EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

IS587-ADD-1: Characterising excited states in and around the semi-magic nucleus ^{68}Ni using Coulomb excitation and one-neutron transfer

January 12, 2017

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The INTC requested a Letter of Clarification regarding a number of issues in respect to the proposed Coulomb excitation of ^{66,68,70}Ni. Below I summarise their concerns for each isotope:

- ^{70}**Ni** - Beam contamination from Ga was much higher in 2016 than in the past. Different contaminations levels must be discussed and a tolerated level quantified.
- ^{68}**Ni** - Second-order excitations may influence the determination of Q_s. The choice of beam energy should be clarified.
- ^{66}**Ni** - Is it worth measuring for such a small amount of time and in what way will it help the measurement of Q_s in ^{68}Ni?

^{70}***Ni*** – Yield measurements were performed by the TISD group in November 2016 [1] and showed that the contamination from ^{70}Ga is about 50-times higher than ^{70}Ni. Since the release of nickel is much slower than that of gallium (see Figure 1), only part of the true ^{70}Ni yield was measured. In the original proposal we estimated a primary yield of 1×10^5 ions/μC for ^{70}Ni. The value from these recent measurements is 4×10^3 ions/μC and accounting for this underestimation, we estimate the true yield to be of the order of 10^4 ions/μC. This represents an order of magnitude drop in the primary yield propose making the experiment unfeasible. With this in mind, we feel it appropriate to delay the measurement of ^{70}Ni until such time that further improvements in the beam intensity and quality can be made. It has been calculated that a beam-to-contaminant ratio of 1:4 can be tolerated, whilst keeping the statistical uncertainty on the normalisation to 20%, assuming a primary yield of 1×10^5 ions/μC and 12 shifts of beam time run in laser on/off mode.

^{68}***Ni*** – Second-order excitations in ^{68}Ni are crucial to the success of the experiment. A beam-energy optimisation has been performed in order to maximise the sensitivity to the spectroscopic quadrupole moment, Q_s, which comes about via the second-order excitation process of the

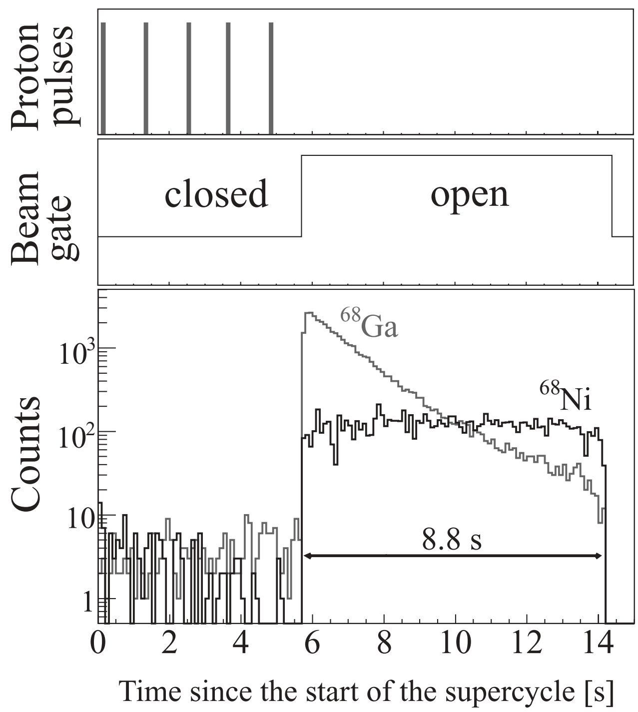

Figure 1: Release curves of ^{68}Ni and ^{68}Ga reproduced from Ref. [2]. Gallium is released relatively quickly, following an exponential function, while nickel is released apparently constantly.

reorientation effect [3]. This involved balancing the need to increase the impact factor to maximise second-order excitations, i.e. the beam energy and centre-of-mass scattering angle, with the widest possible range of the "safe" scattering angles covered in the experiment, i.e. highest statistics. This compromise comes about due to Cline's "safe" energy criterion [4], which dictates the maximum centre-of-mass scattering angle that can be used for a given beam energy. The beam energy that has been chosen is 4.0 MeV/u, leading to only a small amount of recoil events discarded for being in the unsafe regime. A lower beam energy has the added advantage of reducing single-step excitations to higher-energy 2^+ states, further reducing correlations to unknown matrix elements.

A full simulation of the experiment has been performed and shown in the original proposal to give a precision on Q_s down to about 0.1 eb. The question of how multiple-step excitations, to the 0_2^+ state in particular, will affect this precision has been considered and will be addressed here. All other states lie too far in energy to influence the cross-section of the 2_1^+ and 0_2^+ states and their populations are calculated to be $< 1\%$ of the 2_1^+ state at all angles, assuming physically plausible matrix element values. The correlations to these higher-lying states can nevertheless be simulated and are shown to be negligible.

