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Proposal to the INTC Committee

Approaching the r-processs "waiting point" nuclei below ^{132}Sn: quadrupole collectivity in ^{128}Cd

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Abstract: We propose to investigate the nucleus ^{128}Cd neighbouring the r-process "waiting point" ^{130}Cd. A possible explanation for the peak in the solar r-abundances at $A \approx 130$ is a quenching of the $N = 82$ shell closure for spherical nuclei below ^{132}Sn. This explanation seems to be in agreement with recent β-decay measurements performed at ISOLDE. In contrast to this picture, a beyond mean field approach explains e.g. the anomaly in the excitation energy observed for ^{128}Cd rather with a quite large quadrupole collectivity. Therefore, we propose to measure the reduced transition strengths $B(E2)$ between ground state and first excited 2^+-state in ^{128}Cd applying γ-spectroscopy with MINIBALL after "safe" Coulomb excitation of a post-accelerated beam obtained from REX-ISOLDE. Such a measurement came into reach only because of the source developments made in 2006 for experiment IS411, in particular the use of a heated quartz transfer line. The result from the proposed measurement will be complementary to those from other experiments at ISOLDE and will add valuable information to a consistent understanding of this region which is of particular interest for both nuclear astrophysics and nuclear structure.

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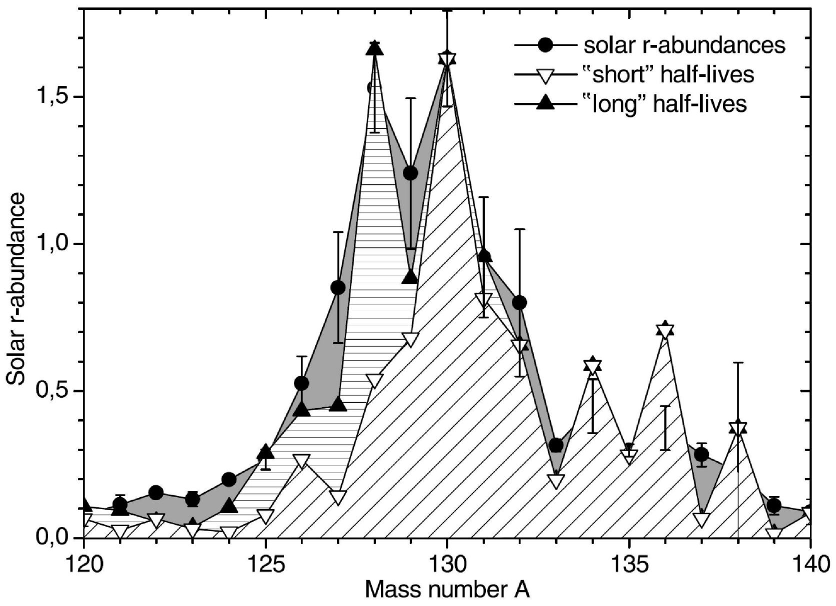

Figure 1: *Solar r-abundances around $A \approx 130$. The observed distribution is compared with simulations without ("short" lifetimes) and with ("long" lifetimes) taking into account new nuclear structure information consistent with a $N = 82$ shell quenching [3].*

1 Physics case

Following our current understanding of nucleosynthesis most of the elements heavier than Fe are produced by neutron captures and subsequent β-decays, the so-called *slow* ("s") process at small neutron densities and, in particular, the *rapid* ("r") process at high neutron densities [1]. The solar r-abundance $N_{r,\odot}$ of nuclei shows distinct peaks which demonstrate the interplay between r-process abundances and nuclear structure. They are caused by so-called "waiting point" nuclei at the magic neutron numbers $N = 50$, 82, and 126 whose long lifetimes delay the progression of the r-process. However, in the past the abundance peak at $A \approx 130$ has been underestimated in network calculations modelling the r-process.

Experimental information on nuclei "south" of ^{132}Sn is still scarce. Only some years ago precise lifetimes could be determined at ISOLDE [2, 3]. It turned out that the half-life, which now was found to be shorter compared to a previous measurement and to theoretical expectations, and the decay properties of ^{130}Cd could be interpreted by assuming a quenching of the $N = 82$ shell gap [3]. Extrapolated to the other waiting-point nuclei, such an effect would *increase* the expected half-lives of ^{128}Pd to ^{122}Zr. As it is demonstrated in Fig. 1, with these new half-lives a better agreement between the observed and modelled solar r-abundances around $A \approx 130$ can be obtained. The weakening of the shell gaps near the drip lines has been predicted [10], however it is not clear if such a scenario can already be applied to the nuclei around ^{132}Sn.

