**Acronym**
ISON82

**Title**
Testing the shell closure at N=82 via multinucleon transfer reactions

**Request type**
New experiment

**Application details**

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**Requested beam time units (1BTU=8h)**

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**Beam details**

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**Special requirements or comments**
Testing the shell closure at N=82 via multinucleon transfer reactions at energies around the Coulomb barrier

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Abstract

We propose to explore the production of neutron rich nuclei in the region of the shell closure N=82 through the multinucleon transfer process in several low-energy binary reactions. Mass and Total kinetic energy distributions will be constructed by measuring time of flight and positions of binary fragments with a two-arm TOF spectrometer CORSET. We request for 8 days of Tandem beam time to run two reactions.

I. SCIENTIFIC MOTIVATION

It has been argued about 20 years ago [1, 2] that neutron excess causes the central potential in the shell model to become more diffuse and the weakening of the spin-orbit splitting. The immediate consequences are a change in the ordering of the single-particle levels and the gradual vanishing of the shell gaps, in the correspondence of the well known magic numbers, known as shell quenching. In other words, it is expected that the shell gaps at magic neutron numbers are less pronounced in very neutron rich nuclei than in nuclei closer to the stability line.

![Image of r-process abundance](image-url)

FIG. 1: r-process abundance (shown with dots) in comparison with two calculations which differ in the strength of the spin-orbit interaction that produces the shell gap at N=82. A spin-orbit splitting weaker at the drip line than for stable nuclei gives a better agreement with the data.

Shell quenching in neutron-rich nuclei is of particular interest for the astrophysical nucleogenesis of the heavy elements as it affects the relative capture and decay rates in the vicinity of the
waiting points of the r-process. The structure of the N=82 isotones below the doubly magic nucleus \(^{132}\)Sn are of crucial importance because of their connection with the peak at \(A \approx 130\) in the solar r-process abundance distribution. It was indeed shown [3, 4] that a quenching of the N=82 shell closure leads to a considerable improvement in the global abundance fit in the r-process calculations, in particular in the region \(A \approx 130\) (see Figure 1). However, an equally good fit in the above mass region have been proposed without invoking shell quenching [5, 6].

The indirect existence of the shell quenching argued from the r-process solar abundance studies is not indeed confirmed experimentally. Two recent spectroscopic studies on the neutron rich \(^{130}\)Cd, which is one of the important isotones at N=82 below \(^{132}\)Sn, have come to opposite conclusions about shell quenching in this mass region. In [7] there is no evidence of shell quenching in \(^{130}\)Cd from the direct observation of the level scheme, whereas in [8] the rather high \(Q_{\beta}\) value of 8.34 MeV found is estimated in agreement only with mass models that include the phenomenon of N=82 shell quenching.

The scarcity of data for \(^{130}\)Cd, and for this neutron rich region is due to the lack of reaction mechanisms suitable to produce these nuclei in large amounts. New (neutron and proton rich) isotopes located far from the stability line are obtained 1) in fragmentation (spallation) processes at intermediate colliding energies, 2) in fission of heavy nuclei and 3) in low-energy fusion reactions. Due to the "curvature" of the stability line, in the fusion reactions of stable nuclei it is possible to produce only proton-rich isotopes of heavy elements which after evaporation of several neutrons shifts even more to the proton-rich side. In [7, 8] \(^{130}\)Cd was produced by the fragmentation of an high energy \(^{238}\)U beam in specialized facilities like GSI and ISOLDE, respectively.

The future radioactive beam facilities like SPES are indeed expected to produce these nuclei. In the meantime it is worth to advance in the studies of possible reaction mechanisms that might be alternative to the ones cited above.

We propose to explore the production of neutron rich nuclei, and eventually \(^{130}\)Cd, via the multinucleon transfer process in low-energy collisions of heavy ions. In the energy regime at around the barrier, and for medium mass partners, it is well established [11] that mass transfer in multinucleon transfer and quasi-fission is strongly driven by shell effects and may induce the production of shell closed neutron rich nuclei far from the stability line after a considerable exchange of nucleons. In other words, shell closures can favor a large net mass transfer in multinucleon transfer reactions between massive nuclei. This approach may open the way to the production of neutron-rich nuclei.

Recently, it has been shown experimentally that even at energies close to the Coulomb barrier, the cross sections for transfer of many protons and neutrons, driven by shell effects, are still rather high [9, 10] (of the order of hundreds of \(\mu b\)), and these reactions could be considered as an alternative way for the production of exotic nuclei. The mass transfer counts on the strength of the shell closures as a stronger shell gap may favor some specific mass transfer among projectile and

![FIG. 2: (left) driving potential at the scission point (the different valleys are due to shell closures); (right) enhancement of the mass production when approaching the region driven by shell closure N=82 [10].](image-url)
target nuclei. One of the many examples is shown in Figure 2. However, the excitation energy of the emerging fragments must be kept as low as possible. It is well known from damped collisions of heavy ions that the relative motion energy is quickly transformed into the internal excitation of the projectile-like and target-like fragments which afterward de-excite by evaporation of light particles (mostly neutrons). This does not seem to give us a chance for the production of nuclei with large neutron excess in such reactions. However, if the colliding energy is rather low and the reaction Q-value is negative or not that large, the formed primary reaction fragments might not be very much excited and will descend to their ground states after evaporation of a few neutrons thus remaining far from the stability line. The main point is how large is the cross section for the multinucleon transfer reactions at low colliding energies and how it is related to the strength of the shell gaps.

