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REX Scientific Report

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Contents

1 Introduction

The Radioactive beam EXperiment (REX) [1] was built as a pilot experiment to investigate the structure of exotic nuclei. The aim was to demonstrate a highly-efficient and cost-effective scheme to bunch, cool, charge-breed, and accelerate the already existing mass-separated singly-charged radioactive ions provided by ISOLDE. In addition, it was planned to equip the target position of the accelerator with an efficient γ array for low-multiplicity events, the MINIBALL array. While there were and there are strong programs to investigate the structure of exotic nuclei at projectile fragmentation facilities, it was the aim of REX and MINIBALL to open new possibilities to study the structure of exotic nuclei using techniques *well established* for stable nuclei.

The aims of the original REX proposal were indeed fulfilled: The first REX beam was accelerated in 2001 and in 2002 the complete MINIBALL HPGe array [2] was installed in the ISOLDE hall. The first stable and the first radioactive beams ($^{23\text{-}26}$Na) were accelerated to 2 MeV/u in 2001 in two very short test beam times employing just one MINIBALL cluster detector around a makeshift target station [3, 4]. In 2002 the design energy of REX of 2.2 MeV/u was reached and first commissioning experiments with the full MINIBALL array installed took place. Starting in 2003 the first physics experiments could be performed. Due to an upgrade of the REX accelerator a beam energy of 3 MeV/u was available for the first time for physics experiments in 2004 [5] and currently beam energies ranging from 1.2 to about 3 MeV/u can be reached. In 2003 and 2004 in total 17 isotopes of 10 elements were accelerated for use at the MINIBALL beamline and also at the second beam line [6].

Based on the experience gained in 2003 a ΔE-E (gas-Si) telescope was installed in the second beam line in 2004 to check the purity of the beam and identify contaminants. Furthermore, for beams with $Z \lesssim 20$ a thin Si detector was installed after the MINIBALL target at an angle of about 5° to continuously monitor the beam composition. In addition, the dead time problem encountered with the MINIBALL setup at high beam intensities was solved. It should also be mentioned that the development of the analysis software is now nearly complete and a faster analysis of the data can be expected in the future. In 2004 the REX accelerator, which started as a user experiment became a CERN user facility, which strongly increased the local support of the accelerator, even though manpower remains an issue.

In the remainder of this document the experimental physics program will be reviewed and an outlook will be given in the end. In addition, while not part of a scientific report, technical problems and wishes mentioned by the users are listed in section 3.

2 Physics Program

Besides one experiment of the solid state group the physics program focused entirely on the investigation of the structure of exotic nuclei. The experimental method used for most of the experiments was "safe" Coulomb excitation well below the barrier studying the collective structure of both neutron- and proton-rich nuclei with a model independent probe.

2.1 Island of Inversion

The study of the "island of inversion", which is one of the aims of the original REX proposal [1], was initiated at ISOLDE already in 1975, when Thibault et al. [7] measured the masses of the neutron-rich Na isotopes. The theoretical and experimental interest in this region continues even today, almost 30 years later, the reason being the still only sparsely available data and the improved capabilities of today's computers in conjunction with advances in the theoretical models. One should note that not even the extend of the "island of inversion" in N and Z is known. In addition, the experimental data available so far are in some cases even contradictory, e.g. the $B(E2\uparrow)$ values of ^{32}Mg measured at different projectile fragmentation facilities deviate by as much as a factor of two from each other. [8, 9]

The aim of the proposal [10] was to measure the $B(E2;\ 0^+_{\rm gs} \rightarrow 2^+_1)$ of ^{30,32}Mg. While in a first experiment in 2003 a measurement of ^{30}Mg was performed it was only in October of this year that the measurement could be extended to ^{32}Mg. The data from 2003 are now completely analyzed and a publication is currently being prepared which should be submitted within the next few weeks. The most interesting result is that our measured $B(E2\uparrow)$ value for ^{30}Mg is lower by about 30% and about 90% with respect to the measurements at MSU and GANIL, respectively, indicating that the measurements at intermediate energies are not as well understood as originally thought.