From the nuclear structure point of view a striking feature is seen in the systematics of the

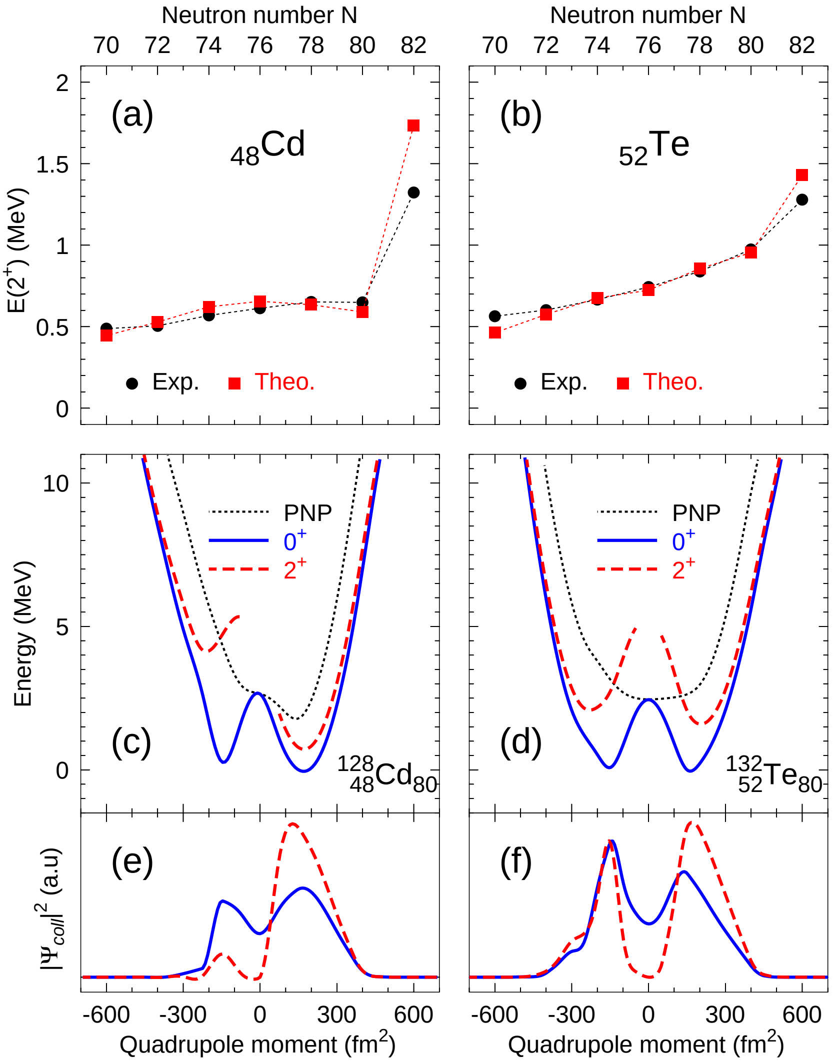

Figure 2: *Experimental and theoretical (scaled by 0.7) energies of the first* 2^+*-states in the Cd and Te isotopic chains (top). Comparison of the* $N = 80$ *isotones* ^{128}*Cd and* ^{132}*Te: calculated potential energy surfaces after particle number projection and mixing calculations (middle), and the corresponding wave functions (bottom) [5].*

excitation energies of the first 2^+-states. In contrast to naive expectations approaching more magic nuclei, the first 2^+-state in ^{128}Cd is *lower* than in ^{126}Cd, different to the Te isotopes above Sn (Fig. 2, top).

Shell model calculations using an effective interaction derived from the CD-Bonn nucleon-nucleon potential are not able to reproduce this trend [13]. However, they predict some collectivity for ^{126,128}Cd reflected in $B(E2; 0^+_{\text{gs}} \rightarrow 2^+_1)$-values of 49.5 W.u. and 31.5 W.u., respectively.

A recent study of the problem has proposed an alternative approach to explain the anomaly in the excitation energy of the first 2^+-state in ^{128}Cd [4, 5]. Instead of shell gap quenching in a spherical nucleus, in this beyond mean field calculations already after angular momentum and particle number projection a pronounced prolate minimum is ob-

	^{126}Cd	^{128}Cd	^{130}Cd
$t_{1/2}$ [12]	0.515 s	0.28 s	0.162 s [3]
$E(2_1^+)$ [keV]	652	645	1325 [5]
$B(E2\uparrow)_{\mathrm{exp}}$ [e^2b^2]	0.22 ± 0.03	/	/
$B(E2\uparrow)_{\mathrm{syst}}$ [e^2b^2]	0.27	0.24	0.14
$B(E2\uparrow)_{\mathrm{SM}}$ [e^2b^2]	0.19	0.12	
$B(E2\uparrow)_{\mathrm{BMF}}$ [e^2b^2]	0.28	0.21	0.22