II. PROPOSED EXPERIMENT

We propose to study the strength of the shell closure at N=82 by exploring the production of neutron rich nuclei in the region N=82, and in particular of the nucleus $^{130}\text{Cd}$, through the multinucleon transfer process in following low-energy binary reactions:

1. $^{50}_{22}\text{Ti}_{28} + ^{140}_{58}\text{Ce}_{82} \rightarrow ^{50}_{22}\text{X}_{N=28} + ^{140}_{N-28}\text{Y}_{N=82}$
2. $^{48}_{22}\text{Ti}_{26} + ^{152}_{62}\text{Sm}_{90} \rightarrow ^{70}_{36}\text{Kr}_{34} + ^{130}_{48}\text{Cd}_{N=82}$
3. $^{48}_{20}\text{Ca}_{28} + ^{142}_{60}\text{Nd}_{82} \rightarrow ^{60}_{32}\text{Ge}_{28} + ^{130}_{48}\text{Cd}_{N=82}$
4. $^{37}_{17}\text{Cl}_{20} + ^{153}_{63}\text{Eu}_{90} \rightarrow ^{60}_{32}\text{Ge}_{28} + ^{130}_{48}\text{Cd}_{N=82}$

The major features of these reactions are listed in Table I. The basic guideline of the reaction partners chosen is to take advantage of the stabilizing effect of the closed proton and neutron shells in both partner nuclei. The method is schematically represented in Figure 3. For instance, in the first reaction, the proton transfer from Ce to Ti might be rather favorable because of the stabilizing shell closure N=28, 82 in the entrance and exit channel. Furthermore, the negative Q value minimizes the available excitation energy to neutron evaporation. In the second reaction, there should be no stabilizing effect in the entrance channel and the production cross section should
drop with respect to the above reaction. Reactions 3 and 4 are possible alternatives to mix shell stabilization effects. By combining partners with different shell closures we can test not only the strength of the shell closures by measuring the amount of mass produced around \( A=130 \), but we can also extract information concerning the entrance channel dynamics.

Even though the expected isotopic cross sections are of the order of \( 100 \text{nb} - 100 \mu \text{b} [11, 12] \), we believe that it is still important to study the basic properties of these reactions in preparation of the studies to be performed with the future RIB facilities, and also because cross sections predicted by the existing few models are scarcely reliable [9] due to the lack of benchmark data on which to test these complex models.

The observables of preference for these kind of reactions are the Mass and Total Kinetic Energy (TKE) distributions of the primary binary fragments. These observables have been proved to be strongly correlated with the shell closures and the cumulative potential energy surface of the colliding nuclei [11]. One advantage of measuring also the TKE is that the exit channel can be further divided in windows of TKE. This is a feature that allows to chose different degrees of excitation energy in the exit channel.

For the implementation of this project we plan to use the Time-Of-Flight CORSET setup. Each TOF arm is equipped with a START and a position sensitive STOP detectors based on MCP. By using 4 arms we can cover an angular range with respect to the beam from \( 35^\circ \) to \( 65^\circ \). The reactions chosen in this proposal are fully covered by this angular range when two fragments are detected in coincidence. Four silicon detectors will be placed at forward angles to normalize cross sections and to monitor the beam alignment during the run. START and STOP detectors allow a time resolution of about 150 ps with analog electronics, which on a flight path of 30 cm may provide in principle a mass resolution of about 1 a.m.u. Indeed, since the Mass and TKE of two fragments in coincidence will be extracted from the two-body kinematics by assuming some average multiplicity for the post-scission evaporation of neutrons, the mass resolution will be broadened. An additional broadening may come from the position resolution and the multiple scattering of the ions in the target and the entrance foils of the MCP. Some of these effects can be minimized by a careful choice of the thickness of the target and entrance foils of the START detectors. The large experience on this kind of setup will allow to get the best operative conditions.

It is important to stress that the TOF setup is not able to identify the atomic number of the fragments, but only the primary masses. But for the purpose of this first approach, it is enough to establish differences between the production cross sections at \( A\approx 130 \) among the different reactions. Therefore, the proposed experiment constitutes a first step in the search for extreme multinucleon transfers. To measure the cross section of the masses produced around \( A\approx 130 \) will give the motivations to trigger further experiments where also the \( \gamma \) probe can be used for a clean identification of the produced isotopes. Such a program has already started at IPN Orsay with the ORGAM array for \( \gamma \) detection [13]

<table>
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III. RATE ESTIMATES AND BEAM TIME REQUEST

In the present proposal we ask to allocate beam time for the reactions 1 and 2 above. Indeed reaction 4 would be more suited than reaction 2 because of the shape of the potential energy surface, but reaction 2 together with reaction 1 would likely minimize the time for changing the beam.

On the basis of the experience with the system $^{136}$Xe + $^{208}$Pb [9] and very recent model calculations [12] we expect a cross section around $1mb$ for the whole mass region $A\approx130$. Two TOF arms will be placed symmetrically around the beam at $60^\circ$ and two others at $45^\circ$ to cover suited angles considering the kinematics for $^{130}$Cd.

Considering a total detector efficiency $\epsilon=2\%$, a target thickness of $T=200\mu g/cm^2$, a beam current $\phi=10pnA$ ($6.24 \times 10^{10}$ ions/s), the expected rate is $2.86 \times 10^{-1}$ s$^{-1}$, namely about 25000 events per day. Therefore we request for 8 days of Tandem beam time to run reactions 1 and 2 in the list above, including the setup time.

[12] A.V. Karpov and V. Saiko, Analysis of the multinucleon transfer processes leading to formation of neutron-rich nuclei, presented at EXON 2016 Conference.