Neutron-rich isotopes in the Ni region studied with fast beams using RISING

H. Scheit

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

The evolution of nuclear shell structure is an important topic in nuclear physics, today. With the advent of radioactive nuclear beams it became possible to study the collective and single-particle properties of nuclei along long isotopic (isotonic) chains and the systematic information gained allows a comprehensive understanding of the evolution of nuclear shells as the driplines are approached. Phenomena expected and already observed in some parts of the chart of nuclei include the melting of shells – the most famous example being the complete vanishing of the $N = 20$ neutron shell for ^{32}Mg – and the emergence of new (sub)shells. Furthermore, tests of global systematics (Grodzins, Raman [2], N_pN_n [3]) can be performed far from stability, if level energies and $B(E2)$ values are available. Information on the structure of these nuclei is also an important input for nuclear astrophysical models, predicting the abundance of nuclei on earth and in the cosmos.

As an example a good candidate for an emerging new shell is $N = 40$ in the vicinity of the Ni isotopes (^{68}Ni). Experimentally, significant progress was made in the techniques for studying neutron-rich nuclei near $^{68-70}$Ni. Many new levels could be established including several isomeric states using fragmentation, deep-inelastic reactions, and fission (see [4, 5] and references therein). A wealth of information originates from β decay experiments [6, 7] and the single particle properties are well known. One peculiar feature is that the $N = 40$ (harmonic oscillator) subshell does not exist for the $Z = 30$ (Zn) isotopes and also seems to vanish completely for the $Z = 26$ isotope ^{66}Fe [8]. The data in the above references also indicate a weakening of the $Z = 28$ shell.

A direct measurement of the collectivity using Coulomb excitation with fast beams usually suffers from poor resolution and large background especially for very high beam energies (≥ 100 MeV; see below). Here the RISING project can provide high quality data not only due to the high resolution of the Ge-detectors, but also due to the high efficiency of the proposed setups.

In order to interpret the measured data large scale shell model calculation are now becoming possible and more accurate in this mass region.

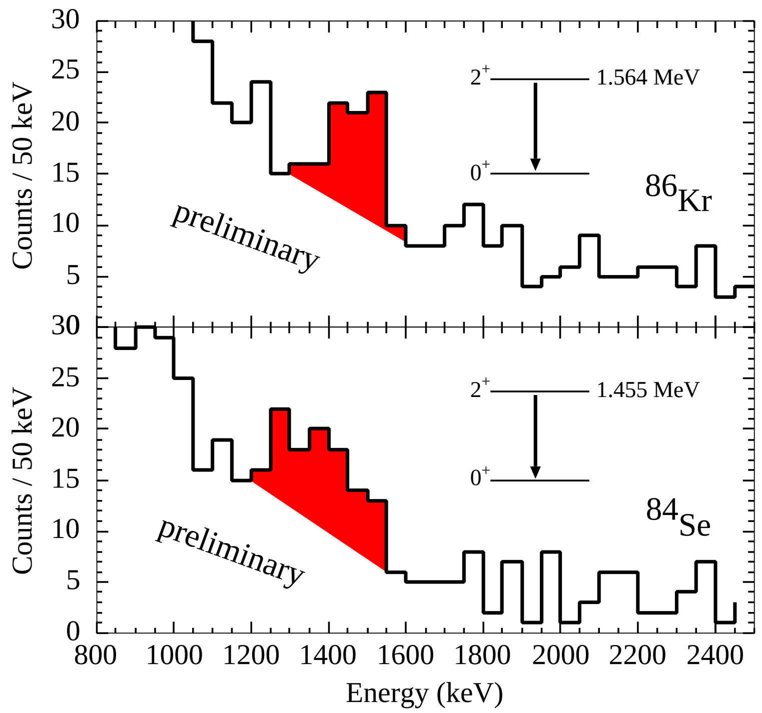

Figure 1: Preliminary results of a recently performed Coulomb excitation experiment. The resolution is about 10% and only a minor improvement is expected, when the γ energy calibration is completed.

Advances in the understanding of these nuclei mainly come from experiments performed with secondary radioactive beams, even though deep inelastic reactions have also proven to be a valuable tool [5].

Coulomb excitation with fast beams (in inverse kinematics) has successfully been applied to a wide range of light nuclei, see e.g. [9] and [10] for a review. So far however the photon detection device was a low-resolution scintillator array (typically NaI(Tl)) and the experimental energy resolution was not better than 8%. Exploiting the high granularity of RISING an energy resolution of about 1% can be obtained, while efficiencies of 1-2% can be reached.

The use of cocktail beams allows to study many isotopes in short time and due to the high beam energies thick targets can be used ($\sim$g/cm^2), compensating to some extend the possibly very low beam intensities ($\sim$10 particles/s).