The analysis of the 2004 data on ^{30,32}Mg has just started and is expected to be completed before spring of 2005. A preliminary analysis revealed that there are about 130 counts in the full energy peak corresponding to the 885 keV state which should result in an error of less than 10 % for the $B(E2\uparrow)$ value of ^{32}Mg.

2.2 Towards the Doubly Magic Nucleus ^{78}Ni

Similarly to the measurements of the neutron-rich Mg isotopes the group of P. Van Duppen is studying the neutron-rich Zn and Ni isotopes using Coulomb excitation [11] with the eventual goal to study the doubly magic nucleus ^{78}Ni ($Z = 28$, $N = 50$).

In a first experiment in 2003 the nuclei ^{74,76}Zn were measured. The measurements were then extended to ^{78}Zn in this year and it is planned to extend these studies next year to the $N = 50$ nucleus ^{80}Zn. Besides determining the $B(E2\uparrow)$ value for these isotopes it was also possible to unambiguously identify the first excited 2^+ state in ^{78}Zn. Next year, in addition, it will be attempted to measure the $B(E2\uparrow)$ of ^{68,70}Ni, which were so far measured only at fragmentation facilities at high beam energies. This will allow for another comparison of the two experimental methods: Coulomb excitation below the barrier and at intermediate energies.

The strong interest in this region arises from the unusual properties of ^{68}Ni, which behaves in some respect like a doubly magic nucleus ($N = 40$). In order to understand its structure it is very important to systematically study the development of the collectivity as a function of the neutron and proton number.

A publication is in preparation and the latest data are currently being analyzed.

2.3 Improvement of B(E2$\uparrow$) Systematics

It is well known that there is a relation between the $B(E2\uparrow)$ value and the energy of the first excited 2^+ state, which is usually expressed in the form of a product of the $B(E2\uparrow)$ value and the $E(2^+_1)$. The first expression, derived by Grodzins, followed a simple Z^2A^{-1} behavior [12]. This formula was subsequently improved by the introduction of other terms. The authors of this proposal [13] introduced an isospin dependence into this expression and obtained a substantially better agreement between the measured and the predicted $B(E2\uparrow)$ values in the region around $Z = 50$ and $N = 82$.

While most data points lie within a narrow band, there are others showing a very large deviation. One aim of the experiment was therefore to remeasure some these points. Furthermore, as for many nuclei in this mass region the $B(E2\uparrow)$ is unknown, it is aimed to fill this gap and thereby test the new formula. In addition to the overall isospin dependence there seems to be a systematic deviation to lower $B(E2\uparrow)$ for the very neutron-rich nuclei where the data are scarcest. This deviation might indicate a strong isovector contribution to the collective 2_1^+ excitation. To test this conjecture more and especially more precise data are needed.

Towards this goal Coulomb excitation of ^{122,124,126}Cd was performed this year and an addendum was submitted to continue these studies.

The data are being analyzed.

2.4 Nuclear Structure near ^{100}Sn

The evolution of $B(E2\uparrow)$ values for neutron-deficient Sn isotopes is the aim of another experiment [14] to shed more light on core polarization effects in ^{100}Sn. This experiment is part of an ongoing push toward the doubly-magic nucleus ^{100}Sn (also at other laboratories). A first successful measurement of ^{110}Sn was performed this year and most notably the intensity of the ^{110}Sn beam was so high (~ 100 epA) that it had to be reduced due to the count rate limit of the particle detector. The measurements are to be extended to ^{108}Sn and ^{106}Sn next year.

The data are being analyzed.

2.5 The Neutron-Unbound Nucleus ^{10}Li

The structure of the unbound nucleus ^{10}Li is of key importance for the theoretical description of the two-neutron halo nucleus ^{11}Li. The aim is therefore to measure the energies and widths of the single particle states in ^{10}Li [15, 16]. A first experiment toward this goal was performed in 2003 [15] and a publication has already been submitted [17, 18]. Here ^{10}Li was studied using the ^{9}Li(d,p)^{10}Li reaction with a ^{9}Li beam. In addition to the (d,p) channel also the (d,t) channel populating several states in ^{8}Li could be observed, serving as a test of the method. The (d,p) channel gave clear evidence of a low-lying structure in the ^{10}Li excitation energy spectrum, which is consistent with a p-wave resonance positioned at 350 keV above threshold with a width of about 300 keV. The measurement, however, does not allow to distinguish between p and s waves, nor to determine if one or more states were populated. Therefore more data are needed, to be measured with an improved setup to better understand the structure of ^{10}Li.

