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Experiments with Neutron-Rich Isomeric Beams

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A review of experimental results obtained on μs–isomeric states in neutron–rich nuclei produced in fragmentation reactions and studied with SISSI-Alpha-LISE3 spectrometer system at GANIL Caen is given. The perspectives of experiments based on secondary reactions with isomeric beams are presented.

1 Introduction

Fragmentation of heavy–ions at intermediate and relativistic energies studied at projectile fragment separators has been proven an efficient way to reach and investigate new exotic nuclei. Among recent spectacular studies at the frontiers of known isotopes are the experiments approaching neutron–deficient doubly–magic nuclei ^{100}Sn [1,2,3,4] and ^{48}Ni [5] as well as the investigations focussed on neutron–rich doubly–magic ^{78}Ni [6,7]. In the case of the most proton–rich N=50 isotone, ^{100}Sn, twelve neutrons were removed from the primary 63 AMeV ^{112}Sn beam particles at GANIL [1,2], and as many as 24 nucleons were stripped from 1 AGeV ^{124}Xe beam at GSI [3,4]. The most neutron–rich known N=50 isotone, ^{78}Ni, was observed [6,7] among the very neutron–rich fission products of relativistic ^{238}U beams incident on a ^{9}Be target, at the GSI FRS set–up [6]. In these experiments, other new nuclei were identified, in the vicinity of ^{100}Sn (over twenty new isotopes [2]) and ^{48}Ni (for example the very neutron–deficient T_Z=-7/2 nuclei ^{49}Ni and ^{45}Fe [5]) and in the fission region (over hundred new isotopes [7]). This illustrates the broad distributions in mass, A, and atomic

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number, Z, extending to exotic nuclei, typical for fragmentation reactions with high energy heavy–ions. However, the spectroscopic studies of excited states in such exotic fragments are limited. The "in–beam" γ–spectroscopy at the target position will be blocked by the high background rates from the large numbers of products closer to stable isotopes. For many years, information on the excited states of nuclei produced in heavy–ion fragmentation has been basically limited to the data obtained by means of decay spectroscopy of implanted reaction products, see e.g [8,9,10] for recent examples. Coulomb excitation studies with neutron–rich secondary beams from fragmentation are the exception, see e.g. a contribution to this conference [11].

However, a new area of nuclear structure studies based on heavy–ion fragmentation reactions has been opened just a few years ago. Forty known μs–isomers in heavy nuclei between ^{18}F and ^{105}Cd were populated in the fragmentation of a 58 MeV/u ^{112}Sn beam [12] and studied within one (!) spectrometer setting at the final focus of the LISE3 separator [13,14] at GANIL. This pioneering run was followed by about ten experiments employing fragmentation of ^{112}Sn, ^{106}Cd, ^{92}Mo, ^{86}Kr, ^{78}Kr, ^{40}Ar and ^{36}S beams at GANIL, and ^{238}U projectiles at GSI. These studies profited from the *implanted fragment–γ* μs–correlation technique [12]. Among other results, almost thirty new isomeric states in exotic nuclei have been discovered, and their main decay properties have been established. Evidence for over twenty other new metastable states in exotic nuclei such as ^{102m}Sn and ^{72m}Ni with halflives in the μs–range has been obtained. In this contribution, after the brief description of the experimental method, the selected results obtained for neutron-rich nuclei at GANIL are presented and discussed (see also [15,16,17] for earlier reports and [18] for complete presentation).

