Proposal to the ISOLDE–Neutron–Time–of–Flight Committee

Coulomb Excitation of ^{72}Zn — Vibrational Proton-Neutron Structure of the Even-A Z=30 Isotopic Chain

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Abstract

We propose to measure low-lying multiphonon excitations in the ^{72}Zn nucleus. Intense beam of neutron rich zinc isotopes are available at ISOLDE and successful Coulomb excitation experiments have been performed up to A=80.

The main goal is to understand the proton-neutron structure in this shell-model driven region. Shell model calculations suggest that the 2_2^+ state in this nucleus is the main fragment of the fundamental proton-neutron mixed-symmetry state[1], i.e. that the $2_2^+ \rightarrow 2_1^+$ transition gets a significant magnetic component. We therefore propose to measure the multipole mixing ratio of the $2_2^+ \rightarrow 2_1^+$ transition by inspecting the differential cross section of Coulomb exciting the 2_2^+ state. Furthermore, we would like to search for the yet unknown

2_3^+ state in the ^{72}Zn nucleus, that may play an important role as well. The results would help to understand the anomalous behavior of 2^+ MS states in the even-A zinc isotopes with respect to the complicated underlying shell structure around the N=40 subshell closure.

Our proposal is a good add-on to the accepted proposal of A. Jungclaus to measure g(2_1^+) in ^{72,74}Zn (P-253). The measurement of g(2_1^+) may give information on the role of the $\nu(g_{9/2})$ orbital that is most likely responsible for the anomalous behavior of low-lying M1 transition strength in this region. Thus, the two proposed experiments on ^{72}Zn will yield many important new insights into the structure in this interesting region of the nuclear landscape. However, as both experiments need different setups and especially different target chambers, they cannot be combined. Moreover, as we will outline below, the drastic behaviour of the low-lying M1-stregth is not reflected in the more smooth behavior of the magnetic moments in these nuclei.

1 Physical motivation

The Z=30 zinc isotopes are located two protons above the Z=28 proton shell. In former times these nuclei were ascribed to behave like vibrational nuclei. A closer inspection of the level schemes and decay strength shows deviations from the simple vibrational picture. From a shell model point of view the zinc nuclei are fp shell nuclei, but towards the last stable even-A nucleus ^{70}Zn especially the $\nu(g_{9/2})$ shell becomes more and more important. Furthermore, it is known that core excitations of the ^{56}Ni core nucleus have to be considered describing the nuclear structure properties of the stable even-A nuclei, especially around the N=40 mass region. Therefore shell model calculations using a ^{48}Ca core and the full fp orbitals including the $\nu(g_{9/2})$ orbital are needed to gain insight into the details of this interesting region. Such shell model calculations are at the limit of today's computer capacity. As a consequence it is not even possible to calculate the energy of the low-lying first excited 0^+ state in the ^{70}Zn nucleus correctly. Therefore, it is highly important to improve knowledge on the effective interaction in this region around the proposed N=40 subshell closure and to clarify a possible weakness of the Z=28 proton shell around N=40.

The special case of the stable ^{70}Zn (N=40) nucleus was extensively investigated by our group at the University of Cologne within the last years using different techniques like (γ,γ'), $(n,n'\gamma)$, and Coulomb excitation experiments (including g-factor measurements). We were able to demonstrate that the ^{70}Zn nucleus behaves more strongly like a vibrational nucleus than it was expected. This finding was based on new lifetime measurements of the low-lying phonon excitations, what was especially important in case of the 2_3^+ state. This state at 1.957 keV could be clearly identified to be of MS character [4]. Furthermore, we were able to identify candidates of multiphonon MS states $2_{2,ms}^+$ and $4_{1,ms}^+$ [4]. Only very few examples of such states have been found in atomic nuclei, underlining the good vibrational properties of this nucleus. Altogether we can nicely describe the ^{70}Zn nucleus using a F-Spin symmetric U(5) IBA-2 Hamiltonian [11]. All known states in the ^{70}Zn nucleus up to 2.7 MeV can be assigned to symmetric or mixed-symmetric phonon excitations in a simple vibrational picture. This is a surprise as the underlying shell structure around N=40 is very complicated.

