, energy loss and total kinetic energy. An unambiguous and independent identification was also obtained via observation of the characteristic γ-decay of μs-isomers produced simultaneously with nuclei in the ^{100}Sn region[7]). The counting rate for $^{100}Sn^{48+}$ was about 5 ions per day, however, a relatively low selectivity of the separation technique used in this experiment preserved the measurement of the half life. In a recent experiment performed with the ^{112}Sn beam at GANIL a higher selectivity was obtained by means of a thin (1.5 μm) charge-changing Al foil placed at the entrance of the LISE3 spectrometer. This method eliminated in a very effective way nuclei with $Z \leq 40$. Decay positrons were measured in a silicon strip detector and via correlated 511 keV γ-rays in a segmented high-efficiency BGO array and 70% Ge detector (see figure 3). Examples of half-life spectra obtained using the above setup are presented in fig. 4. Full analysis of the data is in progress.

The nucleus **^{132}Sn** was studied recently at OSIRIS in Studsvik via β-decay of ^{132}In produced in the thermal neutron induced fission of ^{235}U[8]). A high neutron flux (10^{11} n/cm^2), use of a target of several grams of uranium in combination with an efficient ion source provided for the production and extraction of about 10^4 ^{132}In atoms per second. A detailed level scheme of ^{132}Sn including multipolarities of the

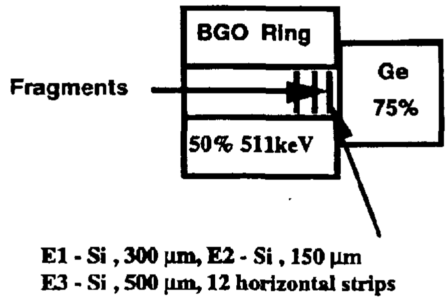


Fig. 3. Experimental set-up used for decay studies of nuclei close to ^{100}Sn at GANIL.

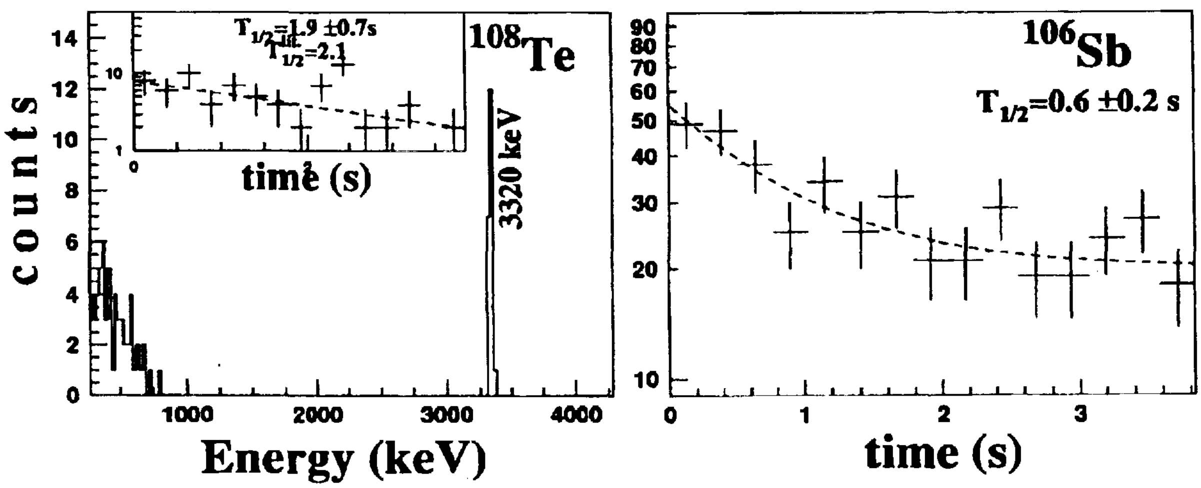


Fig. 4. Decay spectrum of ^{108}Te (left panel) measured at GANIL. The characteristic α-line at 3320 keV is clearly visible. The corresponding decay curve is presented in the insert. Time distribution of decay of ^{106}Sb (preliminary) measured for the first time is plotted in the right panel where the deduced half-life is noted.

strongest transitions and half-lives of several levels down to about 10 picoseconds were measured in this experiment. The above results show clearly that thermal neutron induced fission is presently the most efficient method of production of nuclei in the vicinity of ^{132}Sn.