2 Experimental technique

The modern projectile fragment separators such as SISSI-Alpha-LISE3 complex [13,14,19,20] at GANIL and FRS [21] at GSI offer a very high selectivity for the studies based on the fragmentation of high–energy heavy ion beams. Due to the use of position–sensitive, transmission detectors like paralel plate avalanche counters, microchannel plate detectors, multiwire counters,multisampling ionization chambers or position sensitive silicon detectors the tracking of the ions in space and time is possible. This information, together with energy loss and total energy measurements, allows an identification of the mass (A), atomic number (Z) and charge state (Q) of individual fragmentation products. During the experiments aiming in the detection of μs–isomeric states, a standard stack of silicon detectors (or other type of the counters and catchers system measuring the time and energy loss signals of implanted ion) is surrounded by the

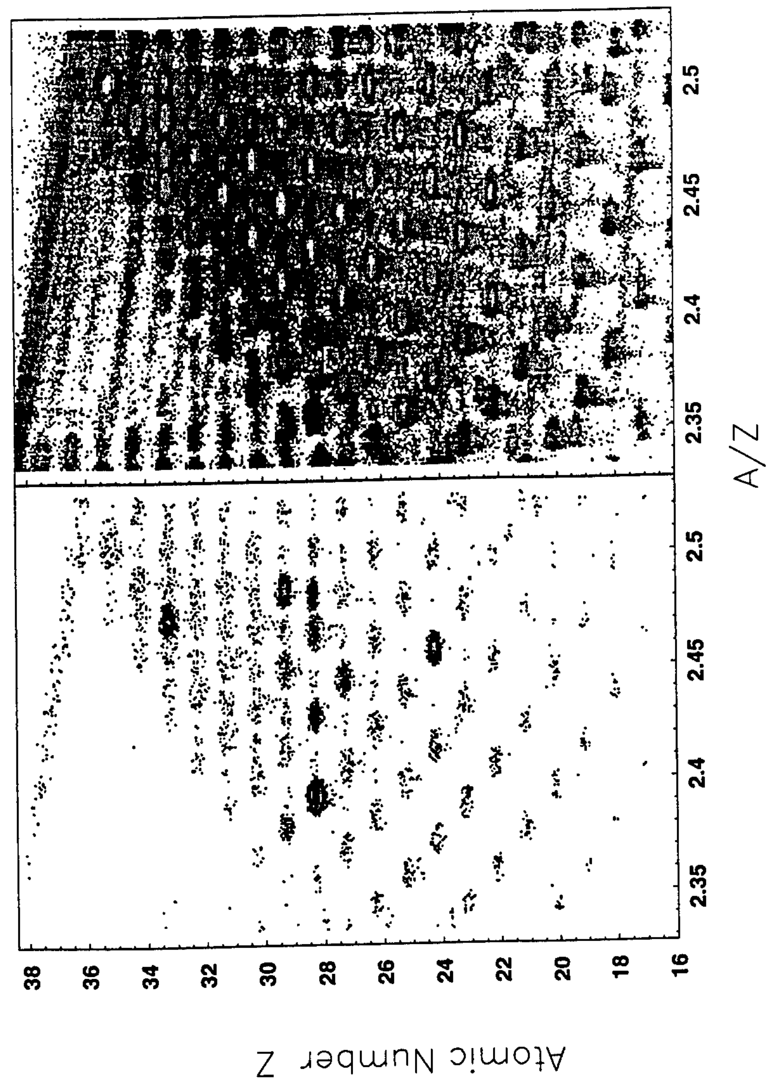

Figure 1: Products of the fragmentation reaction of a 60 MeV/u ^{86}Kr beam on a 89 mg/cm^2 ^{nat}Ni target selected and identified by magnetic rigidity, time–of–flight, and energy loss with the SISSI-Alpha-LISE3 spectrometer complex at GANIL (right panel). Events displayed in the left panel, observed in the μs–correlation with γ–radiation, indicate clearly the presence of several isomers.

photon detectors at the final focus of the spectrometer. To obtain high resolution information on the detected γ–radiation, an efficient array of γ–detectors consisting e.g. of several clover- or cluster-type detectors, is crucial for the success of such experiment.