In order to illustrate the advantages of RISING, preliminary results of a recently performed Coulomb excitation experiment are shown in figure 1. The top and the bottom panels show the Doppler corrected γ spectra for Coulomb excitation of ^{86}Kr and ^{84}Se on a lead target, respectively. (The statistics are so low, since only a low statistics run could be analyzed so far, even though ^{86}Kr is stable and ^{84}Se is not far from stability.) It can be seen that the resolution is only about 10%; RISING would bring a considerable improvement in this case, since the peak widths would be reduced by a factor of ten.

In addition to Coulomb excitation also other reaction channels can be considered. Mentioned here should be *secondary fragmentation* reactions, where γ rays emitted after fragmentation of the *secondary* beam particles are detected. In these reactions states of high spin can be populated, yielding complementary information to Coulomb excitation. Through the use of a RDDS type method even lifetimes of such states can be determined (see contribution of J. Gerl for details).

Other reaction channels include neutron and proton stripping and giant resonance excitation with subsequent neutron emission, which can be detected in the LAND detector.

A possible experimental setup corresponds to the LAND setup [11], which allows for the tracking and identification of the particles before and after the secondary target. However, the standard LAND target detector will be replaced by RISING.

One of the major drawbacks of experiments with fast beams, the Doppler broadening, is addressed by RISING, since the detectors are arranged in such a geometry that the energy resolution is always $< 1\%$.

Another drawback is the severe atomic background due to scattered target electrons. The background spectrum is shown in figure 2 on the example of a ^{78}Zn beam impinging on a Pb target with a energy of $E/A = 300$ MeV. The largest contribution stems from secondary electron bremsstrahlung (SEB), which is isotropic in the laboratory frame. The scale on the plot should be noted: the differential cross section can reach values of tens of b/keV/sr and the integrated total cross section is in excess of 10^4 b. An appropriate absorber can suppress most of the low energy background, however. For further details see [12].

The transitions of interest are Doppler shifted in the laboratory system. This is illustrated in figure 2 by the line pointed to by the arrow. This line corresponds to a transition in the projectile nucleus with an energy of

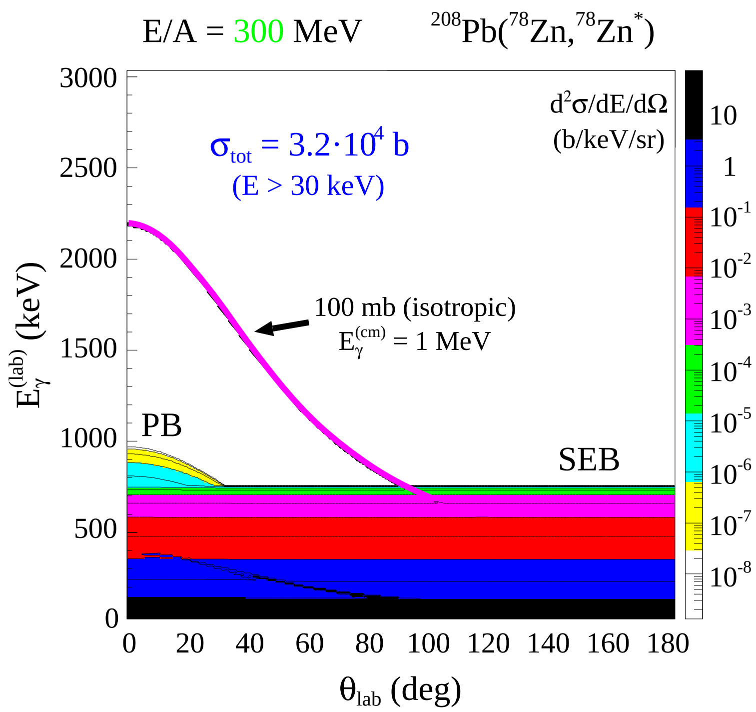

Figure 2: Atomic background spectrum.

1 MeV (in the projectile rest frame). One can clearly see that the energy of this photon is significantly Doppler shifted to higher energies for small angles. Therefore, by placing the photon detectors at forward angles the γ ray energy of interest is shifted above the atomic background and even pure Coulomb excitation experiments, where the γ decay after Coulomb excitation and the emission of bremsstrahlung have the same signature, can be performed.

When other reaction channels are used, where a clear tag of the reaction is given, e.g. neutron-, proton-stripping or GR excitation with subsequent neutron emission, the atomic background is strongly suppressed and rather background free spectra can be obtained, also at low photon energies.

In conclusion, RISING will allow for an excellent use of the exotic beams that can be produced at GSI and high-quality experimental data can be obtained in a systematic way, which will give further insight in the interplay of collective and single particle degrees of freedom at extreme isospin.

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