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Coulomb excitation of neutron deficient Sn–isotopes using REX-ISOLDE

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ABSTRACT

It is proposed to study the evolution of the reduced transition probabilities, B(E2; $0^+ \rightarrow 2^+$), for neutron deficient Sn isotopes by Coulomb excitation in inverse kinematics using REX-ISOLDE and the MINIBALL detector array. Measurements of the reduced transition matrix element for the transition between the ground state and the first excited 2^+ state in light even–even Sn isotopes provide a means to study e.g. core polarization effects in the ^{100}Sn core. Previous attempts to measure this quantity have been carried out using the decay of isomeric states populated in fusion evaporation reactions. We thus propose to utilize the unique opportunity provided by REX-ISOLDE, after the energy upgrade to 3.1 MeV/u, to use the more model-independent approach of Coulomb excitation to measure this quantity in a number of isotopes in this region.

1. Introduction

Atomic nuclei with closed neutron and proton shells, so called doubly magic nuclei, are fix points for nuclear structure calculations using the shell model. The reason for this is that they provide a way to reduce, or truncate, a many body problem with an extremely large number of degrees of freedom into a computationally tractable model space. The core corresponding to the double-shell closure nucleus itself is in this picture considered inert to first approximation and the excitations of the surrounding isotopes can be seen as single and few particle states on top of the core. This approach is as indicated, however, only true to a certain extent since the core particles will take part in the overall interaction which ultimately decides the exact properties of a specific nucleus and its excitations. To what extent the core does take part in these excitations is not only a measure of its stiffness and thus the applicability of the shell model itself, but when core polarization is measured far from stability it will also provide experimental evidence for the overall evolution of shell structure. This is because the shell closures as commonly used in the shell model are inferred from properties such as binding and particle separation energies close to stability. Another very important piece of information that has validated the nuclear shell model in the past and should be mentioned in this context is the determination of the spins and parities of the intruder orbitals that are pushed down into a lower lying oscillator shell by the nuclear spin-orbit force. Studies of exotic nuclear systems in the vicinity of assumed closed shells will thus provide information about how the shell structure, caused by the spin-orbit force, evolves as a function of the number of protons and neutrons in the nucleus. Furthermore, a detailed knowledge of the properties of the nuclear forces in simple few particle systems provides a way to ultimately connect first principle derivations of the nucleon-nucleon force to realistic cases where collective excitations do not play a dominant role.

2. Physics Case

Although double shell closure nuclei have been under study for a long time, this branch of research has regained a remarkable impetus in the past few years with the advent of new advanced detector systems that have made it possible to approach shell closures in very exotic systems. One example of this is manifested in the ongoing push towards ^{100}Sn while the other system that experiences a similar high level of interest, from experimentalists and theoreticians alike, is ^{78}Ni which also is the topic of a recently approved REX-ISOLDE experiment [1].

What in addition makes ^{100}Sn particularly interesting to study from the theoretical point of view is that it is the heaviest isospin symmetric doubly-magic nucleus which is particle bound. As neutrons and protons occupy the same orbitals in such a system the effects of neutron-proton pairing may also become important in the theoretical interpretation of its excited states.

The first observation of ^{100}Sn itself occurred a few years ago at GANIL [2] and GSI [3] in projectile fragmentation reactions. The extremely low yield made it possible only to estimate the mass and half-life of ^{100}Sn. It is therefore clear that an intense RNB facility of the next generation will be needed to make ^{100}Sn available for as detailed studies as its counterpart on the neutron rich side, ^{132}Sn.

PH	0	1	2	3	4	EXPT
^{100}Sn						
E(2^+) MeV	-	4.8	6.30	4.58	4.56	
B(E2) e^2fm^4	-	196	219	251	270	
^{102}Sn						
E(2^+) MeV	1.05	1.1	1.24	1.22		1.47
B(E2) e^2fm^4	19	79	93	137		
^{104}Sn						
E(2^+) MeV	0.86	0.82	0.84	0.79		1.27
B(E2) e^2fm^4	41	41	192	209		

Table 1: Theoretical and experimental values for E(2^+) energies in the light Sn isotopes and theoretical predictions for the B(E2) values are shown here as reference for the background discussion given in the text. The row marked PH refer to the number of particle-hole excitations included. Calculations of F. Nowacki as published in ref. [7].

