EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

for HIE-ISOLDE Proposal P-368

Solving the shape conundrum in ^{70}Se

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Abstract: This Letter of Clarification presents full simulations of the multi-step Coulomb-excitation experiment using the ^{208}Pb(^{70}Se,^{70}Se*)^{208}Pb* reaction at a safe energy of 5.5 MeV/u. We aim at a precise measurement of the $\langle 2_1^+ \parallel \hat{E}2 \parallel 2_1^+ \rangle$ diagonal matrix element as well as gaining information on additional matrix elements.

Requested shifts: 15+3 shifts (fifteen shifts for an uncertainty of approximately ± 0.06 eb in the $Q_S(2_1^+)$ value and three shifts for beam tuning)
Installation: [MINIBALL + CD at [$17^\circ, 53^\circ$] forward angles]

1 Motivation

This proposal was defended at the INTC meeting last November 2012 and the referees found the physics case interesting and relevant. Full simulations of the experiment were requested to ascertain whether a definite value for the spectroscopic quadrupole moment of the 2_1^+ state can be obtained. The full referees' report is provided below:

CERN-INTC-2012-067, INTC-P-368, Solving the shape conundrum in ^{70}Se.

"It is proposed to determine the sign and the magnitude of the spectroscopic quadrupole moment of the first 2^+ state in ^{70}Se, with the aim to provide a definite answer on the shape of this nucleus. The proposed method is the multi-step safe Coulomb excitation with the MINIBALL setup. Besides that, other transition matrix elements of higher-lying states can be obtained, to yield more spectroscopic information of this nucleus. This information is important to understand shape coexistence phenomena in this region, especially that discrepancies between experiment and theory are present. The physics case was found interesting and relevant. It was, however, not clear, whether the proposed experiment can provide definitive values for the $E2$ matrix elements from which the shape of ^{70}Se can be determined. Therefore, full simulations of the experiment should be performed and a **Letter of Clarification** should be provided clarifying this point, before the shifts can be awarded. Thus, at this point, the Committee has **not recommended** any shifts for the approval of the Research Board."

2 Experimental Details and Full Simulations

The main goal of this proposal is the accurate determination of the spectroscopic quadrupole moment for the 2_1^+ state in ^{70}Se, which currently spans in the range $-0.15 \lessapprox Q_S(2_1^+) \lessapprox +0.8$ eb [1, 2]. To achieve this goal, we propose the study of the ^{208}Pb(^{70}Se,^{70}Se*)^{208}Pb* reaction at 5.5 MeV/u. This bombarding energy makes full use of the potential for Coulomb-excitation measurements at HIE-ISOLDE. We use a heavy target to enhance the reorientation effect (see Eq.(25) in Ref. [3]). Pure ^{70}Se beams have previously been delivered with an average yield of 10^4 ions/s at REX-ISOLDE, using SeCO$^+$ molecules and breaking them in the electron beam ion source (EBIS) [2]. Nonetheless, RIB yields are expected to gain approximately a factor of two with the upgrade to 2 GeV proton energies as well as a factor of three with the proton-intensity upgrade at HIE-ISOLDE; moreover, this gain in yield comes with the same damages in the production target for a given intensity [4]. More experimental details regarding the MINIBALL + CD set up are given in our original proposal and henceforth, we focus on the full simulations and prospects of this experiment.

