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COULOMB EXCITATION OF A NEUTRON–RICH ^{88}Kr BEAM — SEARCH FOR MIXED SYMMETRY STATES

J.Iwanicki*, N.Amzal, C.Andreoiu, A.Andreyev, R-D.Herzberg, G.Jones, G.Rainovski, Oliver Lodge Laboratory, Liverpool, UK
U.Bergmann, P.Butler, J.Cederkäll, S.Franchoo, T.Nilsson, T.Sieber, F.Wenander, B.Wolf, CERN, Geneva, Switzerland
W.Korten, E.Bouchez, Y.Le Coz, Ch.Theisen, CEA, Saclay, France
F.Becker, J.Gerl, S.Mandal, GSI Darmstadt, Germany
T.Czosnyka, J.Kownacki, P.Napiorkowski, M.Zielińska, HIL Warsaw, Poland
J.Eberth, J.Jolie, A.Scherillo, N.Warr, D.Weißhaar, IKP, Cologne, Germany
P.Van Duppen, M.Huyse, P.Mayet, IKS, Leuven, Belgium
F.Ames, D.Habs, O.Kester, LMU Munich, Germany
R. Krücken, T. Kröll, T. Faestermann, R. Gernhaeuser, TU Munich, Germany
D.Schwalm, H.Scheit, MPI Heidelberg, Germany
T.Davinson, Z.Liu, P.Woods, University of Edinburgh, UK
D.Jenkins, University of York, UK

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contact person: J.Iwanicki (`iwanicki@slcj.uw.edu.pl` , `iwanicki@ns.ph.liv.ac.uk`)

Abstract

We propose to use the ISOLDE/REX/MINIBALL/CD set-up to perform a Coulomb Excitation experiment with a ^{88}Kr radioactive beam. The motivation includes a search for *Mixed Symmetry* states predicted by the IBM–2 model, gathering more spectroscopy data about the ^{88}Kr nucleus and extending shape coexistence studies (performed previously[1] by the proposers for neutron-deficient Kr isotopes) to the neutron-rich side.

The proposed experiment will provide data complementary to the Coulomb Excitation of a relativistic ^{88}Kr beam proposed by D.Tonev et al. [1] for a *RISING* experiment.

* on leave from Heavy Ion Laboratory, Warsaw University

[1] Some of the co-authors of this proposal were involved in the Coulex experiment with ^{76,74}Kr beams performed at GANIL in June 2002.

A total of 12 days of beam time is necessary for the experiment, equally divided into two runs. One run with a 2.2 MeV/A beam energy on a ^{48}Ti target and a second run with the maximum available REX energy of 3.1 MeV/A on a ^{208}Pb target are requested.

Using either a UC_x or ThC_x fissioning primary target coupled with a plasma source by a cooled transfer line seems to be the best choice for the proposed experiment.

Introduction

The concept of post-acceleration of radioactive species produced by the ISOLDE facility opens the possibilities of unique studies using the world's widest range of unstable nuclei.

Succesful REX system operation giving around-Coulomb barrier energies of radioactive beams makes it, together with the ISOLDE source, an ideal tool for Coulomb Excitation studies of nuclei inaccessible by this method before.

Unbeatable ISOLDE yields of interesting nuclei are still not very high compared to stable beams delivered by other facilities, therefore high efficiency of γ detection provided by the Miniball array is necessary for performing radioactive beam Coulomb Excitation experiments.

Another element necessary for a succesful experiment of this kind is particle detection, which can be achieved by using the Silicon Strip CD detector.

In the following paper we propose to use the ISOLDE/REX/Miniball/CD system to study the properties of the unstable ^{88}Kr nucleus using the Coulomb Excitation method and measuring particle-γ coincidence.

1 Physical Background

1.1 *Mixed Symmetry* states predicted by the Interactive Boson Model (IBM)

The IBM model is based on a description of the nucleus as a system consisting of a core and valence nucleon pairs (of particles of the same type) forming bosons of spin zero or two. The variation of the original IBM model (IBM-2) introduces different boson pairs. The concept of *boson isospin* called *F-spin* is introduced to distinguish between a proton-proton boson (F projection equal $+1/2$) and a neutron-neutron boson (projection $-1/2$).

A given even-even nucleus has a fixed number of bosons of the two types, N_π and N_ν, respectively. The projection of the F-spin: $F_z = (N_\pi - N_\nu)/2$ is a good quantum number and a minimum value of the F-spin. The maximum value of F-spin is $F_{max} = (N_\pi + N_\nu)/2$.