However, already the yield supplied for unstable Sn isotopes at REX-ISOLDE provides a new and world unique opportunity to use the MINIBALL array to study Coulomb excitation of some of the light Sn isotopes. A number of experiments have been carried out in this region in the past by several of the proponents using other techniques. These experiments include beta-decay studies, but an emphasis has been put on the use of fusion-evaporation reactions as a means to study the de-excitation of excited states. The level structure has been measured in a set of nuclei and as a consequence of this effort the lightest Sn isotope with known excited states is now ^{102}Sn [4] where the first excited 2^+ state is at 1.47 MeV. One particular feature of the lighter Sn isotopes is the presence of a low lying 6^+ isomer with a lifetime in the ns-us range. The presence of this isomer made it possible to use a recoil tagging technique in a previous experiment in order to reduce the influence of reaction channels produced with much higher cross-sections. For the ^{102}Sn case the production cross-section was estimated to be 2μb in the ^{50}Cr(^{58}Ni,α2n)^{102}Sn reaction where an effective neutron charge of 2.3e (+0.6e,-0.4e) was deduced. A similar approach was also used in a study of ^{98}Cd [5] by the same group for the proton effective charge. We would like to mention that we are presently investigating the feasibility of performing experiments at REX-ISOLDE to this end as well and will submit an addendum to this proposal in case the feasibility study gives a positive result. This study also looks into the feasibility of transfer experiments for the deduction of spectroscopic information. Research of the structure of the odd Sn isotopes is highlighted by the experiment reported in ref. [6].

The advantage to use Coulomb excitation of a radioactive beam in inverse kinematics to measure the B(E2) values of the first excited 2+ states in even light Sn isotopes is two-fold. As mentioned above, the existence of higher lying isomeric states hamper a direct measurement of the lifetime of these states via traditional Doppler methods and secondly their short life times also makes a measurement using electronic methods difficult.

The first excited 2^+ state in ^{100}Sn has not been observed experimentally. A rather recent theoretical study by F. Nowacki [7], based on the realistic interaction derived by the Oslo group [8], indicates an excitation energy of 4.56 MeV for this state if excitations up to the 4ph-level are