The acquisition system is triggerred by the signal corresponding to the implantation of the identified reaction product. The gate opens for a fixed time interval, usually of the order of 10 to 100 μs. The overall rate of the products with spectrometer setting optimized to exotic products is usually below 1000 events per second. This means the average time interval between the subsequent implantation of the products is greater than one millisecond. It was experimentally demonstrated, see e.g. [12,22,16,18,23], that fragmentation reactions efficiently populate the isomeric states in nuclei. If the halflife of such metastable states is long enough for the ion to be transmitted through the spectrometer, the γ–signals related to the isomer decay may be observed at the focal plane and they are time–correlated with the identified fragment. The γ–energy and its time relative to the ion implantation is recorded with the same coincidence record as the product identification signals. Background γ–radiation consists of natural (laboratory) background, prompt photons from reactions at the catcher (detector) material and β–delayed γ–ray transitions following the decay of previously implanted isotopes. The background rate is drastically suppressed by requiring *implanted ion–γ* correlation times within the μs–range. One may consider the γ–spectra obtained after isomer decay similar to the singles, however, recorded only for a very short time intervals after the implantation of the identified ions. The range of this time interval is variable and might be adjusted during off-line analysis accordingly to the halflife of the analyzed isomer. Therefore, the resulting typical γ–background rate is at a level of 1% of all correlated events related to the short lived isomer decay. The intensity of the recorded γ–transitions must be unfolded with respect only to the detector response function (photopeak efficiency, summing effects). Spectra are not affected by γ–γ coincidence requirements or Doppler broadening effects. In case of an isomer produced with a rate sufficiently high to achieve the necessary γ–γ statistics, it should be possible to determine the multipolarities of the observed cascading transitions by their angular correlations. The use of e.g. a segmented clover array is highly advisable for such studies.

Unambigous atomic and mass number assignment to the fragmentation products separated and identified by energy–loss (ΔE) versus time–of–flight (TOF) signals is an another application of this method. The spectra of ΔE - TOF signals from transmitted heavy–fragments obtained in μs–correlation with γ–transitions following isomeric decay contain mostly the events corre-