Various descriptions of the model may be found in the literature, either in the original works of Arima and Iachello [2] or in textbooks (e.g. R.F.Casten [3] or W.Pfeifer [4]).

The model predicts a new class of collective states called *Mixed Symmetry* (*MS*) states. Their wave functions contain at least one pair of neutron and proton bosons that is antisymmetric with respect to the neutron-proton exchange.

Mixed Symmetry states may be recognized by their low excitation energy and weak E2 transitions to the symmetric states, while M1 transitions are expected to be enhanced.

Two basic types of such states may be identified this way: 1^+ states interpreted as the *scissors mode* excitation and 2^+_{MS} states, called "building blocks" of the *Mixed Symmetry* state structures [5].

1.2 Search for possible ***Mixed Symmetry*** states in the ^{88}Kr nucleus

As mentioned in the previous sub-section, *Mixed Symmetry* states are expected to appear in nuclear systems, which may be described as a core interacting with a proton boson and a neutron boson combination. The neutron number of 52 (just a pair above the N=50 shell) and the proton number of 36 (2 proton holes in the Z=38 sub-shell) give the boson combination necessary to form *MS* states. The energy of a possible *MS* state is predicted to be around 2 MeV and a 2_3^+ state of energy 2.216 MeV is present in the ^{88}Kr level scheme (see Figure 1).

The nature of an excited state may be interpreted more easily when electromagnetic matrix elements, coupling that state to the other states are estimated. Exotic excitations are expected to be weakly coupled to the symmetric states, by enhanced M1 and suppressed E2 transitions. E2/M1 mixing ratios of the $2_i^+ \to 2_1^+$ may be determined and compared with the values expected for *Mixed Symmetry* states. Strong M1 component of the the mentioned transition will also increase the $\frac{2_i^+ \to 2_1^+}{2_i^+ \to 0^+}$ branching ratio.

Moreover, if the experimental sensitivity allows for that, the deformation parameters of the states may be determined and compared. Possibilities of finding these answers depend only on the statistics collected during the Coulomb Excitation run.

Such an experiment with the ^{88}Kr beam is within the reach of REX-ISOLDE. A standard UC$_x$/graphite target coupled to an ISOLDE MK7 ion source gives high yields ($\approx 1.8 \times 10^8/\mu$C [6]) and a high beam purity for krypton (due to the water-cooled transfer line) make such an experiment very feasible. Also the trapping/ionizing process in REXTRAP/REXEBIS system, preparing the beam for post-acceleration, was successfully tested[2].

2 Experimental goals

Our counting rates calculation (see Table 1) shows that the available beam intensity is sufficient to observe transitions between first five (0^+, 2_1^+, 2_2^+, 4_1^+, 2_3^+) states (see Figure 1) within a reasonably long experimental run. This will allow one to determine E2 and M1 matrix elements linking these states. To reach this goal we need a high energy (3.1 MeV/A) beam excited on a heavy (preferably ^{208}Pb) target.

The minimum number of matrix elements necessary to describe this system is 7 transitional (5 × E2 + 2 × M1 transitions) + at least one diagonal matrix element ($\langle 2_1^+ \| E2 \| 2_1^+ \rangle$), which gives 8 parameters to be fitted using 5 experimental data points. Additional data can be obtained by performing another experiment with different beam energy on a significantly lighter (e.g. ^{48}Ti or ^{58}Ni) target.

Measuring the matrix elements listed above will give experimental indications about the interpretation of the 2^+ states as well as various spectroscopic data like lifetimes, E2/M1 mixing ratios and branching ratios for the $2_{2,3}^+$ state deexcitation.

Depending on the completeness and precision of the obtained matrix element set, a quadrupole deformation parameters of the 2_1^+ state may be determined in a model-independent way using the *Quadrupole Sum Rules* method (see [7] or a brief description in [8]). Possible shape coexistence phenomena may be studied this way.

Calculations of the gamma yields show (see Section A.5 and Figure 3) that changing the sign of the diagonal matrix element of the 2_1^+ state may change the expected γ yield by about 20% for the current particle detector angular coverage. The sensitivity may be increased up to 30% if the coverage is shifted into higher angles.

[2] Private information from F.Ames.