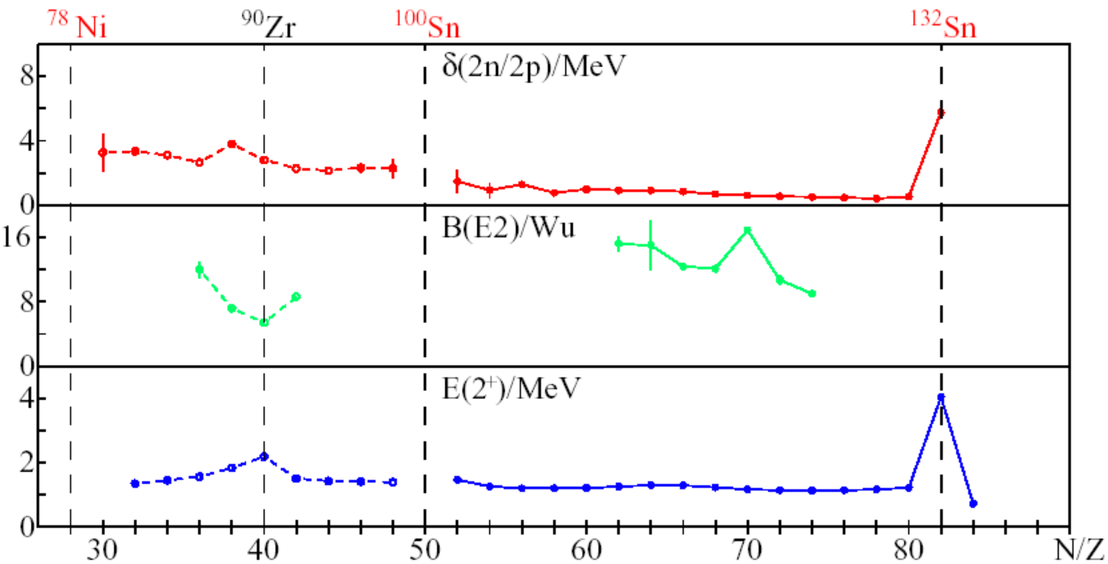

Fig. 1: The evolution of the excitation energy of the first excited 2+ state in even Sn is shown together with the measured B(E2) values as of date. Top panel: The second difference in neutron and proton separation energy. Note the very limited knowledge of B(E2) values away from the line of stability. The aim of the present proposal is to initiate a program to measure these values (middle panel, right hand side). The graph is taken from ref. [9].

taken into account (see Table 1). The B(E2) value is estimated to be 270 e^2fm^4. The same study places the first 2^+ state in ^{102}Sn at 1.22 MeV but on the 3ph excitation level. In the Sn isotopes the ground state is a super fluid condensate where the last proton sub-shell in this simplified picture is given by the $g_{9/2}$ orbital. The 2^+ excitation is of pure-particle hole type where the correlations are due to pairing effects. As the neutron shell fills the 2^+ state keeps its character to the extent that it is built upon a double shell closure (the 0^+ ^{100}Sn core) coupled to a broken neutron pair which now is spread over the lowest states in the next major shell, notably the $g_{7/2}$ and $d_{5/2}$ single particle orbitals.

The energy of the 2^+ states also remains stable as the neutron shell fills towards ^{132}Sn where a jump of about 2 MeV occurs for the new doubly magic core. It becomes strikingly obvious in the diagram of Fig. 1 where the present frontier lies in this field as the missing link in excitation energies for the 2^+ state in the even Sn isotopes now lies at ^{100}Sn itself. The structure of the first excited 2^+ state in the chain of Sn isotopes is an example of the generalized seniority scheme as e.g. discussed by N. Sandulescu et al. in ref. [10].

Fig. 1 also shows the current level of knowledge concerning the B(E2) values. Here it becomes evident that the experimental knowledge is much more scarce. It is limited to the stable Sn isotopes. One can in first approximation assume that although the exact value of the B(E2) and thus the structural information is unknown, the reduced transition probability will have a size that lie in the region between the value of ^{112}Sn and the one predicted for ^{104}Sn. In our calculations we have thus used a value of 10 W.U for the B(E2) when estimating the count rates.

As pointed out above, REX-ISOLDE provides a unique opportunity when coupled to the MINIBALL to increase our knowledge in this region even if for the time being the lightest systems are not available. We will therefore as a starting point focus on measuring the B(E2)