The main experimental signature of the $2_{1,ms}^+$ state is a strong M1 decay into the 2_1^+ state. In Fig. 1 the evolution of E($2_{1,ms}^+$) and B(M1;$2_{1,ms}^+ \rightarrow 2_1^+$) in the even-A zinc isotopes is shown. The first important feature is the almost constant B(M1;$2_{1,ms}^+ \rightarrow 2_1^+$) strength of roughly 0.1 μ_N^2, indicating the observed B(M1) strength originating from the same mecha-

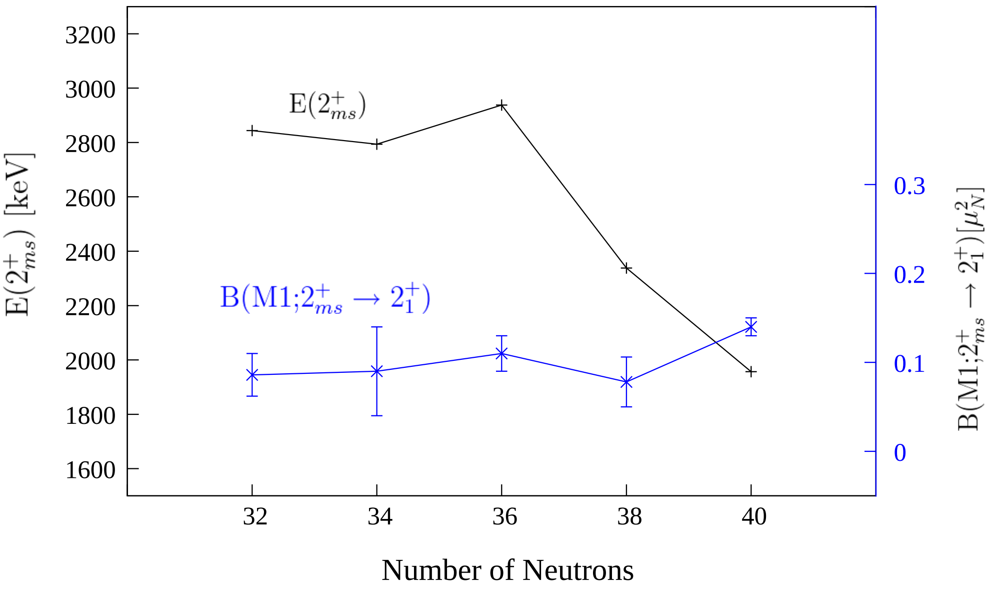

Figure 1: Systematics of MS states in the even-A zinc isotopes $^{62-70}$Zn. Plotted are excitation energies E($2^+_{1,ms}$) as well as the transition strengths B(M1;$2^+_{1,ms} \to 2^+_1$). Data are from [7] for ≤38, and from [4] in case of N=40

nism, described by the proton-neutron version of the Interacting Boson model. The second important point is the drop of the excitation energies E($2^+_{1,ms}$) towards N=40. In the nuclei $^{62-66}$Zn the excitation energies are around 3 MeV, which is quite high for these states. The reason for these unusually high lying energies are not fully understood yet. Going towards the more neutron-rich nuclei $^{68-70}$Zn, the energy of the mixed-symmetry state drops by roughly 1 MeV. Such an abrupt change has never been observed in any region of the nuclear chart. It is of current interest to understand the microscopic mechanism which allows such drastic changes of collective features in this region around N=40.

The driving force for the evolution of collective states is the proton-neutron interaction. In case of zinc isotopes, this interaction causes the single particle $\nu g_{9/2}$ orbital to come down in energy rapidly. Our current understanding of the anomalous behavior of mixed symmetry states is, that the down-sloping of E($2^+_{1,ms}$) states is caused by the decreased energy difference of the fp orbitals to the $g_{9/2}$ orbitals.

This interpretation seems to be in contradiction to our results from g-factor measurements [5] in ^{70}Zn. Here we were able to determine the g(4^+_1) value at N=40 for the first time. No drastic effect around N=40 was found (see Fig. 2). Obviously, the magnetic moments of the 4^+_1 states show a smooth evolution with increasing neutron number, whereas the behavior of low-lying M1 strength is very sensitive to changes in the underlying shell structure. We therefore think, that the study of low-lying M1 strength is a powerfull tool to understand the evolution of the shell configurations in this region towards neutron-rich nuclei.