In another experiment the structure of ^{10}Li was studied by an investigation of the isobaric analogue states in ^{10}Be. The data taken so far look interesting, and are currently under analysis.

2.6 Bandgap of Widebandgap Semiconductors

In this project the electronic properties of the technologically important semiconductor SiC are to be investigated using Photoluminescence, Deep Level Transient Spectroscopy (DLTS) and Thermal Admittance Spectroscopy [19]. The method applied exploits the extreme sensitivity of the electrical properties of semi-conductors to minor traces of impurities and defects. By using the elemental transmutation of radioactive isotopes as a tracer, it will be guaranteed that the impurity-related band gap states can definitively be distinguished from intrinsic or process-induced defects. For SiC up to now only detailed investigation of Er related deep levels have been reported, preliminary data exist for Sm and Gd impurities. Here the implantation of Pr and Eu isotopes is used for detailed level studies. The advantage of employing the REX beam (only RFQ) is that a deeper implantation is possible (the final implantation energy was 7 MeV after decelleration of the 45 MeV RFQ beam in a carbon foil) in comparison to the implantation of the singly charged ions from ISOLDE.

The results of an initial measurement look promising but there were problems with the energy adjustment to reach a suitable depth in SiC for the DLTS measurement. The experiment will be continued.

2.7 Other

Several other experiments are either in the preparation or development phase:

- a study of sub-barrier fusion of neutron-rich Mg isotopes on ^{28}Si [20]
  A first test was performed this with a ^{28}Mg beam which is currently being analyzed.

- mixed symmetry states in ^{88}Kr [21]
  The experiment was scheduled earlier this year, but could not be performed due to problems with the EBIS HV supply.

- the shape (sign of quadrupole moment) of ^{70}Se [22]
  The experiment was scheduled earlier this year, but even though progress was made the Se intensity was not sufficient. It is expected that the experiment is feasible after additional optimizations.

- the measurement of the inelastic branch of the stellar reaction ^{14}O(α,p)^{17}F [23]
  Ditto.

- g-factor measurements [24]
  The experiment had to be cancelled this year due to the problem with the EBIS HV supply.

3 Improvements and Wishes by the Experimenters

A questionnaire was sent out and from the returned information the following is extracted

- Shorter EBIS breeding times are needed for very short lived (heavy) nuclei.
- To reduce the instantaneous beam intensity with the corresponding dead time problem for the experiment a longer EBIS extraction is requested.
- For very short lived isotopes ($\lesssim$ 50 ms) it would be advantageous to synchronize the EBIS cycle with the proton impact in order to minimize decay losses during trapping and breeding.
- A better shielding between the 9 gap IH structure and MINIBALL is needed to reduce the strong x-ray background (up to 300-400 keV) when the 9 gap IH runs at high power levels.
- The counting capabilities of the MINIBALL PPAC at low beam intensities need to be improved.
- Better beam diagnostics for low intensity beams is needed.
- Increased overall reliability is needed. From the information I received on average only about half of the allocated beam time could be used for data taking, even without considering the experiments that had to be cancelled completely.
- Better and accurate REX control software is needed (“ 'X' is 'X' and not 'Y' ”). This is especially important, as the REX users are encouraged to take part in the operation of the accelerator.
- A reduced beam spot is advantageous. It not only increases the resolution, but also the β decay background, from the part of the beam hitting the target frame, could be reduced.
- An adjustable solid (general purpose) platform at the second beam line was requested.

While the even higher beam energies that will be available after a further REX upgrade are important for some experiments, also the operation and improvement of the current REX accelerator should have high priority.

4 Summary and Outlook

The goals of the original REX proposal [1] were fulfilled.