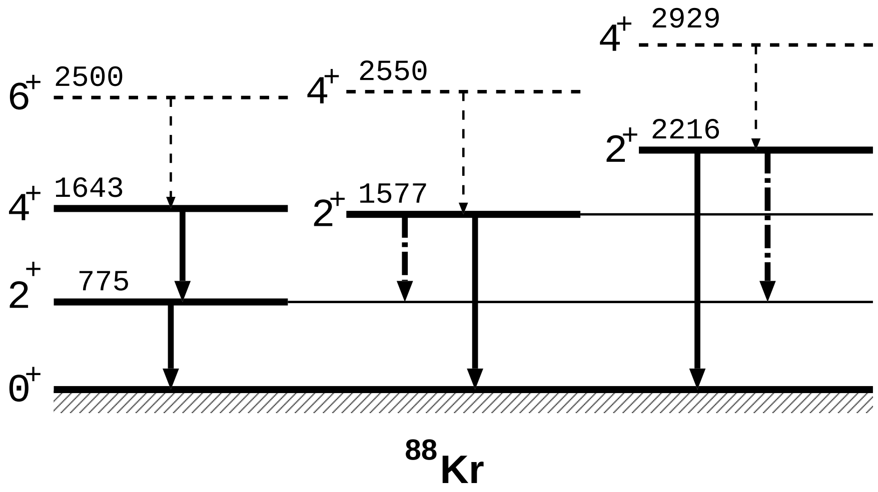

Figure 1: Excited states of the ^{88}Kr nucleus taken into account for Coulomb Excitation calculations. Dashed line states and transitions are "buffer" ones (see Section A.1 for explanation). Thick arrows represent transitions expected to be measured in the proposed exepriment. Dot-dashed arrows denote mixed E2/M1 transitions.

2.1 Comparison to the relativistic Coulomb Excitation experiment

Low and high energy Coulomb Excitation differ by two basic facts:

- Relativistic Coulex, due to a short interaction time, is a one-step process, so only 2^+ states are expected to be populated in this case;
- High energy states are difficult to reach with low energy Coulex, which is not a problem in the high energy experiment.

Both methods may provide B(E2) values for the transitions from 2^+ states, while a high energy experiment will give no information about 4^+ states so this excludes applying the Quadrupole Sum Rules method to the high energy data.

Methods of low energy Coulomb Excitation data analysis are well established, while relativistic Coulex analysis is still being developed. Possible comparison of the results will be important.

3 Summary of experimental simulations

This Section summarizes detailed descriptions presented in Appendix A.

Two targets were finally chosen to perform ^{88}Kr beam excitation: ^{48}Ti target for the 2.2 MeV/A beam and ^{208}Pb target for the 3.1 MeV/A beam. A ^{58}Ni target, giving larger scattering angles, was also considered.

Multi-step Coulomb Excitation calculations, described in more detail in Appendix A, show that measuring 2_3^+ state deexcitation γ-rays is within the range of REX-ISOLDE/MINIBALL system. The results, obtained after integration over 1mg/cm^2 targets, are presented in Table 1. Further target optimisations show that higher yields may be obtained for approx. 2 mg/cm^2 Ti target and 5 mg/cm^2 Pb target (see Figure 2).

It is expected to achieve about 20% sensitivity to the quadrupole moment sign of the 2_1^+ state (see Figure 3).

Table 1: Chosen transition yields after Coulomb Excitation and corresponding count numbers calculated for 1mg/cm^2 targets.

transition	^{48}Ti (2.2 MeV/A)	^{58}Ni (2.2 MeV/A)	^{208}Pb (3.1 MeV/A)
Coulex yield $\left[\frac{\text{mb}}{\text{sr}}\frac{\text{mg}}{\text{cm}^2}\right]$			
	backward kinematic solution		
$2_1^+ \to 0^+$	7.1	4.2	
$4^+ \to 2_1^+$	0.08	0.03	
$2_2^+ \to 0^+$	0.006	0.002	
$2_2^+ \to 2_1^+$	0.002	0.0005	
$2_3^+ \to 0^+$	0.006	0.002	
$2_3^+ \to 2_1^+$	0.0017	0.0005	
	forward kinematic solution		
$2_1^+ \to 0^+$	25.	21.	57.
$4^+ \to 2_1^+$	0.18	0.11	0.37
$2_2^+ \to 0^+$	0.017	0.007	0.02
$2_2^+ \to 2_1^+$	0.005	0.002	0.005
$2_3^+ \to 0^+$	0.017	0.007	0.018
$2_3^+ \to 2_1^+$	0.005	0.002	0.005
expected number of photopeak counts (per 8 h shift)			
	backward kinematic solution		
$2_1^+ \to 0^+$	$1.7\cdot10^4$	$8.5\cdot10^3$	
$4^+ \to 2_1^+$	200.	76.	
$2_2^+ \to 0^+$	10.	2.7	
$2_2^+ \to 2_1^+$	4.	1.	
$2_3^+ \to 0^+$	10.	2.7	
$2_3^+ \to 2_1^+$	3.	0.7	
	forward kinematic solution		
$2_1^+ \to 0^+$	$6.1\cdot10^4$	$4.3\cdot10^4$	$3.2\cdot10^4$
$4^+ \to 2_1^+$	440.	218.	210.
$2_2^+ \to 0^+$	28.	10.	7.
$2_2^+ \to 2_1^+$	12.	4.2	3.
$2_3^+ \to 0^+$	28.	10.	7.
$2_3^+ \to 2_1^+$	8.	2.8	1.9