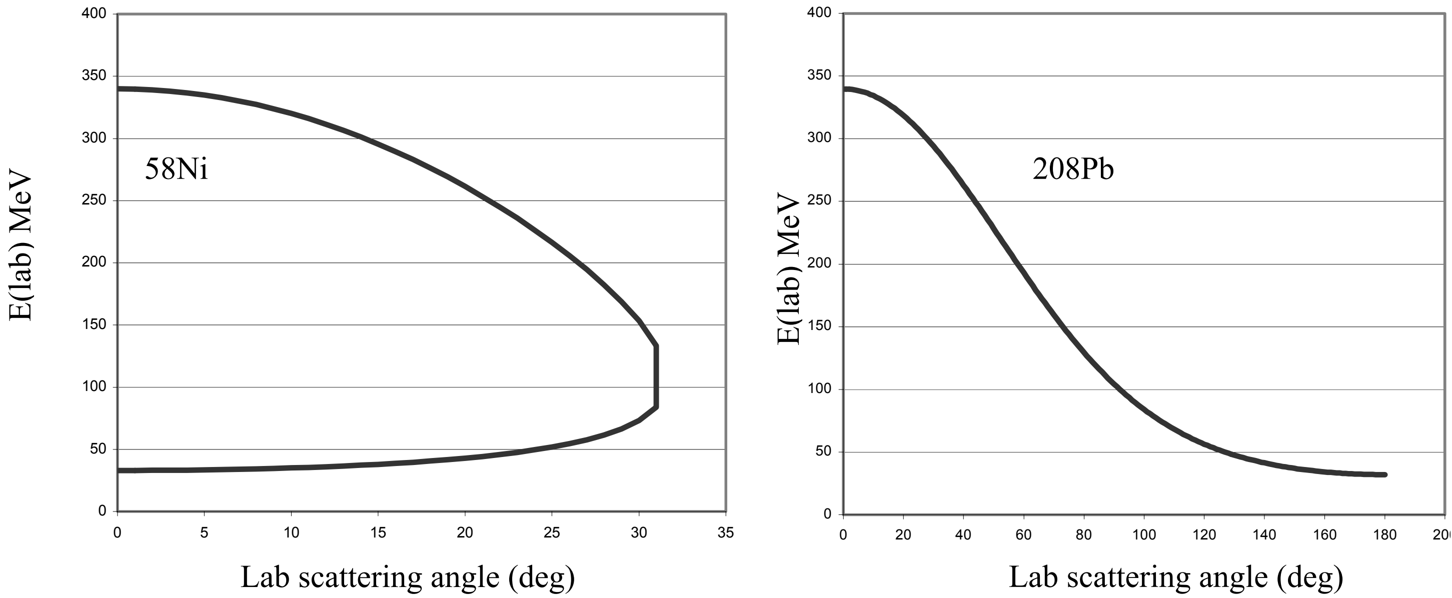

Fig. 2. The energy in MeV of a scattered Coulomb excited ^{110}Sn nucleus impinging on a ^{58}Ni target (to the left) and on a ^{208}Pb target respectively. Beam energy 3.1 MeV/u. The straight line on the right hand side in the left panel is an artifact arising when plotting the two kinematical solutions. The maximum scattering angle is ~30 degrees in the former case while the full scattering range is covered in the latter case.

values for the unstable light Sn isotopes that lie closest to stability namely ^{110}Sn and ^{108}Sn. In the proposed target development we will attempt to establish firm numbers on the production rate of the lighter isotopes ^{104}Sn and ^{106}Sn. We also note that the Coulomb excitation of the odd Sn isotopes may provide a way to gain knowledge on the single particle energy of the $3s_{1/2}$ orbital.

3. Experimental Details

We propose to use the MINIBALL [11] detector array in conjunction with the disc-shaped Double Sided Silicon Strip Detector (DSSSD) [12] to detect the emitted gamma radiation in coincidence with the Coulomb excited beam. The novel techniques developed specifically for MINIBALL, i.e. highly granular segmented Ge-detectors enhanced with a unique way of pulse shape processing, which may determine the interaction point down to a cm, makes this set-up ideally suited for this experiment. We note that the MINIBALL target chamber is currently being updated. It is thus our intention to try to gain increased flexibility in the new target chamber in order to be able to vary the distance between target and the DSSSD in such a manner that we can obtain an optimal count rate. The DSSSD will also be used for normalizing the cross-section by using the Rutherford scattering cross-section of the in-coming beam. We have performed a number of calculations to establish the count rates and to select the first feasible cases for the measurements we propose. On the one hand we have followed the spirit of previous proposals for REX-ISOLDE and MINIBALL experiments [1,13] and calculated the cross sections based on the formalism presented by Alder et al. in ref. [14]. We have also for some specific cases performed more detailed calculations using the Coulomb excitation code GOSIA by T. Czosnyka et. al. as described in ref. [15]. The calculations using GOSIA will continue in order to optimize the experimental set-up parameters such as target thickness in order to use the radioactive beam with