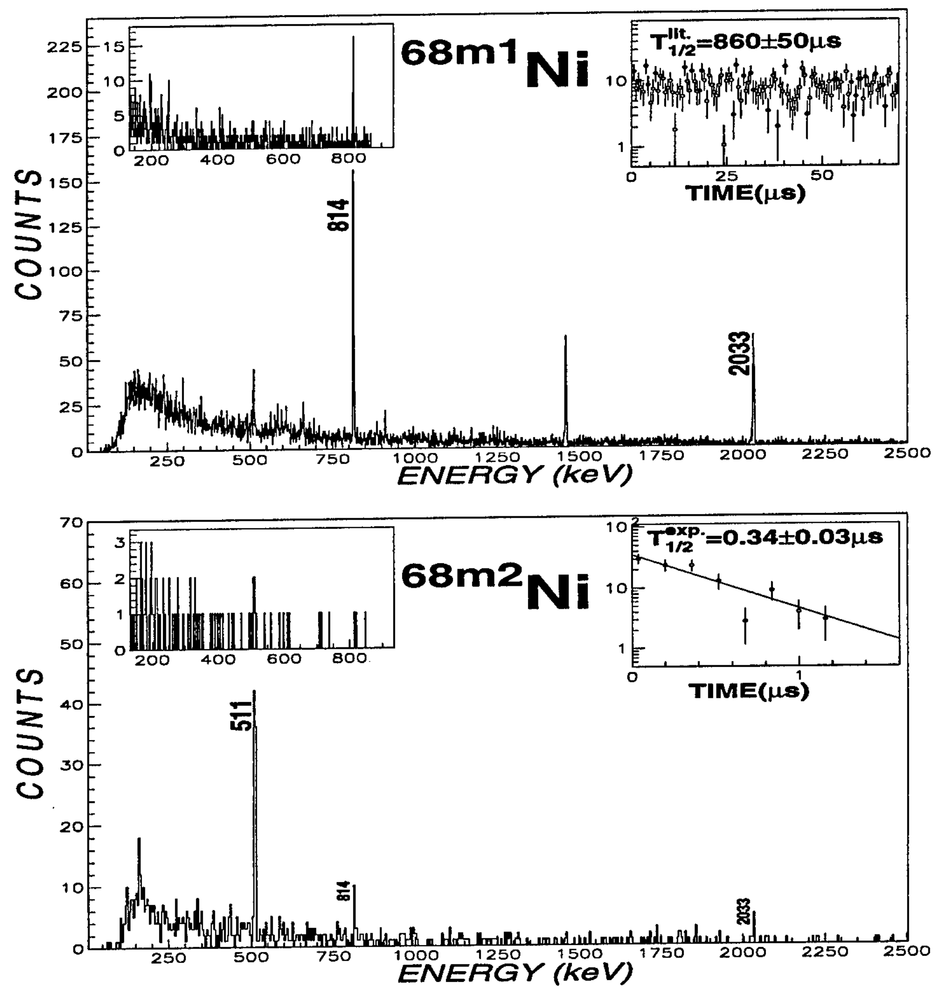

Figure 2: The energy spectrum and decay patterns of γ–transitions correlated with the implantation of ^{68}Ni ions measured at GANIL during an experiment with the 60 MeV/u ^{86}Kr beam. The presence of short–lived annihilation radiation is due to the $0^+ \rightarrow 0^+$ decay of an isomeric state at 1770 keV in ^{68}Ni via Internal Pair Formation.

sponding to implanted nuclei in isomeric state, see Fig. 1. Since μs-isomers occur relatively rarely in the nuclidic chart, such spectra (called *Grzywacz plot*, see e.g. [12,22] and figures therein) provide a background–free response function of the detector system to the ΔE - TOF ion identification signals. This is particularly important for studies at the border of known nuclei and for reporting the observation (i.e. a proof of existence) of new, very weakly produced isotopes. Illustration of this feature with the identification of ^{100}Sn and the proton instability of ^{69}Br is given in refs. [2] and [24], respectively. It is also important for such experiments that the identification of the observed fragments could be made on–line rather quickly, based on the observation of known μs–isomeric decays. This makes the selection of a degrader thickness much easier and the proper implantation profile of selected fragments can be achieved much faster allowing for additional β- and γ-decay spectroscopy measurements.

The time-of-flight of fragmentation products between the target and the final detection system is from a few hundred nanosecond to about 1.5 μs. This suggests a halflife limit of about 100 nanosec for the isomers being investigated with this method. However, the fragmentation products are transmitted as fully–stripped ions through the spectrometer (with various contribution of hydrogen–like and helium–like fragments). Since the conversion electron channel of the isomer decay is blocked during the flight for fully stripped ions, in specific cases the ionic halflife is much larger than for a neutral atom. This allows transmission of such isomeric ions almost without intensity losses during the flight between the target and implantation stations. The recent observation of a new level with $T_{1/2}$= 29±6 nanosecond, intepreted as the I=0^+ state in ^{74}Kr [25,26] was possible due to the much longer ionic halflife of fully stripped ^{74m}Kr^{+36} nuclei.

Particularly interesting application of this μs-correlation technique is related to the investigations of the $0^+ \rightarrow 0^+$ decays in fully stripped ions. In case the 0^+ state is isomeric, the decay constant will be greatly reduced in–flight. This is particularly true, if the excitation energy of the isomer is less than or approximately equal to 1022 keV and doesn't allow for the intense Internal Pair Formation (IPF) decay channel. The halflife may become a few orders of magnitude longer; however the two-photon channel will still contribute to the decay. When the $0^+ \rightarrow 0^+$ transition energy is greater than 1022 keV, e.g. the 1770 keV 0^+ state in ^{68}Ni [27,28,29,30,31], the IPF decay will be followed by the 511 keV annihilation radiation correlated with an implantation of the associated ion [16], see Fig.2. This provides an unique identification of such $0^+ \rightarrow 0^+$ transitions and allows a determination of their halflife via the *background–free* annihilation radiation decay pattern.

This method of decay studies of μs–isomers populated in the fragmentation reactions, together with the Coulomb excitation of radioactive beams, has been labelled *on–beam spectroscopy*[32].