Shell model calculations for the even-A zinc nuclei indicate that the 2^+_2 state in the ^{72}Zn nucleus is the main fragment of the $2^+_{1,ms}$ state. Our shell model calculations were done by A. Lisetzkiy, using his effective interaction [6] being especially optimized to describe best Z=28 and Z=30 nuclei in the neutron-rich region towards ^{78}Ni core. Starting from the ^{56}Ni core, this interaction includes $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $g_{9/2}$ orbitals both for protons and neutrons. We found reasonable agreement of the calculated transition strength with our detailed experimental results for the stable even-A zinc isotopes in the mass range

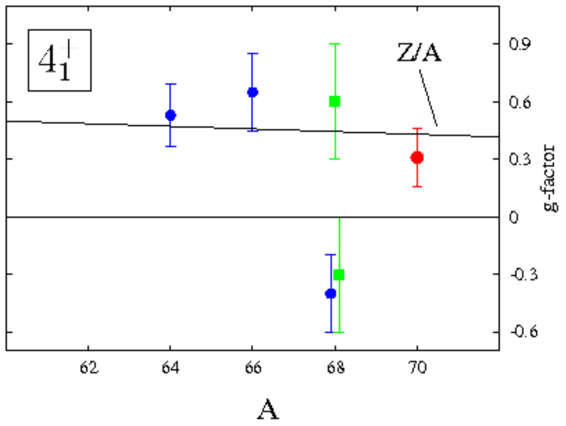

Figure 2: Evolution of g(4_1^+) in even-A zinc isotopes. Apart from the nebulous situation for ^{68}Zn, all results are in good agreement with the simple Z/A prediction (upper black line). Data are from literature except for N=40 which is from [5].

$62 \leq A \leq 70$. In the case of the ^{72}Zn nucleus the calculation predicts a B(M1;$2_2^+ \rightarrow 2_1^+$) strength of 0.06 μ_N^2, which is in the same order of magnitude as the expected total M1 strength of the $2_{1,ms}^+$ state. Although the correct reproduction of multipole mixing ratios is very sensitive to small changes in the parameters of the calculations, this trend confirms the ongoing down-sloping of M1 strength in this region (see Fig. 1).

From the experimental point of view the ^{72}Zn nucleus is very difficult to populate with stable beams. No lifetime information except $\tau(2_1^+)$ are known so far. A Coulomb excitation experiment using an unstable ^{72}Zn beam is very well suited to study the low-lying phonon excitations in such a nucleus, as will be outlined in the following section.

We would like to emphasize that the identification of MS states is essential to correctly interpret the nuclear structure of vibrational-like nuclei. Furthermore, they give important information on the effective proton-neutron interaction which are highly needed to guide shell model calculations.

2 Experimental method

Our main goal is the determination of the magnetic or electric character of the $2_2^+ \rightarrow 2_1^+$ transition. The 2_2^+ state has a known branching ratio that is shown in Fig. 3. The idea is to use the fact that Coulomb excitation amplitudes for magnetic transitions are very weak compared to electric E2 excitations. If therefore the $2_2^+ \rightarrow 2_1^+$ transition is of mainly magnetic nature, the excitation process of the 2_2^+ state is a pure 1-step Coulomb excitation from the ground state. If the $2_2^+ \rightarrow 2_1^+$ transition is dominantly of E2 character, the excitation process is a mixture of 1-step and 2-step Coulomb excitation. This can be tested by measuring the differential cross section, because for large center-of-mass (CM) scattering angles the 2-step processes become more and more important. Thus, the basic idea is to relate the measured branching ratio to the measured shape of the excitation probability to extract the M1 component of the $2_2^+ \rightarrow 2_1^+$ transition.

The experimental level scheme of ^{72}Zn is shown in Fig 3, together with results for transition strengths from our shell model calculations. The 2_2^+ state in the ^{72}Zn nucleus is known to be located at 1657 keV, its experimental branching ratio (from β-decay studies)