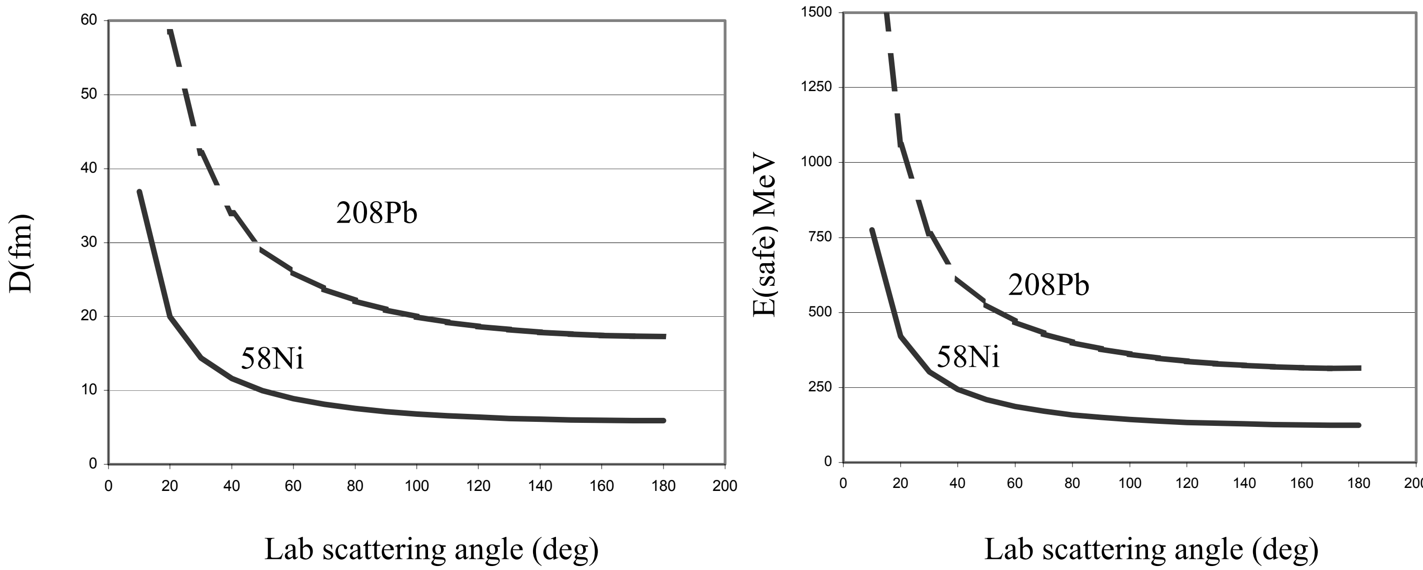

Fig 3. To the left: safe distances for ^{58}Ni and ^{208}Pb targets as function of scattering angle for an ^{110}Sn beam at 3.1 MeV/u. The safe energies for the same case is given to the right. The ^{58}Ni target is safe at S=5fm using r_0=1.28 fm within a few degrees of the maximum scattering angle of approximately 30 degrees.

absolutely maximum efficiency. However our calculations show that measurements of ^{110}Sn and ^{108}Sn can be carried out within feasible time limits using ^{58}Ni as target. Some results from our kinematical calculations are discussed in the following. Note that the test case presented in Figs. 2 and 3 is for a beam of ^{110}Sn. The kinematics change to a very small extent for the lighter masses. Since ^{58}Ni and ^{208}Pb can be seen as standard targets for Coulomb excitation experiments the focus of the kinematical calculation was on these two materials. Looking at the results presented in Fig. 2 it is seen that the maximum scattering angle is approximately 30 degrees in case of a ^{110}Sn beam at 3.1 MeV/u impinging on a ^{58}Ni target whilst the full angular range is covered in the case of the Pb target. Continuing with safe angles and safe distances it is concluded that the safe angle for the ^{58}Ni target almost coincides with the maximum scattering angle at ~30 degrees. We thus conclude that the selection of a ^{58}Ni target will produce a well focused forward cone which will be almost completely safe. The scattering on the Pb target will as expected spread over a larger angular range and be safe for all experimental angles. The selection of target depends therefore more upon the cross section as a function of target charge.