The experimental program, which now entered the production phase, focuses on the systematic study of the interplay between the collective and single particle degrees of freedom in nuclei far from stability. Systematic measurements of the $B(E2\uparrow)$ values in several regions of the nuclear chart are being carried out which yield or will yield valuable information on the development of nuclear properties as the driplines are approached. In figure 1 the regions are indicated in a schematic nuclear chart.

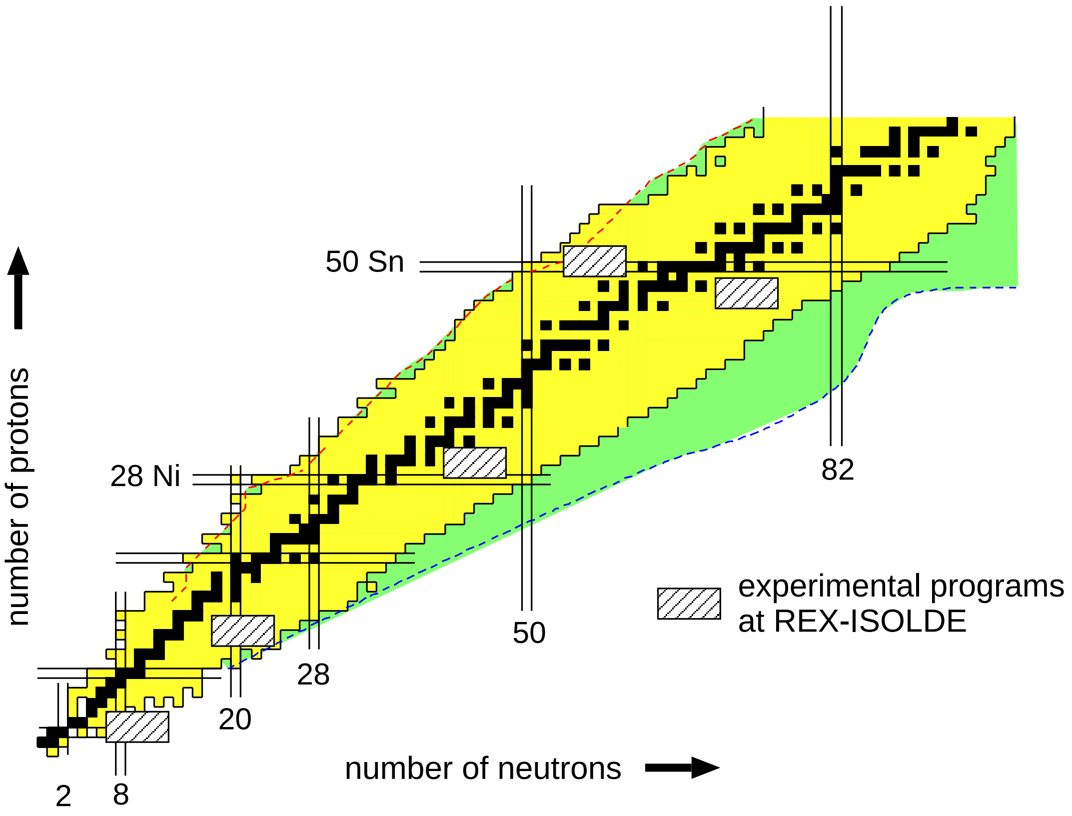

Figure 1: Nuclear chart. The regions were experiments have been or will be performed at REX-ISOLDE are indicated.

The possibility to use the reliable and model-independent results from Coulomb excitation experiments below the barrier lends a new quality to the data, which was so far not achievable at projectile fragmentation facilities. In addition, new methods are being developed, e.g. it is planned to used two-neutron transfer on a radioactive ^{10}Be target to identify the second 0^+ state in ^{32}Mg, which is assumed to be spherical [25].

The results so far show the great possibilities offered by REX and MINIBALL.

References

[1] D. Habs. Radioactive beam EXperiments at isolde: Coulomb excitation and neutron transfer reactions of exotic nuclei. CERN-ISC 94-25, IS347, Proposal to the INTC, 1994.