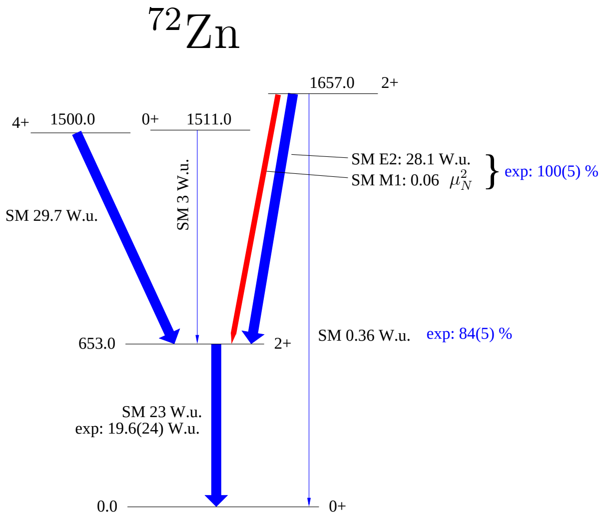

Figure 3: Experimental level scheme of the low-lying states in the ^{72}Zn nucleus. Transition strengths (E2 in W.u., M1 in μ_N^2) are taken from our shell model calculations (see text) using a ^{56}Ni core. The M1 transition strength of B(M1;$2_2^+ \rightarrow 2_1^+$) $= 0.06\mu_N^2$ reaches more than 50 % of the expected M1 strength of the $2^+_{1,ms}$ state in this region.

is $\frac{I(2_2^+\rightarrow 2_1^+)}{I(2_2^+\rightarrow 0_1^+)} = \frac{100(5)}{84(5)}$. As only level energies and branching ratios are known, except for the B(E2;$2_1^+ \rightarrow 0_1^+$) value, we have to estimate E2 transition rates for the 2-phonon candidates.

To do so, we start from the U(5)-limit of the IBA model. Here the ratio $R = \frac{B(E2;2_2^+\rightarrow 2_1^+)}{B(E2;2_1^+\rightarrow 0_1^+)}$ is given by $R = 2 \cdot \frac{N_B - 1}{N_B}$, where N_B is the number of bosons. In a drastic picture, assuming N=40 as closed shell, the number of bosons is N_B=2, thus R=1. This is the most conservative estimate and should be fulfilled in any case. As a consequence we assume B(E2;$2_2^+ \rightarrow 2_1^+$)=B(E2;$2_1^+ \rightarrow 0_1^+$)=19.6 W.u. Using the known experimental branching ratio we estimate a level lifetime of $\tau(2_2^+)$=1.25 ps. This situation describes the case of $\delta(2_2^+ \rightarrow 2_1^+) = \infty$, i.e., a pure E2 transition. As our goal is to determine this multipole mixing ratio, we will vary δ starting from large values, going towards $\delta = 0$. During this process the lifetime of the 2_2^+ state is taken as a constant. This is motivated by the fact that the physics interpretation of measuring M1 strength in the 2_2^+ state is a two-state mixing of the proton-neutron symmetric 2-phonon state and the 1-phonon $2^+_{1,ms}$ state. An increase of M1 strength must lead to a decrease of E2 strength in such a way that the lifetime stays constant. This interpretation was found to be a good approximation for all cases were M1 strength, driven by the proton-neutron MS degree of freedom, was found in the 2_2^+ state, e.g. in the ^{92}Zr nucleus or the N=30 region. It is important to mention, that for the determination of δ the absolute value of the $\left\langle 2_1^+ || E2 || 2_2^+ \right\rangle$ matrix element is not necessary as an input parameter, it will only effect the number of total counts. The multipole mixing ratio δ can be extracted from the known branching ratio and the shape of the differential cross section.

For a successful run of this experiment the choice of the right target material is crucial. In general, target material with higher Z leads to larger cross sections and enhanced two-step Coulomb excitation amplitudes. This is important as we have to maximize the influence of two-step excitations for large CM scattering angles. On the other hand one has to consider the kinematics of the reaction so that the given laboratory scattering angles, given by the MINIBALL DSSSD charged particle detector, are used most efficiently. We performed detailed Coulomb excitation calculations using standard targets ranging from ^{12}C up to ^{208}Pb and found the ^{120}Sn target to be the best choice for our purpose.

