EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Clarification for P-586 to the ISOLDE and Neutron Time-of-Flight Committee

Investigating shape coexistence in ^{80,82}Sr with β^+/EC decay spectroscopy

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Abstract: Neutron deficient ^{80,82}Sr nuclides lie in a rich structural region of the nuclear chart, where sub-shell effects may give rise to rapid shape changes. Large $E0$ strengths, $\rho^2(E0)$, are related to fluctuations in the mean-square charge radius, $\langle r^2 \rangle$, and typically associated with coexisting shapes which become mixed. Although the structure of yrast states in this region is well known from heavy-ion fusion-evaporation reactions – where a shape evolution from spherical at $N = 50$ to strongly deformed in the $N \leqslant 40$ region has been observed as a function of spin – information of non-yrast states remains scarce. Currently, there are no data on excited 0^+ states for ^{80}Sr and little information on $E0$ strengths, in general. Excited 0^+ states can, however, be populated through β-decay and Coulomb-excitation studies. Here, we propose the investigation of shape effects in ^{80,82}Sr with the β^+/EC decay of ^{80,82}Y and with the measurement of internal conversion electrons using the SPEDE electron spectrometer at the ISOLDE Decay Station (IDS), equipped with a tape station, four germanium clover detectors, two $LaBr_3$(Ce) detectors, and a fast plastic detector. These measurements will complement the investigation of the shape effects in ^{80,82}Sr using safe multi-step Coulomb excitation measurements carried out at TRIUMF, where the excited 0_2^+ state has been populated in ^{82}Sr.

Requested shifts: 19 shifts (split into 2 runs over 1 year)

1 INTC-P-586 Minutes

This proposal aims to investigate shape effects in ^{80,82}Sr via beta decay from ^{80,82}Y, using the SPEDE electron spectrometer at the ISOLDE decay station. The measurements aim to complement Coulex experiments at TRIUMF, where the excited 0^+ state was recently populated in ^{82}Sr.
Shape coexistence is predicted to manifest in light Sr isotopes although for ^{76,78}Sr no such states have been identified; low-lying 0^+ states have been identified however in neutron-deficient Se and Kr isotopes. A tentative 0^+ excited state has been assigned from a reaction measurement in ^{80}Sr at $\sim$1 MeV. Although no $E0$ transitions have been observed, the identification of such states would allow the evolution of the nuclear shape to be studied at low excitation energies. Recent TRS calculations predict a narrow separation between oblate and prolate shape minima in ^{80}Sr, motivating the search for excited 0^+ states in this nucleus.
The committee finds that there are interesting results which could be learned from this experiment especially with regard to the $E0$ state of ^{82}Sr to which the previously performed Coulomb Excitation measurements is insensitive. This measurement would be important by itself but also to allow for a proper analysis of the Coulex work. However, there are a number of points that the committee would like the collaboration to address.

Regarding ^{80}Sr the committee feels that previous measurements did not indicate the presence of an $E0$ state and the study of this isotope is of less apparent interest. In addition, previous experiments were performed at facilities where the beam was produced using fusion evaporation reactions:

could the advantage that ISOLDE presents over these facilities be clarified by the collaboration?

The production of Y beams has been observed at the booster but it is possible that the yields of ^{82,80}Y could be substantially lower than the levels previously seen at the SC. The collaboration are advised to contact the target group to obtain an estimation of these yields and to re-evaluate the shift request in this light. In short, the collaboration is requested to prepare a letter of clarification to address the points above.

The INTC recommends the submission of a letter of clarification.

2 Reply to the advantage of running these experiments at IDS/ISOLDE

We shall clarify first why the IDS facility at ISOLDE [1] provides a clear advantage to the investigation of 0^+ states, as compared to facilities where the beam was produced using fusion-evaporation reactions. The main disadvantage of running β-decay experiments with fusion-evaporation reactions is the number of reaction channels that are produced, which – without a mass separator to select the nucleus of interest – typically leads to high backgrounds that overwhelm the data of interest. However, ingenious approaches have been introduced to circumvent this issue, as illustrated by the most comprehensive β-decay work done in ^{80}Sr. That is, the β- and γ-ray spectroscopy experiment carried out by Döring and collaborators [2] at the ATLAS facility, following the bombardment of a thin ^{24}Mg target with ^{58}Ni ions at 190 MeV. The $A = 80$ isobaric nuclei were nicely separated using the Fragment Mass Analyzer (FMA) and implanted onto mylar tape located behind the focal plane position. Deposition and counting times of 20 and 60 s were utilised, where the counting station was $\sim$1 m away from the focal plane. The detection system comprised of three HPGe detectors (55% relative efficiency) and one LEPS detector for low-energy gammas. The four detectors had a thin ($\approx$3 mm) plastic scintillation detector in front to record positrons emitted during the decay. These measurements uncovered fourteen new levels, the assignment of spin and parity of 4^- and 1^- to the parent ground state and the 228.5 keV isomeric state, respectively, and the first observation of negative parity states in ^{80}Sr. The collection of high-energy γ-rays could not be completed though, because of the upper threshold was set too low.