A second-order process to populate the close-lying 0_2^+ state is however, likely. Since there can be only an $E0$ transition between this state and the ground state, single-step excitations are ruled out. It follows then that the ratio $\sigma(0_2^+)/\sigma(2_1^+)$ is governed almost exclusively by $B(E2; 2_1^+ \rightarrow 0_2^+)$, with only a small correlation to $Q_s(2_1^+)$. An experimental determination of this ratio can be made by observing the $E0$ decay as explained in the original proposal [5, 6]. It is estimated that there will be of the order of 50 counts in the 511 keV particle-γ-ray peak over the course of the beam time, assuming $\langle 0_2^+ \| E2 \| 2_1^+ \rangle = 0.29$ eb or 350 counts assuming $\langle 0_2^+ \| E2 \| 2_1^+ \rangle = 0.80$ eb. The correlation between these parameters can be studied and an example is shown in Figs. 2 and 3. These correlation surfaces show that, even without a measurement the $0_2^+ \rightarrow 0_1^+$ transition, which would add further a constraint to the y-axis of the surface, the uncertainty in the extracted matrix element would increase by no more than a factor of 2.

The latest yield measurement, performed in November 2016 [1], give a primary yield of 9.9×10^4 ions/μC, an order of magnitude lower than the value in the proposal. After considering the underestimation of the measurement due to using only part of the release curve (see Figure 1), this represents a reduction of a factor of two in the intensity delivered to Miniball. A beam gate will be used to reduce the contamination from ^{68}Ga (1.3×10^6 ions/μC), while giving only a modest loss of ^{68}Ni intensity. Using event-by-event timing information, correlated to the ISOLDE proton impact, further control can be gained over the beam composition in the data analysis, similar to the technique of Ref [2]. A beam-to-contaminant ratio of 1:4 and 50% of the beam time ran in laser on/off mode to determine the beam composition, would lead to a 6% statistical uncertainty on the target normalisation (1.6% for a pure beam). This is comparable to the statistical uncertainty of the $I_\gamma(2_1^+ \rightarrow 0_1^+)$ intensity in ^{68}Ni (6%), which is affected only by the absolute yield and not by the contamination. Still, the limiting factor will not be the statistical uncertainties, but the correlations to other matrix elements as previously discussed.

^{66}Ni – There is a strong physics case to perform an independent Coulomb-excitation measurement of ^{66}Ni of $Q_s(2_1^+)$ for the first time in ^{66}Ni and also to confirm the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value obtained in via intermediate Coulex [7]. Recent experimental and theoretical work have predicted triple shape coexistence, in the case of Monte-Carlo Shell Model (MCSM) calculations of Otsuka et al. [8, 9], and Leoni et al. [10] have performed lifetime measurements of excited 0^+ states. The interpretation of shape coexistence must be tested experimentally and therefore it is crucial that electromagnetic moments are determined to confirm the conclusion that there