[2] J. Eberth, G. Pascovici, H.G. Thomas, N. Warr, D. Weisshaar, D. Habs, P. Reiter, P. Thirolf, D. Schwalm, C. Gund, H. Scheit, M. Lauer, P. Van Duppen, S. Franchoo, M. Huyse, R.M. Lieder, W. Gast, J. Gerl, and K.P. Lieb. Miniball: a ge detector array for radioactive ion beam facilities. *Prog. in Part. and Nucl. Phys.*, 46:389, 2001.

[3] O. Kester, T. Sieber, S. Emhofer, F. Ames, K. Reisinger, P. Reiter, P.G. Thirolf, R. Lutter, D. Habs, B.H. Wolf, G. Huber, P. Schmidt, A.N. Ostrowski, R. von Hahn, R. Repnow, J. Fitting, M. Lauer, H. Scheit, D. Schwalm, H. Podlech, A. Schempp, U. Ratzinger, O. Forstner, F. Wenander, J. Cederkäll, T. Nilsson, M. Lindroos, H. Fynbo, S. Franchoo, U. Bergmann, M. Oinonen, J. Äystö, P. Van Den Bergh, P. Van Duppen, M. Huyse, N. Warr, D. Weisshaar, J. Eberth, B. Jonson, G. Nyman, M. Pantea, H. Simon, G. Schrieder, A. Richter, O. Tengblad, T. Davinson, P.J. Woods, G. Bollen, L. Weissmann, L. Liljeby, and K.G. Rensfeldt. Accelerated radioactive beams from REX-ISOLDE. *Nucl. Instr. Meth. B*, 204:20, 2003.

[4] D. Habs, O. Kester, T. Sieber, H. Bongers, S. Emhofer, P. Reiter, P.G. Thirolf, G. Bollen, J. Äystö, O. Forstner, H. Ravn, T. Nilsson, M. Oinonen, H. Simon, J. Cederkall, F. Ames, P. Schmidt, G. Huber, L. Liljeby, O. Skeppstedt, K.G. Rensfeldt, F. Wenander, B. Jonson, G. Nyman, R. von Hahn, H. Podlech, R. Repnow, C. Gund, D. Schwalm, A. Schempp, K.-U. Kühnel, C. Welsch, U. Ratzinger, G. Walter, A. Huck, K. Kruglov, M. Huyse, P. Van den Bergh, P. Van Duppen, L. Weissman, A.C. Shotter, A.N. Ostrowski, T. Davinson, P.J. Woods, J. Cub, A. Richter, and G. Schrieder. The REX-ISOLDE project. *Hyperf. Int.*, 129:43, 2000.

[5] O. Kester, D. Habs, F. Ames, T. Sieber, H. Bongers, S. Emhofer, S. Henry, S. Heinz, P. Reiter, P.G. Thirolf, M. Gross, R. von Hahn, D. Schwalm, J. Cederkäll, B. Wolf, F. Wenander, T. Nilsson, U.C. Bergmann, S. Franchoo, K. Reisinger, J. Äystö, P. Van Duppen, M. Huyse, P. Butler, T. Fästermann, and R. Krücken. An energy upgrade of REX-ISOLDE to 3.1 MeV/u an acceleration of heavier masses up to $A = 150$. CERN-INTC-2002-009, INTC-P-152, IS408, Proposal to the INTC, 2002.

[6] T. Sieber. REX-ISOLDE: Betrieb des Beschleunigers. BMBF Zwischenbericht 06ML 185, unpublished, 2004.

[7] C. Thibault, R. Klapisch, C. Rigaud, A.M. Poskanzer, R. Prieels, L. Lessard, and W. Reisdorf. Direct measurements of the masses of ^{11}Li and $^{26-32}$Na with an on-line mass spectrometer. *Phys. Rev. C*, 12:644, 1975.

[8] H. Scheit et al. Coulomb excitation of ^{32}Mg. CERN-INTC-2004-009, INTC-P-159-Add1, IS410, Proposal to the INTC, 2004.

[9] H. Scheit et al. First results on in-beam γ spectroscopy of neutron-rich Na and Mg isotopes at REX-ISOLDE. RNB6 proceedings, to be published in NPA, 2004.

[10] H. Scheit et al. Evolution of single particle and collective properties in the neutron-rich mg isotopes. CERN-INTC-2002-020, INTC-P-159, IS410, Proposal to the INTC, 2002.