In Fig. 4 differential cross sections for the 2_2^+ state assuming different values of δ are shown as a function of the CM scattering angles which are covered by the DSSSD particle detector of MINIBALL. Assuming $\delta(2_2^+ \rightarrow 2_1^+) = 0$ the 2_2^+ state is excited via a 1-step Coulomb excitation from the 0^+ ground state only. Changing δ towards larger values increases the differential cross sections due to an increasing amount of 2-step processes $0_1^+ \rightarrow 2_1^+ \rightarrow 2_2^+$. From this analysis it follows that for large scattering angles the differential cross sections differ by more than a factor of two when comparing $\delta = 0$ with $\delta = \infty$. To extract δ, the statistics of the $2_2^+ \rightarrow 2_1^+$ γ-ray peak must be large enough so that a comparison of counting rates at regions of low and high CM scattering angles is possible. Here it is important to separate the recoiling target nuclei from the scattered beam particles in the DSSSD detector to identify the different CM regions. In the IS412 zinc experiments it was shown that this is already possible using a $2\frac{mg}{cm^2}$ thick ^{120}Sn target. However, as the energy width of scattered particles gets smaller for thinner targets, we performed our calculations using a $1\frac{mg}{cm^2}$ ^{120}Sn target. We will show in the following sections that the current MINIBALL setup at REX-ISOLDE allows, to some extent, the determination of whether or not mixing of proton-neutron symmetric and mixed-symmetric states is present.

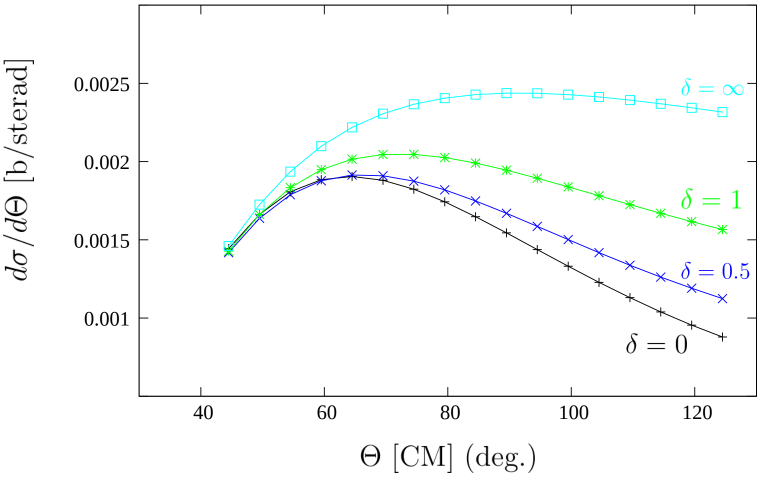

Figure 4: Differential cross section for the 2_2^+ state, calculated using 2.89 MeV/u ^{72}Zn beam on a 1 $\frac{mg}{cm^2}$ ^{120}Sn target. The plotted CM range corresponds to the range covered by the DSSSD detector, including shielding of the inner three strips.

3 Counting rate estimate

Based on the results of the IS412 ^{74}Zn experiment, realistic counting rate estimates can be given for the proposed experiment. The setup used in IS412 campaign was almost identical, furthermore the same target was used. Changing the beam from ^{74}Zn to ^{72}Zn will result in a slightly higher beam intensity. As a conservative estimate we perform our rate estimates using an increased intensity of 20 %. Our starting point are the yields in the ^{74}Zn experiment, obtained after 17h beamtime at ISOLDE. Apart from the 2_1^+ peak, 363(52) counts were collected in the $4_1^+ \rightarrow 2_1^+$ transition. Our rates then follow from corrections due to differences in the Coulomb excitation cross sections in ^{72}Zn relative to ^{74}Zn, differences in the relative γ-ray efficiency at MINIBALL and differences in the beam intensities.

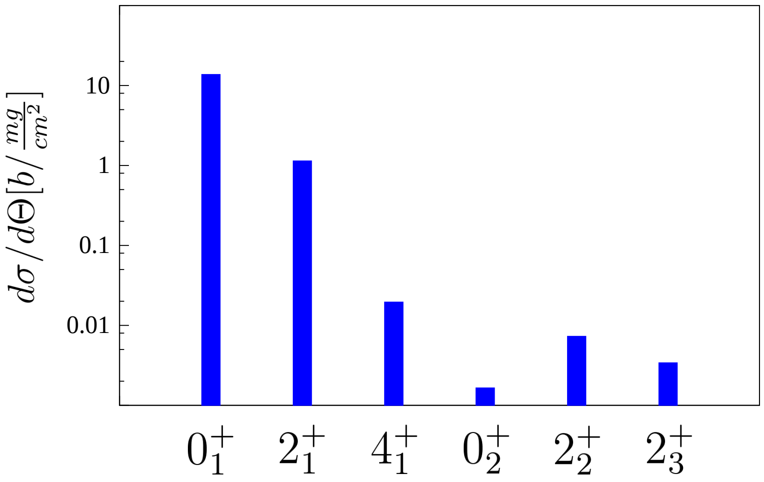

Figure 5: Calculated cross sections for the low-lying states in ^{72}Zn, using 2.89 MeV/u beam energy on a 1 $\frac{mg}{cm^2}$ ^{120}Sn target. The integration was performed using the angular range of the DSSSD detector, including shielding for the inner three annular strips.

