CERN-INTC-2017-002 / INTC-CLL-027
09/01/2017

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Clarification to the ISOLDE and Neutron Time-of-Flight Committee

Determination of the $B(E3,0^{+}\text{->}3^{-})$ strength in the octupole-correlated nuclei ^{142,144}Ba using Coulomb excitation

23/12/2016

M. Scheck[1], D.T. Joss[2], A. Andreyev[3], C. Barton[3], A. Blazhev[4], P.A. Butler[2], J. Cederkäll[6], D. Cline[7], T.E. Cocolios[8], M. Danchev[9], P. Van Duppen[10], L.P. Gaffney[10], R. Gernhäuser[11], K. Gladniski[9], A. Görgen[12], T. Grahn[13,14], P.T. Greenlees[13,14], M. Guttormsen[12], A. Jungclaus[15], K. Hadynska-Klek[16], R.-D. Herzberg[2], M. Huyse[10], A. Ignatov[5], J. Iwanicki[16], D.G. Jenkins[3], J. Jolie[4], R. Julin[13], N. Kesteloot[10], T. Kröll[5], R. Krücken[11], A.-C. Larsen[12], M.T. McEllistrem[18], K. Moschner[4], D. Mücher[11], P. Napiorkowski[16], G. O'Neill[2], R.D. Page[2], J. Pakarinen[13,14], D. Pietak[16], P. Rahkila[13,14],G. Rainovski[9], P. Reiter[4], M. von Schmid[5], M. Seidlitz[4], S. Siem[12], G.S. Simpson[1], J. Srebrny[16], P. Thirolf[19], M. Thürauf[5], D. Voulot[8], R. Wadsworth[3], N. Warr[4], F. Wenander[8], K. Wimmer[20], K. Wrzosek-Lipska[16], C.Y. Wu[17], S.W. Yates[18], and M. Zielinska[21]

1 University of the West of Scotland
2 University of Liverpool
3 University of York
4 University of Cologne
5 TU Darmstadt
6 Lund University
7 University of Rochester
8 CERN-ISOLDE
9 Sofia University
10 KU Leuven
11 TU München
12 University of Oslo
13 University of Jyväskylä
14 Helsinki Institute of Physics
15 Institudo de Estructura de la Materia Madrid
16 HIL University of Warsaw
17 Lawrence Livermore National Laboratory
18 University of Kentucky
19 LMU München
20 Central Michigan University
21 CEA Saclay

Spokesperson(s): M.Scheck (marcus.scheck@uws.ac.uk)
D.T.Joss (dtj@ns.ph.liv.ac.uk)
Local contact: L.P.Gaffney (liam.gaffney@cern.ch)

Letter of Clarification as requested in the minutes of the INTC meeting #54, concerning document: INTC-SR-54, INTC-P-348 (Experiment IS553)

In the minutes of the INTC meeting #54 a letter of clarification is demanded to address the questions of beam quality, the reduction of error achievable and how this relates to theoretical calculations.

First of all, it should be mentioned that the measurements of the B(E3, $0^+ \rightarrow 3^-$) strength at Argonne National Laboratory (ANL) was in the isotopes ^{144}Ba and ^{146}Ba and not, as stated in the INTC minutes, in ^{142}Ba and ^{144}Ba. At the CARIBU facility at ANL, the productions yields for ^{142}Ba are too low to allow a Coulomb-excitation experiment aiming at E3 excitation strength. The capability of ISOLDE to provide this isotope in sufficient quantities together with HIE-ISOLDE for post-acceleration is unique world-wide. The scientific motivation for the study of this particular nucleus and the impact on nuclear models of the experimental campaign is provided below.

The question of beam quality:

1) Beam purity: As stated in our original proposal, a strong contamination of the beam by cesium isobars can be expected. We intend to employ RILIS to purify the measured spectra from events stemming from this (and possible other) beam contaminant(s). We will use 50% of the beam-time with laser ionization to enhance its yield at the secondary Coulomb-excitation target and 50% to use the surface ionized barium nuclei only. Since the original proposal the RILIS group has increased the laser-ionization efficiency from 10 to 25%. Renormalizing the barium γ-ray yields in the two modes allows for a subtraction procedure of the γ-ray spectra containing only the contaminant lines. With this, one can obtain a pure γ-ray spectrum containing only the transitions of the barium isotope of interest is obtained. Consequently, as long as the contaminant to isotope of interest rate does not exceed the factor 1:100, for which the damage caused by the beam particles in the employed particle detector would start to exceed an acceptable limit, the beam contaminants do not pose a major problem. In fact experimental information about the major contaminant ^{144}Cs is sparse and we will be able to obtain new spectroscopic data.
2) Beam intensity: Using the initial Ba yields as given on the ISOLDE web site (from SC), we assumed a transmission efficiency from mass-separation, charge-breeding and through HIE-ISOLDE of 2%, a number based on the previous experience we have collected during experiments employing REX-ISOLDE. From these estimates we obtain intensities of 2.2 x 10^6 nuclei/s (^{142}Ba) and 2.0 x 10^5 (^{144}Ba) at the secondary Coulomb-excitation target. For ^{144}Ba this yield is 25 times higher than the 8000 nuclei/s that the experiment at ANL had.