IV. Other techniques used in the vicinity of DMN : examples

Mass separators + fusion-evaporation reactions

Considerable progress has been achieved using "conventional" methods such as ISOL, IGISOL. The first identification of ^{101}Sn via its beta-delayed proton decay[9], and β-p and β-γ decay study of others nuclei close to ^{100}Sn at GSI mass separator may serve here as representative examples (see Z. Janas et al.[10]).

A very novel technique which uses the second large cyclotron of GANIL as a very high resolution mass spectrometer has recently been developed for precision mass measurements and applied to nuclei in the region around ^{100}Sn (see the contribution of A. Lépine-Szily et al.[21]).

In-beam γ-ray spectroscopy

In-beam γ-ray spectroscopy in conjunction with different particle detectors provided for a recent study of several nuclei in the vicinity of ^{100}Sn, such as ^{102}In[11] and ^{99}Cd (see M. Lipoglavsek et al. [12]).

A constant improvement in efficiencies of 4Π–γ detection and particle detectors illustrated in table 1, and the use of radioactive beams should permit, in the near future, the in-beam study of nuclei close to ^{78}Ni and ^{100}Sn.

TABLE 1

Efficiencies (ε) in % of 4Π–γ detectors and dedicated particle (neutrons, protons and alphas) detectors - examples

	OSIRIS HMI	NORDBALL NBI	EUROGAM II under construction	EUROBALL R&D
ε_γ	0.55	1.35	7	10
ε_n	12	25	15	30
ε_p	26	65	65	~ 90
ε_α	20	45	45	~ 90

Production and study of isomers in fragmentation of heavy ions

The strong production of μ-second isomers observed recently in the fragmentation of the ^{112}Sn beam[7] may be used as a powerful tool to search and study new isomeric states in the vicinity of DMN. This method combines the unambiguous Z and A identification of intermediate or high-energy fragments obtained via time-of-flight and energy-loss measurements with an exclusive, low background detection of γ-rays. This technique due to its very high sensitivity (in some cases even on the basis of several heavy-ion-γ coincidence events it is possible to signal the existence of an isomeric state) may provide a first step towards further detailed in-beam spectroscopy of excited states in exotic nuclei.

New results obtained using this method, including the observation of isomers in ^{94}Pd, ^{96}Ag and possibly also in ^{98}Cd and ^{102}Sn, are presented in the contribution to this conference by R. Grzywacz et al.[13].

The use of different experimental techniques in the region of ^{100}Sn is summarised in figure 5. The fragmentation reactions in conjunction with fragment-separators were used to signal the existence of the most exotic nuclei (or their metastable states) and for half-life measurements. Due to the typically higher counting rates obtained in the fusion-evaporation reactions (see table 2) the detailed spectroscopic information was obtained by the in-beam experiments or in the β-decay studies using mass separators.