3 New neutron-rich μs–isomers

The short–lived states in neutron–deficient nuclei have been studied over thirty years using fusion–evaporation reactions between heavy–ions. The fragmentation based studies recently became a complementary method. The potential to study very exotic nuclei by this technique is similar (sometimes superior) to in–beam experiments using powerful large γ–arrays.

For neutron–rich nuclei, mainly the excited states of nuclei populated in fission have been studied, see other contributions to the proceedings of this conference for recent, spectacular results. Recently, also multinucleon transfer reactions between heavy ions have been successfully applied to such nuclei [29,30,31]. However, the results obtained recently at GANIL and GSI indicate, that the fragmentation of neutron–rich heavy projectiles is presently among the best tools for studying excited states of very neutron–rich isotopes. The basic features of the experimental method were established already during the experiments with 58 MeV/u and 63 MeV/u ^{112}Sn beams [1,12,2,22]. However, it was not obvious till the experiments with the ^{36}S, ^{86}Kr and ^{238}U beams were performed, that the same method could be applied for neutron–rich isomers. The mechanism of isomer production in heavy–ion fragmentation reactions was not well understood. The population of isomers cannot be predicted reliably before the experiment. Since a number of isomers with high isomeric production ratios were measured for the fragmentation products of a 60 MeV/u ^{86}Kr beam at GANIL [16,18] as well as with the 1 GeV/u and 750 MeV/u ^{238}U beams at GSI[23], it became clear that the fragmentation of heavy-ions allow metastable states in neutron-rich nuclei to be populated and studied. These experiments opened a new way of studying the nuclear structure of very neutron-rich systems.

Already before the isomer-oriented experiments at GANIL, it was clear that an efficient method of producing neutron–rich nuclei is achieved by fragmenting the most neutron–rich isotope of a specific element. Therefore, the experiments focussed on the isomers in medium mass neutron–rich nuclei performed at GANIL utilized the beams of ^{36}S [33,34] and ^{86}Kr [16,18].

The metastable 4^+ state in ^{32}Al represents the first neutron–rich isomer found with the μs correlation method [33,34]. It was the only new neutron–rich isomer found among the fragmentation products of ^{40}Ar and ^{36}S beams. However, already this single studied case has led to the conclusion [33], that extrapolations based on existing shell model parametrizations may not be re-

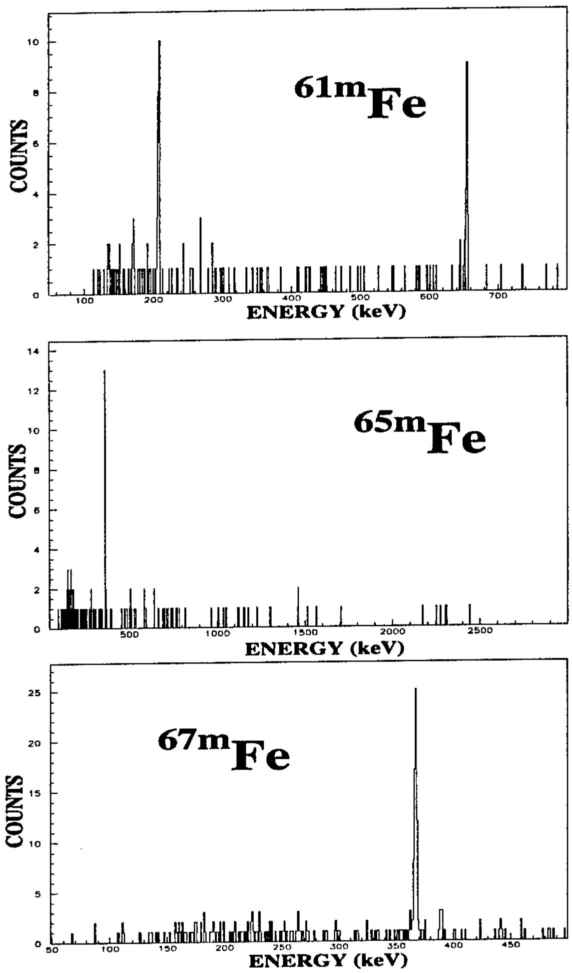

Figure 3: Examples of γ–spectra correlated with the implantation of ^{61}Fe, ^{65}Fe and ^{67}Fe fragmentation products.

liable, and the anomalies of *"universal" sd-shell (USD) interaction* [35], noted before for the N=20 isotones, extend at least to ^{32}Al (N=19, Z=13).