[11] P. Van Duppen et al. Coulomb excitation of neutron-rich nuclei between the n=40 and n=50 shell gaps using REX-ISOLDE and the Ge MINIBALL array. CERN-INTC-2002-017, IS412, Proposal to the INTC, 2002.

[12] L. Grodzins. *Phys. Lett.*, 2:88, 1962.

[13] D. Habs et al. Coulomb excitation of neutron-rich a 140 nuclei. CERN-INTC-2002-015, IS411, Proposal to the INTC, 2002.

[14] J. Cederkäll et al. Coulomb excitation of neutron deficient Sn-isotopes using REX-ISOLDE. CERN-INTC-2003-010, IS418, Proposal to the INTC, 2003.

[15] B. Jonson et al. Study of the unbound nuclei ^{10}Li and ^{7}He at REX ISOLDE. CERN-ISC-98-11, IS367, Proposal to the INTC, 1998.

[16] B. Jonson et al. Investigations of neutron-rich nuclei at the dripline through their analogue states: The cases of ^{10}Li-^{10}Be (t=2) and ^{17}C-^{17}N (t=5/2). CERN-ISC-98-23, IS371, Proposal to the INTC, 1998.

[17] H. Jeppesen, F. Ames, U.C. Bergmann, M.J.G. Borge, J. Cederkäll, S. Emhofer, L.M. Fraile, H.O.U. Fynbo, S. Henry, H.T. Johansson, B. Jonson, M. Meister, T. Nilsson, G. Nyman, M. Pantea, K. Riisager, A. Richter, K. Rudolph, G. Schrieder, T. Siebert, O. Tengblad, E. Tengborn, M. Turrión, R. von Hahn, F. Wenander, and B. Wolf. Experimental investigation of the ^{9}Li+d reaction at REX-ISOLDE. *Nucl. Phys. A*, 738:511, 2004.

[18] H.B. Jeppesen et al. Low energy reactions with radioactive ions at REX-ISOLDE: the ^{9}Li+^{2}H case. submitted, 2004.

[19] Gunnar Pasold et al. Production of rare earth isotope beams for radiotracer-dlts on sic. CERN-INTC-2003-006, IS416, Proposal to the INTC, 2003.

[20] P. Reiter et al. Fusion reactions at the coulomb barrier with neutron-rich mg isotopes. CERN-INTC-2002-014, IS409, Proposal to the INTC, 2002.

[21] J. Iwanicki et al. Coulomb excitation of a neutron-rich 88kr beam - search for mixed symmetry states. CERN-INTC-2003-015, IS423, Proposal to the INTC, 2003.

[22] D. Jenkins et al. Obtaining empirical validation of shape-coexistence in the mass 70 region : Coulomb excitation of a radioactive beam of ^{70}Se. CERN-INTC-2002-003, IS405, Proposal to the INTC, 2002.

[23] P. Woods et al. Inelastic branch of the stellar reaction 14o(a,p)17f. CERN-INTC-2003-026, IS424, Proposal to the INTC, 2003.

[24] K.-H. Speidel et al. Magnetic moments of coulomb excited 2_1^+ states for radioactive beams of ^{132,134,136}Te and ^{138}Xe isotopes at REX-ISOLDE. CERN-INTC-2003-003, IS415, Proposal to the INTC, 200X.

[25] D. Habs et al. New spectroscopy by two-neutron-pickup of neutron-rich nuclei. CERN-INTC-2002-027, P161, Proposal to the INTC, 2002.

[26] H. Scheit et al. Investigation of the single particle structure of the neutron-rich sodium isotopes $^{27\text{-}31}$Na. CERN-ISTC-99-20, IS379, Proposal to the INTC, 1999.

[27] L. Fraile et al. Exploring the dipole polarizability of ^{11}Li at REX-ISOLDE. CERN-INTC-2001-027, IS399, Proposal to the INTC, 2001.

[28] P. Van Duppen et al. Coulomb excitation of neutron-rich nuclei with MINIBALL at REX-ISOLDE: towards the $N = 50$ shell closure. CERN-INTC-2004-002, IS412, Proposal to the INTC, 2004.