Table 1: *Properties of ^{128}Cd compared to the neighbouring isotopes. The reduced transition strengths $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$, abbreviated as $B(E2\uparrow)$, are the preliminary value from experiment IS411 [15], the expectation from systematics [11], and theoretical values calculated with the shell model [13] and a beyond mean field approach [5].*

tained for ^{128}Cd. A calculation of the configuration mixing between the coexisting oblate and prolate structures resulted in an average prolate deformation, see Fig. 2 (left,bottom), in contrast to the isotone ^{132}Te. Such quadrupole collectivity is not predicted by any other microscopic approach. Although the different behaviour of the excitation energies for Cd and Te can be explained, it has to be mentioned that the absolute values of the excitation energies are generally too high and are scaled by a factor of 0.7 in Fig. 2 (top).
Furthermore, the recent measurement of the decay of the 8^+-isomer in ^{130}Cd also showed no evidence for a quenching of the $N = 82$ shell gap [5]. In this measurement also the excitation energy of the first 2^+-state, tentatively assigned as 957 keV [16, 2], could be determined to be 1325 keV.
Hence, there is no conclusive understanding of these nuclei yet. As it was pointed out above, since many nuclei in this region are hardly accessible by experiments, one has to rely on the extrapolation capabilities of theories to model the r-process. Therefore more experimental information is needed in order to pin down the underlying physics and improve the theoretical predictions for nuclei currently out of reach for experiments.
Aim of the proposed experiment is to evidence the proposed quadrupole collectivity by measuring the $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$-value in ^{128}Cd in a Coulomb excitation experiment. Table 1 summarises the relevant information for ^{128}Cd in comparison with the neighbouring isotopes ^{126,130}Cd. The result can be discussed together with the $B(E2)$-values already determined in this region by experiment IS411 [11, 15]. It will complement those from other experiments performed or proposed at ISOLDE in this mass region like the mass measurements at ISOLTRAP [6, 7] and the ultra-fast timing measurements [8]. The combination of all results will the basis of a consistent description of the nuclei around ^{132}Sn which are of particular interest for both nuclear astrophysics and nuclear structure.

2 Experimental set-up

We will use the standard set-up for "safe" Coulomb excitation experiments performed at REX-ISOLDE. This set-up consists of the MINIBALL array to detect γ-rays and the CD detector in forward direction for particles. The CD detector is a double-sided segmented

Si detector (DSSSD). It has four quadrants, each of them is segmented in 16 annular stripes (ϑ-coordinate) on the front and in 12 radial segments (ϕ-coordinate) on the back. The CD detector enables a determination of the reaction kinematics and an improved Doppler correction of the γ-rays.

Depending on the scattering angle, either the scattered beam particle or the recoiling target nucleus is detected, but in some cases also both of them. By choosing a target with sufficiently different mass compared to the beam, scattered beam particles and recoiling target nuclei can be distinguished by their different kinematics.

Downstream of the target a two-dimensional position-sensitive PPAC allows to control both the beam position and intensity. This detector is essential for focusing the beam and monitoring the experiment. As upgrade of the set-up also a segmented diamond detector at the target position will be used for focusing, if available .

A major problem is created by isobaric contaminants in the beam, in particular Cs and In. The composition of the beam will be determined using the well established methods listed in the following:

- An additional Ge detector behind the beam dump measures the decay of the implanted beam particles.
- A Bragg chamber constructed by the TUM group allows to identify mass and charge of the beam particles [14]. In particular, this detector allows also to identify contaminants in the beam which have long lifetimes or are even stable and, therefore, offers information complementary to the beam dump detector.
- A shutter in front of the laser of the RILIS can be closed every second supercycle of the PS Booster ("Laser ON/OFF"). Without the laser the isotope of interest is reduced in the beam and the counting rate decreases correspondingly. Additionally, the number of decays in the beam dump is reduced.

3 Rate estimate and beam time request

The isotopes are produced with a standard UC_x/graphite target irradiated with the proton beam from the PS Booster. As ion source the highly selective "Resonance Ionisation Laser Ion Source" (RILIS) will be applied. For ^{124,126}Cd a breeding time in the EBIS of 248 ms has been used. The shorter half-live of ^{128}Cd will cause a somewhat lower efficiency. The ions from ISOLDE are postaccelerated by the REX-ISOLDE facility. From our experience during the runs of IS411, we estimate the efficiency of REX for such heavy beams to be in the range of a few percent.