According to the estimates, to achieve 5% statistic accuracy for the 2_3^+ state deexcitations, one needs to collect data for about 15 eight-hour shifts. For measuring complete set of matrix elements, two such runs, with different targets and beam energies, are needed.

Beam requirements				
Beam	Min. intensity	Target material	Ion Source	Shifts
^{88}Kr	3×10^8 ions/sec	UC$_x$	MK7	2×15 $+2 \times 3$ (tests)

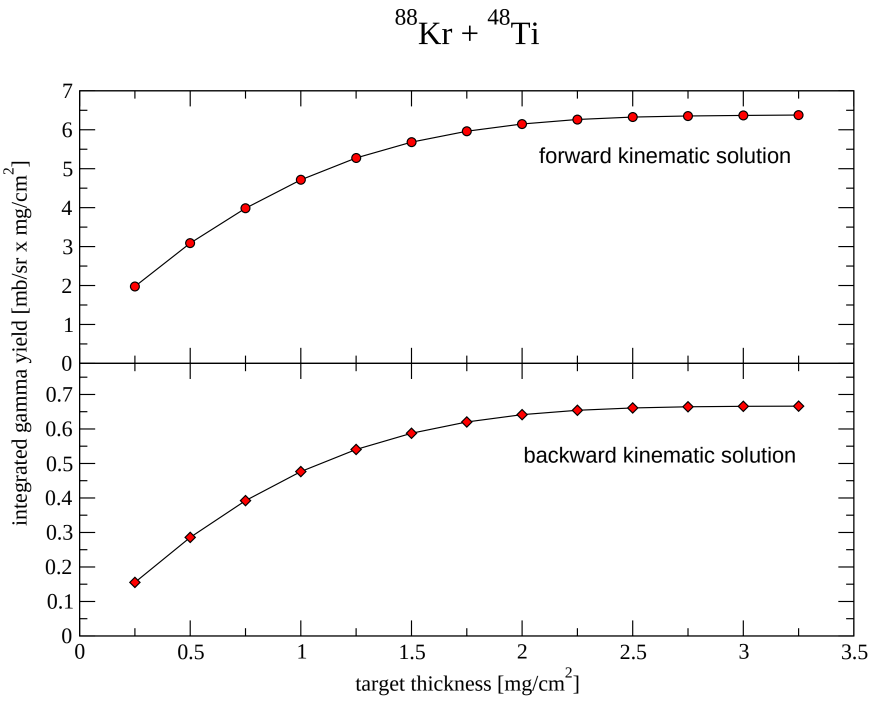

Figure 2: $2_1^+ \rightarrow 0^+$ yield expected from a target of given thickness. Beam energy 193 MeV (2.2 MeV/A), particle detection range: $20° \div 30°$.