TABLE 2

Comparison of typical rates for fragmentation, ISOL and "in-beam" spectroscopy

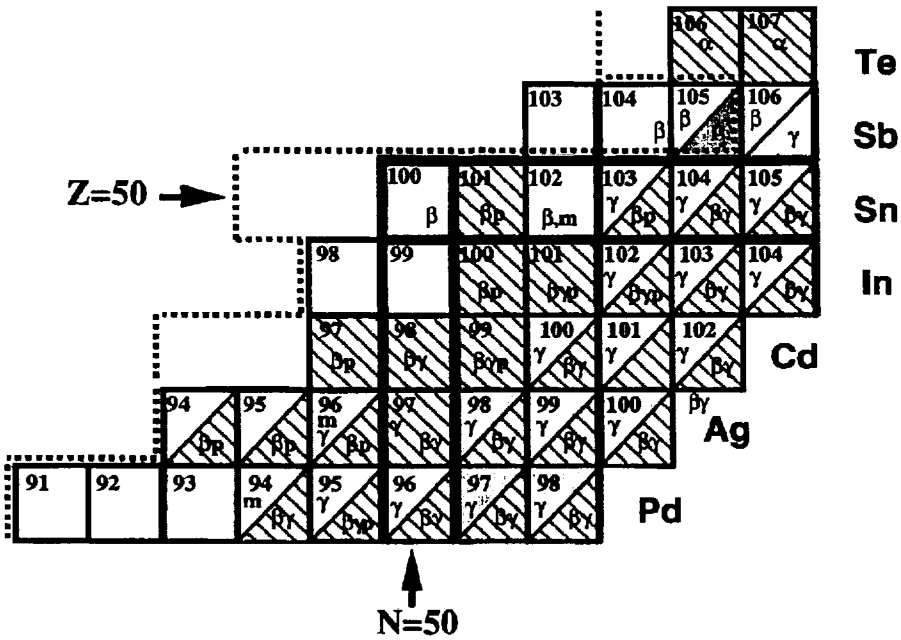
Method	Rate of identified nuclei	Ref.
fragmentation of ^{112}Sn (63 AMeV)SISSI-LISE3, GANIL	~1.5 (^{102}In) ~10 pps (^{102}Cd)	M. Lewitowicz et al. Phys. Lett.B 332(1994)20
^{58}Ni(5.6 AMeV)+^{50}Cr On-line mass separator, GSI	~1400 pps ^{102}In ->^{102}Cd	J. Szerypo et al. GSI-94-38
^{58}Ni(4 AMeV)+^{46,48}Ti In-beam, OSIRIS, HMI	~1800 pps ^{102}Cd	D. Alber et al. Z.Phys.A344(1992)1

V. Middle and long term future

The search for ^{28}O, ^{48}Ni will be continued using fragmentation reactions at intermediate and relativistic energies. In the case of ^{28}O intense beams of ^{36}S or ^{48}Ca at 70 to 100 AMeV seem to be the most promising tool for production of this extremely neutron-rich oxygen isotope. The lightest isotopes of Ni including ^{50}Ni were observed in the fragmentation of a relativistic ^{58}Ni beam at GSI[14]. However, a primary beam with an intensity more than 100 times higher that used previously is necessary to produce ^{48}Ni in this reaction.

Recent results obtained at GSI[15] demonstrate that ^{78}Ni and neighboring nuclei may be reached experimentally in the fission of a relativistic ^{238}U beam (see the contributions to this conference of P. Ambruster[16]), M. Bernas et al.[17]) and S. Czajkowski et al.[18])).

An alternative approach to the study of ^{78}Ni using the IGISOL method with a selective laser source has been presented at this conference by J. Andrzejewski et al.[19]).



Method of production, separation & identification:

······ Drip-line predicted by Janecke&Masson

▧ - fusion evaporation+mass separator

□ - fusion evaporation+in-beam spectroscopy

▨ - fusion evaporation+He-jet

□ - fragmentation+fragment separator

Measured decay:

α, γ, p - alpha, gamma, proton

$\beta\gamma$, βp - beta-gamma, beta-delayed proton

m - isomers observed in fragmentation

Fig. 5. Use of different experimental techniques in the region of ^{100}Sn (April 1995)

The use of radioactive nuclear beams may open up completely new perspectives in studies of double-shell closure. The feasibility of such experiments was recently demonstrated, for example, by the inelastic scattering of a ^{56}Ni beam on protons[20].

Future experiments in this domain should benefit from the new generation of radioactive beam facilities presently under construction (e.g. the Oak Ridge RIB facility and SPIRAL at GANIL) and new detectors such as EUROGAM, total-absorption gamma spectrometers and 4π charged particle arrays.

Acknowledgement
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