Coupled-channel GOSIA calculations [5] based on the semiclassical approximation of Coulomb-excitation theory [6] have been performed in this work to simulate the γ-ray integrated yields for the de-excitation of the 2_1^+ and other high-lying states in ^{70}Se. The 385 MeV bombarding energy is below the Coulomb barrier at about 427 MeV and, assuming Cline's prescription of 5.0 fm for the separation between nuclear surfaces in heavy-ion reactions [7], safe for laboratory scattering angles $\theta_{lab} \leq 65°$. A large Sommerfeld parameter of $\eta = 187 \gg 1$ validates the semiclassical approximation [6] and a small adiabaticity parameter of $\xi = 0.32$ enhances the population of the 2_1^+ state at 944.5 keV in ^{70}Se. The γ-ray integrated yields for five days of beam time as a function of scattering angle in the laboratory frame and at plausible $Q_S(2_1^+)$ values [1] are presented in Fig. 1. These calculations consider the matrix elements extracted from [1, 8], a conservative average yield of 10^4 ions/s, an efficiency with add-back of 8% at 1332 keV for the MINIBALL array (a slightly larger efficiency is expected for the 944.5 keV γ-ray) and a 2-mg/cm^2 ^{208}Pb foil. The finite size of the 24 crystals composing the MINIBALL array as well as the γ-ray absorption in the aluminum absorbers are also considered through the attenuation coefficients for the closest geometry of the MINIBALL array; that is, 0.1 cm, 3.5 cm, 7.8 cm and 12.877 cm for the the inner radius, outer radius, length of each crystal and target-detector distance, respectively.

The integrated yields for six sets of angular ranges (vertical dashed lines in Fig. 1) have been summed up and the angular distributions illustrate the sensitivity to determine $Q_S(2_1^+)$. The cross sections strongly depend on $Q_S(2_1^+)$, being larger as the shape becomes more oblate, and peaking at $\theta_{lab} \approx 40°$. Assuming an average yield of 10^4 ions/s, total numbers of 9,200, 8,500, 7,700 and 7,200 counts are calculated for $Q_S(2_1^+)$ values of +0.8, +0.4, 0.0 and -0.2 eb, respectively. Contributions to these integrated yields from higher-lying states are calculated to be negligible, even considering $\langle 2_2^+ \parallel \hat{E2} \parallel 2_1^+ \rangle$ values ranging from 0.3-0.8 eb; a large $\langle 2_2^+ \parallel \hat{E2} \parallel 2_1^+ \rangle = 0.565$ eb has been predicted by Hinohara and collaborators [9]. Comparatively, the previous ^{70}Se reorientation-effect measurement at 2.94 MeV/u yielded an area of 139(13) counts for the 2_1^+ peak [2]. Five days of beam time will, therefore, provide a measurement of $Q_S(2_1^+)$ with an approximately ± 0.06 eb statistical uncertainty given by the error bars in Fig. 1. It is important to outline here that the six-times increase in RIB yields at HIE-ISOLDE are not considered in the aforementioned count rates. The measured integrated yields can be normalized to the accurate $B(E2, 2_1^+ \rightarrow 0_1^+) = 20.4(9)$ W.u. in ^{70}Se [1, 10] and the Rutherford cross sections in order to minimize experimental unknowns in the setup, such as systematic uncertainties in the absolute beam energy, target thickness, particle detection efficiency and dead time of the data-acquisition system. Uncertainties in the γ-ray efficiency and the 4.4% error in the $B(E2, 2_1^+ \rightarrow 0_1^+)$ value will also be considered, although the statistical uncertainty will dominate the quoted error on this measurement. A recent plunger experiment at MSU will soon provide an additional lifetime measurement for the 2_1^+ state in ^{70}Se and probably yield a more accurate weighted average [11].

Another exciting prospect regards the population of higher-lying states. With a total cross section of tens of mb, we expect to gain information on transitional matrix elements relating the 2_2^+, 4_1^+, 4_2^+ and 6_1^+ states. Assuming again a yield of 10^4 ions/s and five days of beam time, about 250 counts are calculated for the population of the 4_1^+ state at 2038.1 keV, which would yield a measurement of the $B(E2; 4_1^+ \rightarrow 2_1^+)$ value with an $\approx 8\%$ uncertainty. Only about 100 counts are calculated for the population of the 2_2^+ state at 1599.9 keV through the favorable two-step process; the one-step $0_1^+ \rightarrow 2_2^+$ $E2$