In 2006, the measurement of ^{126}Cd used the neutron converter to suppress the ^{126}Cs contaminant. Furthermore, the beam purity greatly benefited from the use of a heated quartz transfer line between the ISOLDE target and the ion source. Compared to the ^{126}Cd test performed in 2004 (also with the converter target), the beam purity increased from around 10% to about 75%! The total beam intensity on the MINIBALL target was $1.4 \cdot 10^4$/s at an overall efficiency of REX of 7%. Because of a missteered proton beam (now hitting the target instead of the converter) and/or a target anomaly temporarily the beam intensity increased even by a factor up to 8.

The gamma yield is estimated from Coulomb excitation calculations [9]. The value of the reduced transition strength $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$ is estimated applying the modified Grodzins-Raman rule from the excitation energy of the first 2^+-state [11, 15]. We included also the first 4^+ state and extrapolated the corresponding reduced matrix element in the harmonic oscillator limit. The reorientation effect is included in the calculations as well. The cross-section for excitation of the first excited 2^+-state in ^{128}Cd integrated over the solid angle of the CD detector is 0.55 b (compared to 0.64 b in ^{126}Cd).

All calculations were done at an energy of 2.6 MeV/u. This takes into account the energy loss of beams at 2.8-2.9 MeV/u, the energies obtained in IS411, in a Zn target of 1.8 mg/cm^2 thickness. An efficiency of 10% for MINIBALL in the range of interest and of 90% for the CD detector is assumed.

As in the IS411 run in 2006, a ^{64}Zn target is considered. The $2^+ \rightarrow 0^+_{\mathrm{gs}}$ transition of ^{64}Zn is at 991.6 keV, hence far away from the $2^+ \rightarrow 0^+_{\mathrm{gs}}$ transition of ^{128}Cd. The intensity of the transitions from the target is used for normalisation, since the electromagnetic properties of ^{64}Zn are well known [12]. All transitions with known transition strengths in this nucleus have been taken into account. The cross section for Coulomb excitation of the first 2^+-state is approximately 0.6 b. In order to serve as a normalisation, the $2^+ \rightarrow 0^+_{\mathrm{gs}}$ transition is needed with similar statistics as the transitions from the beam.

For our rate estimate we assume that the production rate of ^{128}Cd will be about a factor of 30 lower compared to ^{126}Cd. The drop in fission yield is not as large as usually, a factor of 10 per neutron, because ^{128}Cd is already quite near to ^{132}Sn which is preferred in fission. Therefore the increase in mass yields compensates somewhat the decrease due to the larger N/Z ratio. We assume that the fission yield is reduced roughly by a factor of 7, consistent with the value of 6.4 given in Ref. [17]. Furthermore, we take into account a reduced efficiency of REX (see above) and typical fluctuations in the properties of ISOLDE targets by a conservative factor of 4. For the obtainable beam purity we assume a value around 50%. With these assumptions we would obtain a γ-particle-rate about 20/day.

As option, the experiment could be performed without the neutron converter which would increase the intensity by a factor of 3. The purity which could be obtained has to be checked, however.

We are aiming at the determination of $B(E2)$-values within an error below 15%. Even with our conservative rate estimate, we will be able to measure around 140 γ-photopeak events in coincidence with particles within **21 shifts**, hence the statistical error will be well below 10%. Therefore we ask for **21 shifts** to measure the isotope ^{128}Cd. Additionally, we ask for **3 shifts** to prepare the beam.

We request in total 24 shifts (8 days).

References

[1] K.-L. Kratz et al., ApJ 403, 216 (1993).

[2] T. Kautzsch et al., Eur. Phys. J. A 9, 201 (2000).

[3] I. Dillmann et al., Phys. Rev. Lett 91, 162503 (2003).

[4] A. Jungclaus and J. L. Egido, Phys. Scr. T125, 53 (2006).

[5] A. Jungclaus et al., NUSTAR Annual Meeting, GSI (2007); private communication.

[6] A. Herlert et al., Proposal INTC-P-160-ADD-1 (2006).

[7] M. Kowalska et al., DPG Spring Meeting, Giessen (2007).

[8] H. Mach et al., Proposal INTC-P-201 (2006).

[9] K. Alder and A. Winther, "Electromagnetic Excitation", North-Holland (1975).

[10] J. Dobaczewski et al., Phys. Rev. Lett. 72, 981 (1994).

[11] D. Habs et al., Proposal INTC-P-156 (2002).

[12] *http://www.nndc.bnl.gov/ensdf.*

[13] A. Scherillo et al., Phys. Rev C 70, 054318 (2004).

[14] W. Weinzierl, Diploma Thesis (TU München, Germany).

[15] T. Behrens et al., ISOLDE Workshop 2007.

[16] K.-L. Kratz et al., Z. Phys. A 325, 489 (1986).

[17] T. R. England and B. F. Rider, LA-UR-94-3106, ENDF-349; *http://ie.lbl.gov/fission/238uf.txt.*