The present study of 0^+ states via the decay of ^{80m}Y and ^{82}Y at the new IDS/ISOLDE presents three clear advantages with respect to previous work and other facilities, which are discussed in detail below. Namely, i) a uniquely versatile and superior array, ii) a dedicated experiment aimed at the study of 0^+ states, and iii) pure beams that result in cleaner spectra.

i) The new detection system at the IDS is shown in Fig. 1, and comprises the SPEDE electron spectrometer, a minimum of 8 clover detectors and at least two fast-timing $LaBr_3$(Ce)

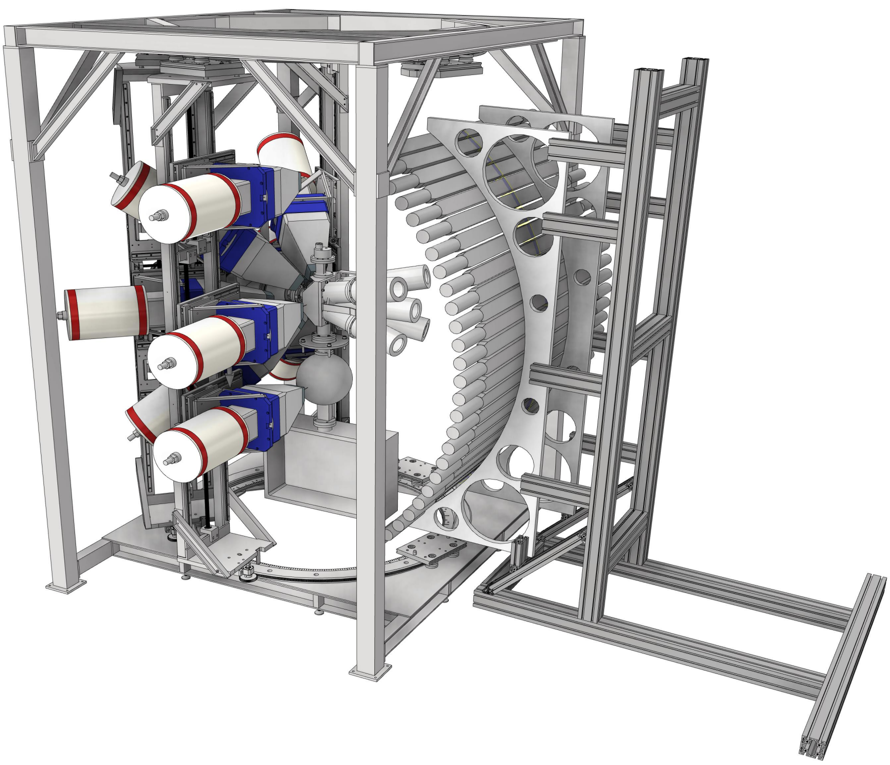

Figure 1: The new IDS multifaceted array at ISOLDE.

detectors. This multifaceted array allows for our preferred two-measurement position:

- the implantation position with 4 clovers (or up to 15 clover detectors in total) and SPEDE, in order to measure $E0$ electrons, K-shell ratio and $E0$ strengths;

- the decay position with another 4 clovers (or up to 15 clover detectors in total) and $LaBr_3(Ce)$ fast-timing detectors to do γ-ray spectroscopy and measure ps lifetimes using $\beta-\gamma_{Ge}$-γ_{LaBr} coincidences. Although GRIFFIN can accommodate up to 16 large clover detectors, beams of ^{80,82}Y are not available at TRIUMF.

ii) The population of excited 0^+ states in ^{80}Sr will also benefit from a dedicated experiment using the decay of the 1^- isomeric state ($T_{1/2}$ = 4.7(3) s) in ^{80m}Y – where the β-decay selection rule is $\Delta J = 0, \pm 1$ for the fastest decays – with a 19(2)% β-decay branch to low-lying states [3]. Shorter deposition and counting cycles ($\sim$10 s) than the ones used previously (20 and 60s) will enhance the ^{80m}Y decay with respect to the 4^- ^{80}Y ground sate. The latter favours the strong population of higher-spin states, in particular of spins 4 and 5, but will not directly populate the 0^+ states, which can only be populated via feeding down through a cascade of transitions (e.g. the 2^+ and 4^+ members of the 0^+ band). This is an incredibly inefficient way to populate excited 0^+ states.

iii) The use of pure $^{80}YF_2$ molecular beams is a clear advantage with respect to fusion-evaporation experiments. In fact, even using the FMA at ATLAS, the decay of the other $A = 80$ isobars could not be avoided. This could have impeded the observation of the $0_2^+ \to 2_1^+$ γ-ray transition in ^{80}Sr. For instance, a strong $2_1^+ \to 0_1^+$ 619-keV transition in ^{80}Kr is observed from the coincidence data [2], which could overlap with the potential $0_2^+ \to 2_1^+$ 614-keV transition in ^{80}Sr, assuming that the excited 0_2^+ state lies at 1.0 MeV.