Sixteen new isomers (from Z=33 ^{79m}As to Z=21 ^{54m}Sc) were identified and studied among the fragmentation products of the 60 MeV/u ^{86}Kr beam of 10^{11} particles per second (pps) [16,18,15]. Evidence for over twenty other new isomers also was obtained ranging from Z=34 ^{86m}Se to Z=20 ^{50m}Ca. The main isomeric decay properties including the halflives and characteristic γ-transitions have been measured. By comparing the intensities of cascading γ-transitions, first isomeric transition deexciting the isomer can be identified. For most cases, the multipolarity of isomeric transition can be deduced from the comparison of measured decay constant with respective Weiskopff estimation based on the measured energy of isomeric transition, see Table 1. For a number of isomers, the M2 multipolarity was postulated indicating the change of parity between the states involved. This must be related to the contribution of the states originating from the positive parity $g_{9/2}$ neutron orbital which is located above the negative parity $f_{5/2}$ and $p_{1/2}$ orbitals responsible for low–lying and ground-state configurations. The examples of the γ-spectra obtained for the isomeric decays in iron isotopes during the experiment with the ^{86}Kr beam at GANIL are shown in Fig.3. Interpretation of the very rich nuclear structure information is in progress, however a few interesting conclusions already have been obtained[36]. They are related to the structure of magic Z=28 nickel isotopes between the neutron subshell and shell closures at N=40 and N=50. The isomer ^{70m}Ni ($T_{1/2}$=210 ns, $I^{\pi}=8^{+}$) and an isomer of a similar structure (the 8^{+} state of ^{70m}Ni coupled to the odd $p_{3/2}$ proton) in ^{71}Cu ($T_{1/2}$=275 ns, $I^{\pi}=19/2^{-}$) were observed. Their measured decay properties, dominated by a cascade of four E2 transitions, have led to a revision of the "realistic interaction" used for the shell model description of neutron-rich nuclei in this region [36]. The experimental and calculated 2^{+} energies in ^{70}Ni were in agreement, however differences became apparent when comparing observed and predicted states at higher excitation energies. It is important to note that the production rate of ^{70m}Ni at the target was only about 1 pps. For Coulomb excitation studies, see e.g. [11], the rate of ^{70}Ni should be two orders of magnitude larger. Even with a 100 pps ^{70}Ni beam, one can probably obtain information on the first excited state only. In the case of ^{70}Ni, the observation of the first 2^{+} state only might result in the misleading conclusion that the existing "realistic interactions" parametrization can be used for a description of the structure of very neutron–rich nickel isotopes, see [36]. The experiment by *Pfützner et al* using 1 GeV/u and 750 MeV/u ^{238}U beams of 10^{7} pps fragmented by a 1g/cm^{2} ^{9}Be target performed in December 1996 at the GSI is described in details in a separate contribution to this conference [23]. To compare with the