In Fig. 5 the calculated cross sections for the low-lying phonon states in the ^{72}Zn nucleus are plotted. As the 2_3^+ state has not been discovered yet, the calculation of $\sigma(2_3^+)$ is based on several assumptions. From the systematics in the even-A zinc isotopes we assumed the 2_3^+ state to be located at E(2_3^+)=2.1 MeV, a branching ratio of $\frac{I(2_3^+\rightarrow 0_1^+)}{I(2_3^+\rightarrow 2_1^+)}$=0.15 and an E2 matrix element of $\left\langle 0_1^+||E2||2_3^+\right\rangle$=0.17 eb. Under these assumptions the spectroscopy of the 2_3^+ state will be possible in the proposed experiment. In the following table, calculated yields after 6 days of beamtime are given.

$I_i \rightarrow I_f$	Counts (after 6 days of beamtime)
$2_1^+ \rightarrow 0_1^+$	3.3×10^5
$4_1^+ \rightarrow 2_1^+$	5700
$2_2^+ \rightarrow 0_1^+$	700
$2_2^+ \rightarrow 2_1^+$	1070
$2_3^+ \rightarrow 2_1^+$	370

To demonstrate our sensitivity for the multipole mixing ratio $\delta(2_2^+ \rightarrow 2_1^+)$, in Fig. 6 calculated yields including statistical error bars are plotted, using integrated yields for 4 different CM regions. On condition that the beam intensities are comparable to the IS412 experiment, a determination of $\delta(2_2^+ \rightarrow 2_1^+)$ is possible and will allow a successful study of the anomalous behavior of the low-lying M1-strength distribution in even-A zinc isotopes. The influence of diagonal matrix elements $\left\langle 2_1^+||E2||2_1^+\right\rangle$ as well as $\left\langle 2_2^+||E2||2_2^+\right\rangle$ was checked in our Coulex calculations. Its influence is not completely negligible but will increase the error bars on δ by roughly 15 - 20 %.

Consequently, the beamtime request is:

Beam requirements				
Beam	Min. intensity	Target material	Ion Source	Shifts
^{72}Zn	2.2×10^6 ions/sec	UC$_x$	RILIS(W)	18 (data taking) +3 (set-up)

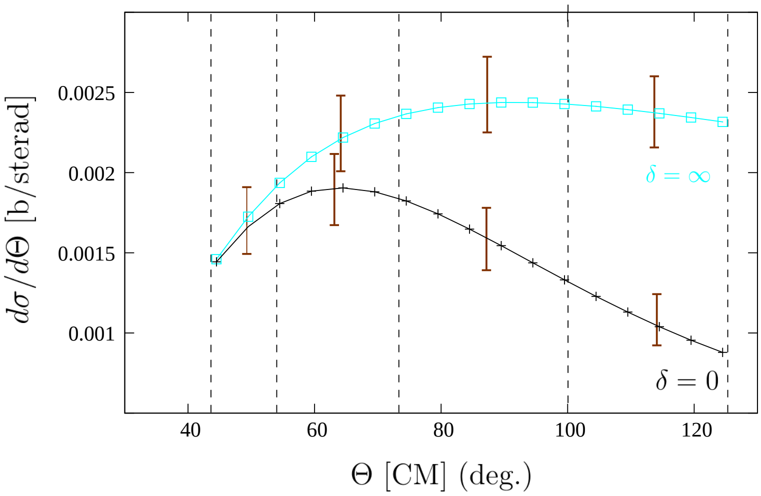

Figure 6: Differential cross section for the 2_2^+ state as in Fig. 4 for $\delta = 0$ and $\delta = \infty$. Calculated yields are shown for 4 different CM regions. The plotted error bars correspond to statistical errors $\Delta N = \sqrt{N}$ after 18 shifts of beamtime.

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