As mentioned above the cross section calculations have followed two paths. We present in Table 2 the results based on the paper of Alder et al. for four cases. Two of these cases are immediately feasible from the experimental point of view with the current information on expected production yields. For the lighter cases, ^{106,104}Sn, we use a rule-of-thumb saying that the production cross-section of the secondary beam falls one order of magnitude per mass step away from the line of beta-stability. It is clear from Table 2 that both of these two isotopes cannot be studied within a reasonable experimental time period. In the calculations we have used a ^{58}Ni target of 1 mg/cm^2 thickness and a MINIBALL efficiency of 10%. The REX-ISOLDE transport efficiency has conservatively been set to 1%. The total energy loss in a target of 1 mg/cm^2 is approximately 40 MeV for a ^{110}Sn beam at 3.1 MeV/u. This value has been used to deduce an energy averaged

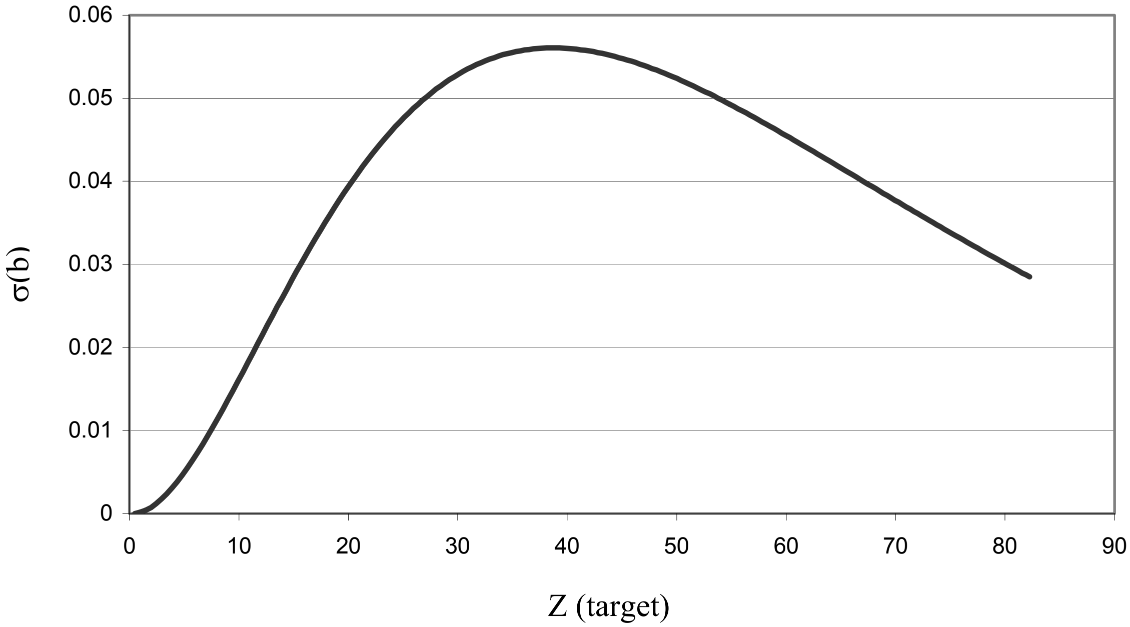

Fig. 4. Cross section for ^{110}Sn at 3.1 MeV/u on a target of varying mass and charge. A differentiated mass formula was used to describe the location of the line of stability in the nuclear chart. The calculations are thus not exact and do not address possible background effects that would arise from using a (electromagnetically) soft target. A seventh order polynomial was used for the interpolation of the f-function given by Alder et. al. [14].

cross section. The calculated rates are for a typical B(E2) of 10 W.U. and refer to counts in the photo-peak. The rates assume that half of the proton pulses are devoted to ISOLDE. The calculation presented in Fig. 4 also indicates that the general cross sectional trend favor a Ni over a Pb target.

The production of secondary beams of light Sn isotopes was first studied at ISOLDE-1 using a $TeCl_4$ target [16]. This material cannot be heated to a very high temperature due to the excessive vapor pressure. In a recent attempt to improve the yields for light Sn isotopes a LaC_x graphite target was used together with the RILIS. The expected in-target production rate of this target is according to the semi-empirical model by Silberberg and Tsao [17] expected to be comparable to or higher than that of a $TeCl_4$ target. The target used for the test had previously been used in experimental runs and furthermore lacked a Sn mass marker to tune the RILIS correctly.