	E^* keV	$T_{1/2}$ μs	I^π	Mult.	E_i^γ keV	F %
^{54m}Sc	110.	7(5)	(5+)	E2	**110**	30(10)
^{64m}Mn	135.	> 100.	(8-)	M2	**135**	10-100
^{54m}V	108.	0.9(5)	(5+)	E2	**108**	6(3)
^{59m}Cr	503.	96(20)	(9/2+)	M2	**208**	60(10)
^{61m}Fe	861.	0.25(1)	(9/2+)	M2	**654**	30-100
^{65m}Fe	364.	0.43(13)	(5/2-)	M2	**364**	8^{+10}_{-3}
^{66m1}Co	175.	1.21(1)	(5+)	E2	**175**	12.(7)
^{66m2}Co	642.	> 100	(8-)	M2	**252**	4-90
^{67m}Fe	367.	43(30)	(5/2-)	M2	**367**	17(8)
^{67m}Ni	1007.	13.3(2)	9/2+	M2	**313**	61(2)
^{68m1}Ni	2847.	860(50)	(5-)	E3	**814**	43(4)
^{68m2}Ni	1770.	0.34(3)	0+	E0	511	<1
$^{69m}Cu^*$	2740.	0.36(5)	(13/2+)	E2,M1	**75,190**	2(1)
$^{69m}Ni^*$	2701.	0.439(3)	(17/2-)	E2	**148**	10(3)
^{70m}Ni	2860.	0.21(5)	(8+)	E2	**183**	7-52
$^{71m}Cu^*$	2756.	0.275(14)	(19/2-)	E2	**133**	9(3)
^{72m}Cu	270.	1.76(3)	(4-)	E2	**51**	51(1)
^{78m}Zn	>1070	>30			1070	
^{79m}As	773.	1.206(8)	9/2+	M2	**542**	25(2)

Table 1: Isomers observed in experiment with ^{86}Kr beam at GANIL are listed. E^* indicates deduced excitaton energy, $T_{1/2}$ - measured half-life, I^π - proposed assignment for the spin and parity of the isomer, Mult. - multipolarity of the isomeric transition, E_i^γ - energy of isomeric transition and F - isomeric ratio.

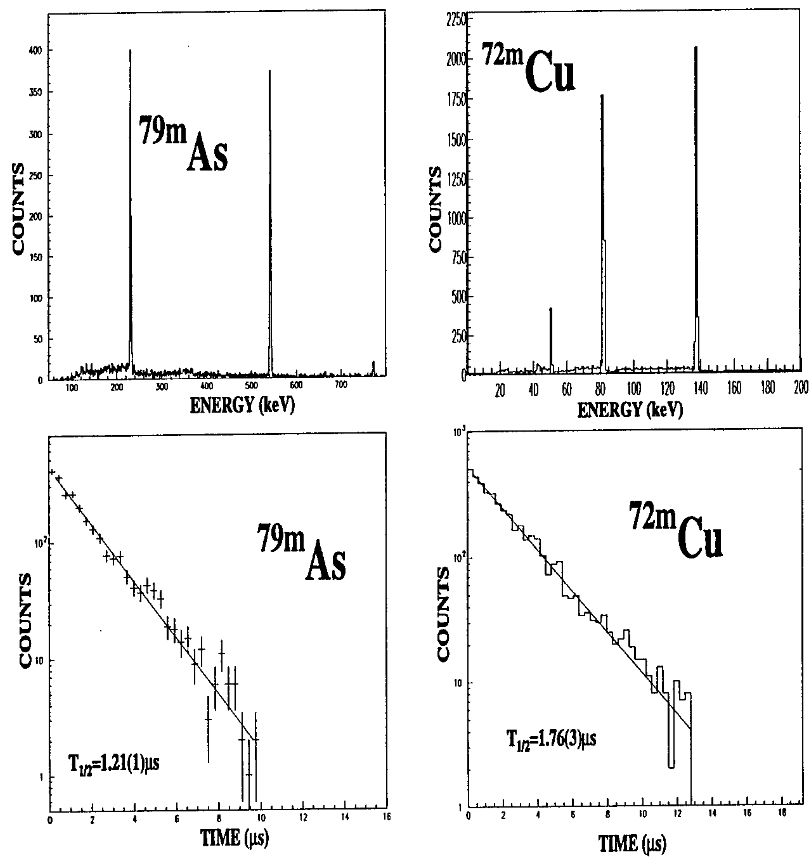

Figure 4: The energy spectrum and decay pattern of γ–transitions correlated with the implantation of ^{79}As and ^{72}Cu ions measured at GANIL during an experiment with the 60 MeV/u ^{86}Kr beam.