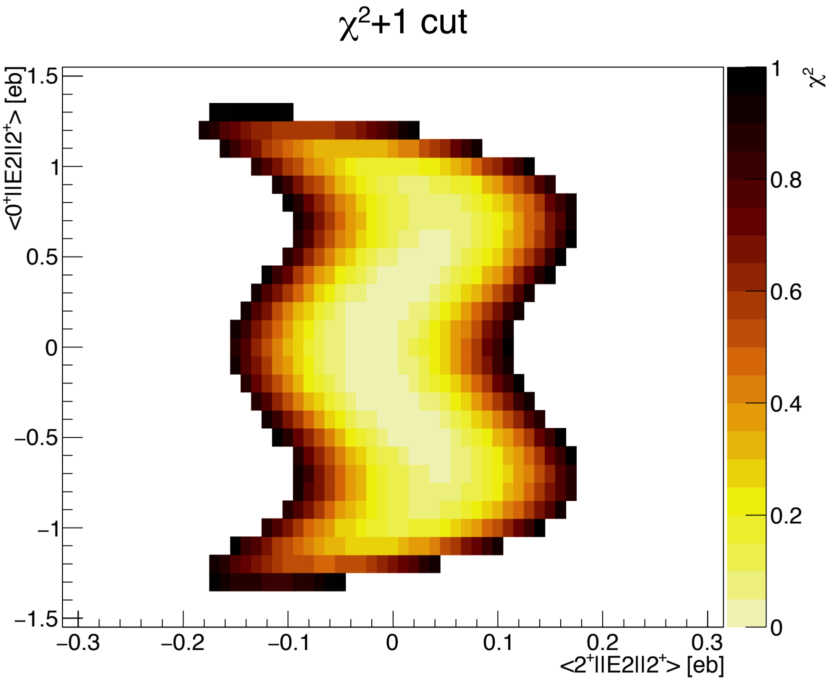

Figure 2: A simulated two-dimensional χ^2 surface plot for the $\langle 2_1^+\|E2\|2_1^+\rangle$ and $\langle 0_2^+\|E2\|2_1^+\rangle$ matrix elements (fit parameters) in ^{68}Ni. The simulated data has been produced assuming $\langle 2_1^+\|E2\|2_1^+\rangle = 0.00$ eb and $\langle 0_2^+\|E2\|2_1^+\rangle = 0.29$ eb. It is cut at $\chi^2 = \chi^2_{\rm min} + 1$ representing 1σ uncertainty. It is equivalent to the correlation surface between the two parameters and is independent of the sign of $\langle 0_2^+\|E2\|2_1^+\rangle$ since the cross-section is proportional to the square of the matrix element, or $B(E2; 2_1^+ \to 0_2^+)$. Only the experimental information on $I_\gamma(2_1^+ \to 0_2^+)$ is included in the calculation of χ^2.

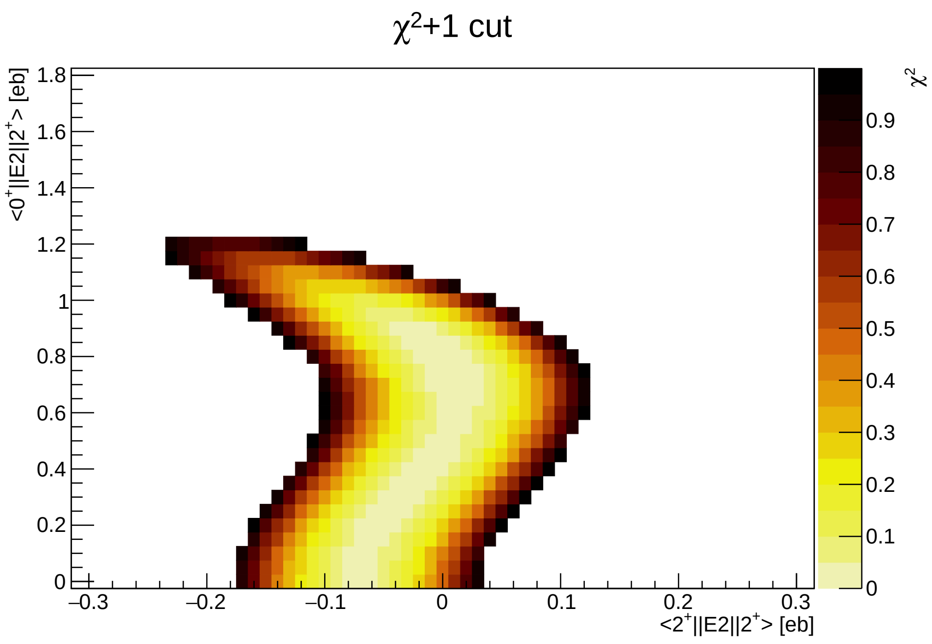

Figure 3: The same as Figure 2 but where the simulated data has been produced assuming $\langle 2_1^+\|E2\|2_1^+\rangle = 0.00$ eb and $\langle 0_2^+\|E2\|2_1^+\rangle = 0.80$ eb.

are indeed two competing shapes in this nucleus.

A second route to inferring shape coexistence experimentally is via $\rho^2(E0)$ values. In our proposed Coulomb-excitation experiment we expect to populate the excited 0^+ states only very weakly due to the large energy gap between the 2_1^+ and 0_i^+ states and small $B(E2; 2_1^+ \to 0_i^+)$ values predicted by the MCSM calculations [8, 9]. Particle-γ-γ coincidences will be used to identify γ-rays depopulating 0_i^+ states, where we expect ≈ 10 counts in the $0_2^+ \to 2_1^+$ transition assuming $B(E2; 2_1^+ \to 0_2^+) = 0.8$ W.u.. The number of observed γ-rays is directly proportional to this $B(E2)$ value and therefore a larger than expected $B(E2)$ would give a larger statistical significance to any measurement. This means that we are at least sensitive enough to determine a lower limit of $B(E2; 2_1^+ \to 0_2^+)$ that can be used in combination with the new experimental lifetimes to give an upper limit on $\rho^2(E0; 0_2^+ \to 0_1^+)$.

While ^{66}Ni is a wholly independent measurement to that of the original ^{68}Ni, the analysis procedure will be exactly the same. Since the former case provides a much higher statistical precision, it will also serve as an empirical demonstration of the systematic uncertainties involved in the determination of $B(E2; 2_1^+ \to 0_1^+)$ and $Q_s(2_1^+)$, which will dominate the final errors. It is worthwhile noting that in addition to being a very intense beam, ^{66}Ni is also very pure [11], meaning there are no additional uncertainties introduced in the normalisation procedure.

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