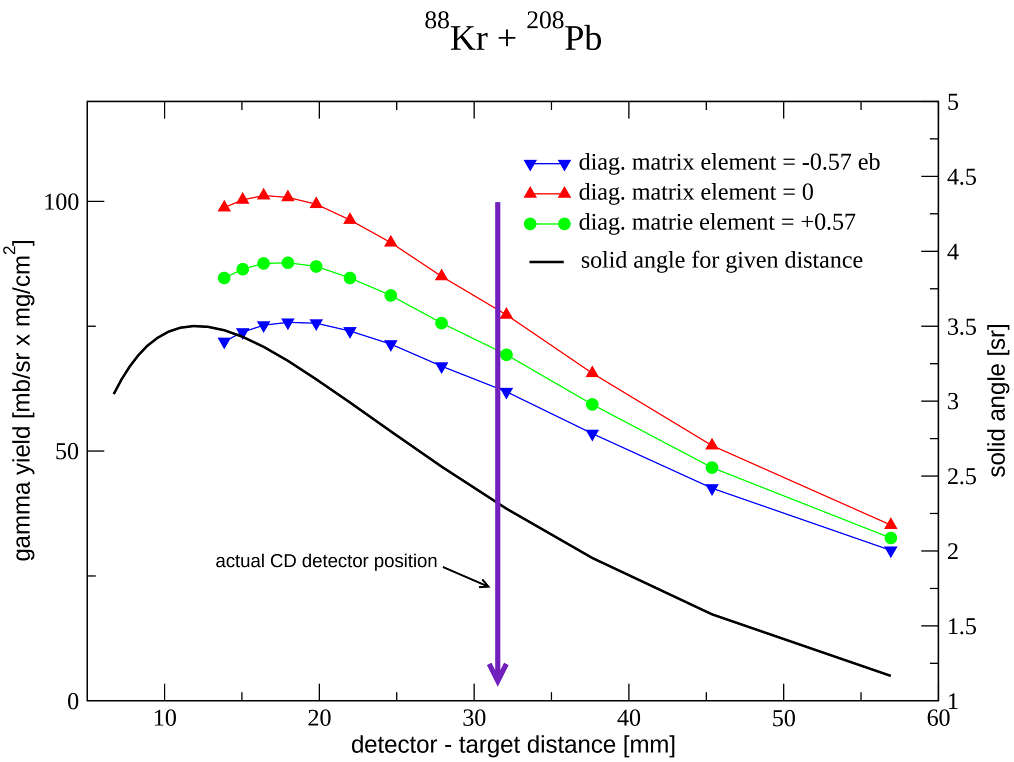

Figure 3: Gamma yields of the $2_1^+ \rightarrow 0^+$ transition after excitation on the lead target. CD detector is placed at various positions marked along the X axis. The three lines correspond to different values of the 2_1^+ diagonal E2 matrix element. CD detector solid angle dependence is plotted also and it's values are marked along right Y axis.

Table 2: Coulomb Excitation *safe energies* and maximum scattering angles.

Target	*safe* $^{88}_{36}$Kr beam energy [MeV]	[MeV/A]	Maximum scattering angles for inverse kinematics
$^{24}_{12}$Mg	205	2.33	15.8°
$^{48}_{22}$Ti	214	2.43	33.1°
$^{58}_{28}$Ni	237	2.69	41°
$^{98}_{42}$Mo	253	2.88	—
$^{208}_{82}$Pb	337	3.83	—

A Appendix: Details of the Coulomb Excitation cross section calculations

Coulomb Excitation calculations were made using the GOSIA code [9].

A.1 Assumptions

Three 2^+ states were taken into account for cross section calculations. The ground state band is assumed to consist of 0^+_1, 2^+_1 and 4^+_1 states. For the proper description of Coulomb excitation populations of considered states, 2^+_2, 2^+_3 and 4^+_1 ones are coupled to another 4^+ (or 6^+ in g.s.b) *buffer* state. A set of necessary electromagnetic matrix elements coupling these states was assumed.

Figure 1 shows the considered level scheme.

A.2 Estimation of the matrix elements values

The B(E2) value for the coupling of the 2^+_1 state was assumed to follow the Grodzin's formula and the adopted value is equal to 0.48 eb.

The 2^+_2 and 2^+_3 states of 1.577 MeV and 2.216 MeV energies were taken into account and assumed to be coupled to the ground state by a 0.15 eb E2 matrix element. These are the typical values supported by the simple calculations made with Ritsschil implementation of the Shell Model and more advanced studies performed for neighbouring nuclei [1, 10]

Other states of spin 4 and 6 were assumed to form a rotational band with the respective 2^+ states and the remaining matrix elements were assumed to follow the Rotational Model predictions.

A.3 Targets

Performing measurements on different targets is essential when dealing with multiple Coulomb Excitation, when the number of matrix elements involved demands more experimental data coming from excitations performed at different conditions.

Safe energies and maximum scattering angles are summarized in Table 2.

As a first choice, three metallic targets were considered (^{48}Ti, ^{58}Ni and ^{208}Pb) and detailed calculations show that the Ti and Pb targets should be finally used (see Table 1).