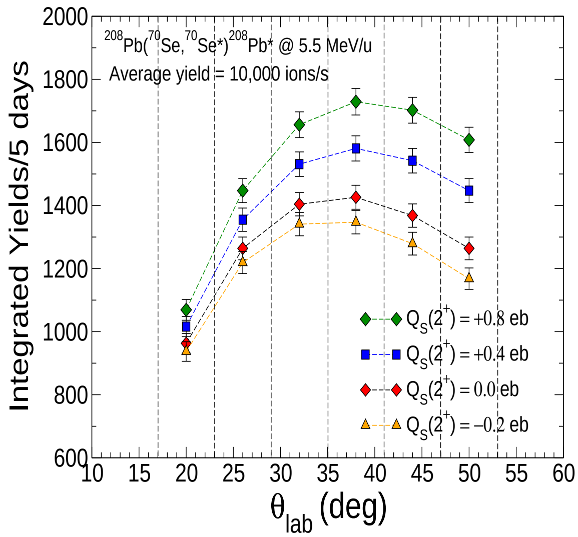

Figure 1: Simulated γ-ray integrated yields for five days of beam time as a function of the scattering laboratory angle for the de-excitation of the 2_1^+ state. The vertical dash lines indicate the angular range covered for the integrated-yield data points. The distinct angular distributions for plausible $Q_S(2_1^+)$ values indicate that a precise determination of $Q_S(2_1^+)$ can be achieved with statistical uncertainties of approximately ± 0.06 eb

strength is extremely weak [8]. These statistics, even with the expected six-times yield increase at HIE-ISOLDE, do not allow a determination of $Q_S(2_2^+)$ from a distinct angular distribution. However, following the method of Hurst *et al.* [2], a few hundred counts may provide information on the sign of $\langle 2_2^+ \mid\mid \hat{E2} \mid\mid 2_2^+ \rangle$ by overlapping the Coulomb-excitation curve with the available $\langle 2_2^+ \mid\mid \hat{E2} \mid\mid 2_1^+ \rangle$ matrix element [2, 12]. The large uncertainty of the available $B(E2; 2_2^+ \rightarrow 2_1^+) = 33(14)$ W.u. [8] is a limiting factor and arises from the large uncertainties in $\delta(655.1 \text{ keV}) = -1.0^{+1}_{-2}$ [13] and $\tau(2_2^+) = 4.7(13)$ ps [10]. An alternative way to determine directly the $B(E2; 2_2^+ \rightarrow 2_1^+)$ value is given by running a second Coulomb-excitation experiment with a lighter target in order to minimize the reorientation effect. Instead, we choose to collect higher statistics aiming at sensitive reorientation-effect measurements. Moreover, a more accurate determination of the $B(E2; 2_2^+ \rightarrow 2_1^+)$ value could also be available from the MSU experiment [11]. In any case, we shall propose a complementary high-statistics angular-distribution measurement at iThemba LABS using the ^{58}Ni(^{14}N,pnγ) reaction at about 39 MeV; the study of this reaction has yielded the only measurements of $\tau(2_2^+)$ [10] and $\delta(655.1 \text{ keV})$ [13, 14]. More accurate measurements can be achieved with the AFRODITE array at iThemba LABS, which currently comprises 9 standard escape-suppressed clover detectors. The identification of the elusive 0_2^+ state is another exciting incentive for this experiment. If it lies above the 2_1^+ state, we may populate it through a two-step process. Predictions, nevertheless, place it right below the 2_1^+ state with a $2_1^+ \rightarrow 0_2^+$ $E2$ strength of only 18 e^{2}fm^4 [9], which yields a negligible effect in the integrated yields calculated for the de-excitation of the 2_1^+ state. As a precautionary measure, we shall use position-sensitive Si pad detectors behind the thin annular CD silicon detector in order to detect the electrons.

Summarizing, full simulations of this experiment are shown in Fig. 1 and described in detail in section 2, and will be presented at the next INTC meeting this June 2013. Additional reorientation-effect measurements with stable beams are scheduled at iThemba LABS during 2013 and 2014. Such experiments will prepare our students with hands-on and data-analysis skills for similar RIB measurements at HIE-ISOLDE.

Summary of requested shifts: 15+3 shifts: fifteen shifts for an uncertainty of approximately ±0.06 eb in the $Q_s(2_1^+)$ value and the additional determination of matrix elements involving higher-lying states, assuming a conservative 10^4 ions/s. Three additional shifts are requested for beam tuning.

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