Isotope	^{104}Sn	^{106}Sn	^{108}Sn	^{110}Sn
σ (mb)	32	38	40	42
σ (mb) (energy averaged)	22	27	29	31
ISOLDE yield (at/μC)	$5 \bullet 10^2$	$5 \bullet 10^4$	$5 \bullet 10^6$	$4 \bullet 10^8$
Rate/s (E=3.1 MeV/u)	-	0.00004	0.004	0.36
Rate/h	-	0.15	16	1300

Table 2. Cross sections and photo-peak count rates for the four different radioactive beams indicated in the top row. Note that this table quotes rather conservative estimates for the yield of the secondary beams based on ISOLDE-1 data. For the lighter isotopes (^{104,106} Sn) we assume a decrease of one order of magnitude per mass unit. The rates are given for the cross section in the second row and may be scaled by the energy averaged cross section given in the third row.

Yield		106Sn	107Sn	108Sn	109Sn	110Sn	111Sn
$TeCl_4$	1/μC			5.0 •10^6	3.0•10^7	4.0 •10^8	7.0 •10^8
LaC_x	1/μC	2.5 •10^4	3.5 •10^5	1.9 •10^6	6.0•10^6	1.7 •10^7	5.0 •10^7
Prod La	1/μC	2.6 •10^6	1.6 •10^7	1.4 •10^8	6.1•10^8	2.6 •10^9	4.8 •10^9
Ce_2S_3	1/μC	2.2 •10^5	1.3 •10^6	1.1 •10^7	3.4•10^7	1.5 •10^8	2.7 •10^8

Table 3. Measured and estimated experimental yields of light Sn isotopes as discussed in the text. For LaC_x the calculated production yield is also given. From refs. [17,18].

The overall efficiency, derived from calculated production yield was therefore only 1%. This is about a factor of 10 lower than a normal RILIS yield and it is assumed that the test conditions were the main reason for this effect. Details concerning count rates for different target options can be found in Table 3. One should note however that the amount of other surface ionized species, e.g In, will still be a problem if LaC_x is used. Estimates say that for A=110 the In content of the beam would be equal to the Sn content and for A=108 it would even be one order of magnitude stronger [19]. In line with a recent breakthrough in the production of light Sn isotopes at GSI [19], we instead propose to use a Ce_2S_3 target. Calculated experimental yields for this target is given in Table 3 together with the two alternatives mentioned above. The great advantage of this target is that is will suppress isobaric contaminants in the beam with more than a factor of 200 if the Sn-isotopes are extracted as SnS [19]. For the case of In the expected suppression factor is as high as 20000 [19]. Experimental results from GSI show that up to 60% of the produced Sn can be brought into the molecular sideband. The SnS beams extracted in this way will be injected into REXTRAP for cooling and the molecular binding will be broken at the latest in REXEBIS during charge breeding. The proposed procedure is similar to the one that is planned to be used for an already accepted proposal for accelerated Se beams where Se will be carried out of the target-ion source as SeCO [20]. When preparing this proposal it was also noted that the material for a Ce_2S_3 target will be available at ISOLDE during 2003 as part of the ISOLDE target test program.

Summary and Beam Request

We propose to initiate a series of experiments to investigate the structure of nuclei in the light Sn region. As a first step in this program we suggest to measure the B(E2) values of ^{110,108}Sn and possibly ^{106}Sn using the MINIBALL array and REX-ISOLDE. The physics question we want to address is one of the most pressing ones in nuclear structure, namely the evolution of shell structure far from stability. The suggested experiments can be seen as a continuation of a number of experiments that some of the proponents have performed in the past using other methods, e.g. large gamma-ray spectrometers. The advent of accelerated radioactive beams at ISOLDE provide us with a new unique tool for these studies.

^{106}Sn	^{107}Sn	^{108}Sn	^{109}Sn	^{110}Sn	Calib.(^{112}Sn)	Set-up(REX)
-	-	10	-	5	2	2

Table 4. Suggested shift structure for the proposed experiment.

In conclusion we therefore ask for a total of 19 shifts of radioactive beam from a Ce_2S_3 target connected to a hot plasma source as detailed in Table 4. We will also, if needed, provide manpower for possible target tests to firmly establish the yields of the lighter isotopes before the experiment. In case the target test for the yield of ^{106}Sn turns out to be successful we ask to be able to relocate shifts to this isotope.

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