GANIL studies, remember that two regions of neutron–rich nuclei have been investigated, near ^{208}Pb and fission products near and above ^{68}Ni. Six new neutron–rich isotopes and three new isomeric states were observed near ^{208}Pb. In particular, the data for ^{212m}Pb should allow the shell–model description along the magic Z=82 shell to be extended to more neutron–rich nuclei. Also previously observed isomers in the vicinity of ^{208}Pb were populated with the isomeric ratio of about 30% via the fragmentation of the 1 GeV/u ^{238}U beam. This is only slightly lower than the typical isomeric ratios of about 40% observed for intermediate energy fragmentation reactions at GANIL, see [12] and Table 1. However, it is sufficiently large to suggest a successful continuation of such isomeric studies at relativistic energies. The μs–isomeric states were also observed in the fission region, when the ^{238}U beam energy was lowered to 750 MeV/u. Under such experimental conditions, the doubly–magic ^{78}Ni nucleus was observed previously [6]. During this experiment, a few known μs-isomers were observed on–line, e.g. ^{79m}As (which was observed for the first time at GANIL, see Fig. 4) and ^{98m}Y. Also ^{70m}Ni and ^{72m}Cu, both identified for the first time among ^{86}Kr fragmentation products at GANIL, see [16,18] and Fig. 5, were found in the off-line analysis of the GSI data [23].

4 Experiments with isomeric beams

The idea of extending experimental studies to the reactions with unstable projectiles has fascinated nuclear physicists for many years. In particular, for studying high spin states and angular momentum transfer, a projectile with high spin state is very attractive, see e.g. [37].

Recent theoretical developments, see e.g. [38,39,40,41,42], related to nuclear physics at the drip lines have resulted in the increased interest in the study of unbound systems. Large scale new projects, for example second generation Radioactive Beam Facilities, aiming at such investigations are planned to be constructed [43]. Access to microsecond isomers in exotic nuclei via the fragmentation reactions offer an opportunity to perform experimental studies of such systems. In addition to decay properties such as γ–transition rates and level energies above the proton binding energy or near the neutron binding energy, new observables should become experimentally available from secondary reactions with such isomeric beams. Total reaction cross section measurements made recently at GANIL [44,45] for ^{42m}Sc and at the FRS (GSI) for radioactive sodium isotopes [46] can be taken as the reference studies. An increase of the cross-section values observed for the most neutron-rich sodium isotopes studied was intepreted as the result of an increased nuclear radius. Such FRS experiments were performed with quite low secondary beam intensities, e.g.

only about 1 pps for the ^{32}Na ions. Indeed even higher intensities of isomeric beams already have been achieved in fragmentation experiments[12]. Therefore, a measurement of the total reaction cross section related to the density distribution for exotic isomeric states already are technically feasible. This creates new opportunites for obtaining new experimental observables such as the radii of nuclei in excited, loosely bound states.

5 Summary

Experiments with isomeric beams produced in fragmentation reactions have led to the new field of *on–beam* spectroscopy measurements. Many new isomeric states, including neutron–rich ^{32m}Al, ^{54m}Sc, ^{54m}V, ^{59m}Cr, ^{61m}Fe, ^{64m}Mn, ^{65m}Fe, ^{66m1,m2}Co, ^{67m}Fe, ^{69m}Cu, ^{69m}Ni, ^{70m}Ni, ^{71m}Cu, ^{72m}Cu, ^{78m}Zn, ^{79m}As, ^{203m}Tl, ^{204m2}Tl, ^{211m}Bi and ^{212m}Pb have been identified and at least partially studied. The properties of new isomeric states resulting from these investigations based on radioactive ion–γ μs correlation technique have already contributed to a refinement of the shell–model parametrizations in the regions near doubly closed shell nuclei, ^{78}Ni, ^{100}Sn and ^{208}Pb, and near N=20. The production rates of isomers seem to be sufficient for total reaction cross section measurements. Information on the matter distribution in loosely bound nuclear systems can be obtained in such measurements. Isomeric nuclei may be used to simulate the properties of the ground–states of much more exotic neutron–rich nuclei, beyond the present capabilities of experimental studies.

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