Coulomb Excitation cross sections for 1 mg/cm^2 target thickness and angular range 15.5 to 51.5 degrees.

The *GOSIA* code can use the assumed set of matrix elements to simulate an experiment.

Population equations are solved to derive excitation amplitudes for every state defined in the input and then deexcitation gamma yields are calculated. The procedure is performed in energy and particle scattering angle space. After an integration, gamma yields for every assumed transition are calculated, taking into account target thickness and particle detection geometry. The CD geometry used in previous runs, giving the 15.5° to 51.5° angular coverage, is assumed.

The yields can then be easily used to calculate either differential cross sections for every transition or expected counting rates.

The results obtained for ^{88}Kr excited on 1 mg/cm^2 targets of Ti, Ni and Pb targets are presented in Table 1. Assumed target thicknesses are not optimal and this will be discussed later in Section A.4.

Assumptions made for counting rates calculation

ISOLDE yields of noble gases were measured recently ([6]) for the plasma-discharge ion source connected to the UC$_x$/graphite primary target with a water-cooled transfer line, which seems to be an optimal configuration for krypton isotopes production until an ECR-type source becomes available.

The quoted yield is 1.8×10^8 ^{88}Kr ions per 1 μC of the primary beam. Assuming a primary beam of about 2μA, this gives 3.6×10^8 ions/sec.

REX is able to deliver more than 1% of the ISOLDE yield to the target, which lets us assume the beam current to be 3.6×10^6 pps (on the target).

Miniball efficiency around 800 keV energy is assumed to be $\epsilon_{MB} \approx 15\%$. For the high energy $2^+_{2,3} \rightarrow 0^+$ transitions the efficiency is assumed to be equal to 10%.

Both assumptions concerning REX and MINIBALL efficiencies are conservative, real numbers are expected to be higher.

Table 1 shows calculated yields and expected counting rates for the assumed targets. For light targets, values for forward and backward kinematic solutions are listed. The lower REX energy (2.2 MeV/A) is assumed for titanium and nickel targets, while the upgraded energy (3.1 MeV/A) is taken for the Pb target.

A.4 Target thickness optimization

The Coulomb Excitation cross section depends on energy. A thicker target gives more γ-yield, but due to beam slowing down in the target, the yield gain is smaller when the target is already thick.

Figures 2 show this dependence calculated for 775 keV transition with Ti target .

One can notice that target thicknesses of 2 mg/cm^2 give significant increase of Coulomb Excitation yields compared to the values shown in Table 1. For the $2^+_1 \rightarrow 0^+$ transition it is possible to increase the cross section and counting rates by a factor of 1.5 for Ti target.

The same calculation for the 1 and 5 mg/cm^2 Pb target and other considered transitions show:

transition	increase
$2^+_1 \rightarrow 0^+$	3×
$4^+ \rightarrow 2^+_1$	2×
$2^+_{2,3} \rightarrow 0^+$	4×
$2^+_{2,3} \rightarrow 2^+_1$	4×

A.5 Discussion of the $2^+_1 \rightarrow 0^+$ transition γ-yields sensitivity

The angular coverage of the CD detector depends on its active area, minimum and maximum radii and the detector-target distance. A set of distances was assumed and the yield integration was performed between minimum and maximum angles corresponding to these distances. A recently used geometry gave $\Theta_{min} = 15.5°$ to $\Theta_{max} = 51°$ angular coverage. Results of the simulation for a 1 mg/cm^2 Pb target and 3.1 MeV/A beam are presented in Figure 3.

One may notice, that the maximum yield is obtained for a detector–target distance $d = 18$ mm, which corresponds to $\Theta_{min} = 24°$.

The maximum in this dependence is caused both by Coulomb excitation and solid angle dependence on the detector–target distance d. However, the $\sigma_{Coulex}(d)$ relation is not a trivial solid angle dependence, which is also plotted on Figure 3.

Absolute cross section for observing the $2_1^+ \rightarrow 0^+$ transition depends on the diagonal matrix element $\langle 2_1^+ \| E2 \| 2_1^+ \rangle$. For the estimated value of this matrix element, changing its sign gives about 20% difference in the observed γ-yield. The difference grows above 30% if the detector–target distance is reduced to about 14 mm, giving an angular coverage 30° to 72°. The γ yield dependence on the diagonal matrix element sign is plotted in the Figure 3 also.

For the summary of experiment simulations and the requested beam time see Section 3, page 4.

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