The question of uncertainties:

1) ANL experiment: The large uncertainty in the Coulomb-excitation experiment at Argonne has two major reasons. The low statistics, which results in a statistical error exceeding 30% and a systematic uncertainty related to uncertain Coulomb-excitation paths, i.e. correlations to other matrix elements. The ANL experiment employed solely a ^{208}Pb target. However, in Coulomb excitation the proton number (Z) of the scattering partner strongly influences the probability for one-step or multi-step excitation, which leads to ambiguities if the set of variables given by the nuclear matrix elements is under-determined by an insufficient number of experimental observables (γ-ray yields, branching ratios, etc.)

2) Proposed ISOLDE experiment: In the original proposal (INTC-P-348), we used conservative estimates for the matrix elements involved in the Coulomb-excitation process to calculate the yield for the critical $3^- \rightarrow 2^+$ γ-ray transition depopulating the 3^- level. The beam-time request was adjusted to guarantee a yield, which results in a statistical error of 6% or less. Considering the previously mentioned subtraction procedure, the statistical error has to be multiplied by a factor corresponding to the square root of 2 (assuming 50/50 ratio of contaminants). The above mentioned systematic uncertainty in disentangling the one-step and multi-step Coulomb-excitation paths is considered in the proposed use of two scattering targets with strongly differing Z values (Ni: Z= 28 with preference for $0^+ \rightarrow E3 \rightarrow 3^-$ one-step excitation, Pb: Z=82 with enhanced multi-step excitation, e.g. $0^+ \rightarrow E2 \rightarrow 2^+ \rightarrow E3 \rightarrow 3^-$) and a segmentation of the data in terms of center-of-mass scattering angle using the granularity of the CD detector. This approach guarantees an over determination of the set of unknown matrix elements and reduces the statistical error. Furthermore, the influence of the error of the lifetime of the first 2^+ and 4^+ levels, which are used to normalize the number of beam-particles is reduced or even eliminated. In a worst-case scenario these errors (3.5%) would fully enter the final result. Based on the experience that our collaboration has gained during the analysis of the IS475 experiment (L.P.Gaffney at el., Nature 497, 199 (2013)) with similar experimental conditions and similar observed γ-ray yields, we can estimate the influence of other sources of uncertainty to be less of the order 2%. Additional sources of uncertainty include the error in determination of the relative γ-ray efficiency, the energy distribution of the beam particles, and target thickness. Too summarize, in a conservative estimate, we expect a worst-case scenario of 15% relative uncertainty for the extracted B(E3) strength.

The question how the result and its error relate to theory:

Status of theory at the time of the original proposal (2011): In the original proposal we quoted the theoretical values from calculations performed by the Madrid group using the BCP density functional approach and Hartree Fock Bogoliubov mean-field calculations with the GOGNY D1S interaction (L.M.Robledo et al., PRC 81, 034315 (2010)). While these calculations predict a similar B(E3) value for ^{142}Ba (~10W.u.), they differ for ^{144}Ba (BCP: ~10 W.u.; HFB: ~ 20 W.u.). Meanwhile the Madrid group has improved its HFB beyond mean-field formalism by the inclusion of particle number and angular momentum projection, which removes the need to rely upon the rotational formula to compute transition strengths. A new calculation using this improved energy density functional approach employing the Gogny D1S interaction resulted for ^{142}Ba in a B(E3) value of

12 W.u. (L.M.Robledo, private communication) and 25 W.u. for ^{144}Ba (R.N.Bernard et al., PRC 93, 061302(R) (2016)). The latter value is two times lower than the value extracted from the ANL experiment of 48^{+25}_{-34} W.u. (B.Bucher et al., PRL 116, 112503 (2016)), however still within the large errors. In fact the large error bars of the experimental value render this value as benchmark for the theoretical calculation almost obsolete. Interestingly, these new calculations indicate that ^{148}Ba is the nucleus with the strongest octupole correlations in this mass region and not ^{144}Ba as previously thought. However, at present it is not possible to measure E3 values for ^{148}Ba.

An alternative approach in an alpha-cluster model (e.g., T. Shneidman et al., EPJA 25, 387 (2005)) calculates for ^{144}Ba an octupole moment Q_3, which is compatible with the currently measured B(E3) value. Triggered by the prospect of reliable B(E3) the Dubna group started to recalculate the A~144 mass region. Within their cluster approach a similar B(E3) strength for ^{142}Ba can be expected (T.Shneidman, private communication), while the mean-field based models predict a lower B(E3) value due to a vanishing octupole moment in the ground state (e.g., see Z. Wei et al., Chin. Phys. C34, 1094 (2010)).

It can be seen that the evolution of B(E3) strength along the isotopic chain determined from the experimental values for ^{142,144}Ba (from the proposed experiment) together with the value for ^{146}Ba, measured by the Argonne led collaboration, will serve as benchmark to distinguish between the classes of models. The ^{146}Ba value, so far unpublished, is in the similar to the value for ^{144}Ba extracted from the ANL measurement but its errors will be smaller. Furthermore, the systematic evolution of the B(E3) strength will allow the models to determine, whether there are strong octupole correlations in the ground states of these nuclei, which is of utmost importance for clarifying whether atoms containing the odd-mass neighbors are suitable candidates to search for CP-violating effects. This task demands experimental values with relative errors less than 15% as will be provided by the proposed experiment.