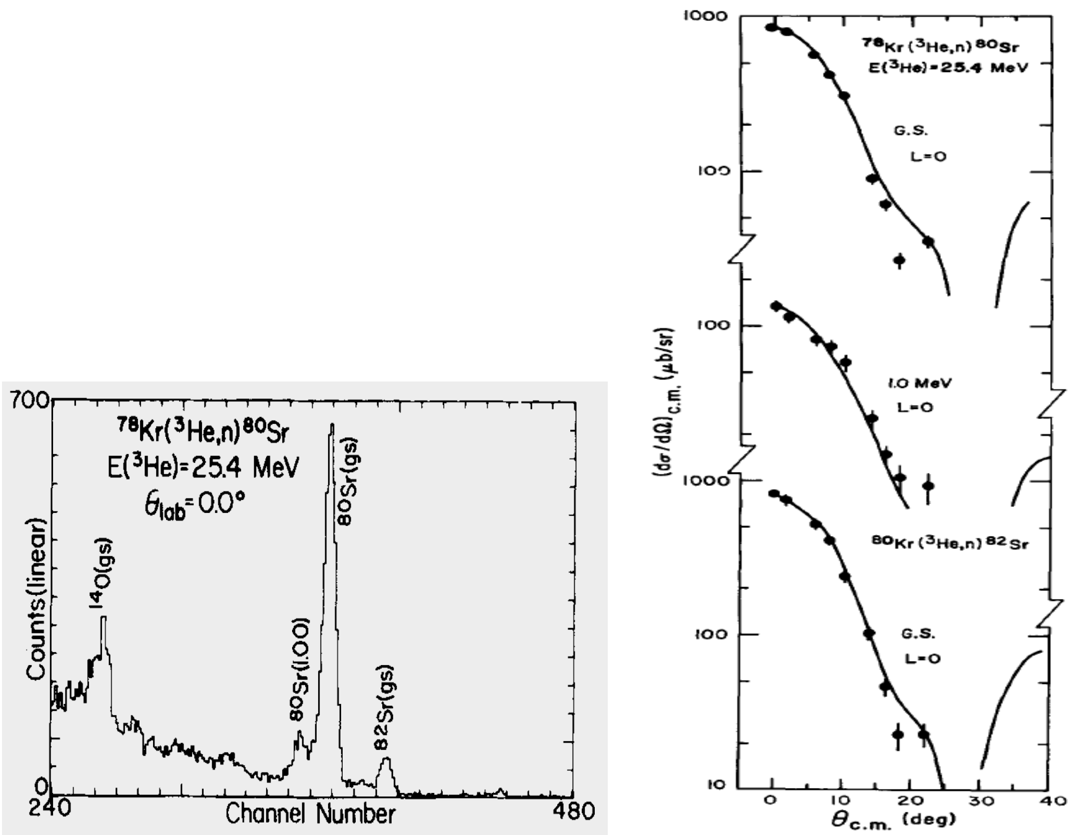

Figure 2: The left panel shows the neutron time-of-flight spectra at 0° from the ^{78}Kr(^{3}He,n) reaction at 25.4 MeV, where an excited 0^+ state at 1.0(1) MeV in ^{80}Sr is observed. As shown in the middle of the right panel, its angular distribution is consistent with an $L = 0$ transfer.

Furthermore, we disagree with the statement that previous experiments did not indicate the presence of an excited 0^+ state in ^{80}Sr. The assignment of 0^+ states has typically been done through the investigation of complementary two-proton (e.g. (^{3}He,n)) and two-neutron (e.g. (p,t)) transfer reactions, which selectively populate 0^+ states. The angular distributions at different angular ranges usually provide the characteristic $L = 0$ transfer, in agreement with DWBA calculations. The first excited 0^+ state in ^{82}Sr was solely assigned through the investigation of the ^{84}Sr(p,t) reaction [4]. Because ^{82}Sr is unstable, no such (p,t) study can easily be carried out in order to populate 0^+ states in ^{80}Sr. Moreover, similar information can be determined from γ-ray angular correlations using powerful γ-ray spectrometers. These kind of measurements could be performed using the new IDS facility, which may accommodate up to 15 HPGe clover detectors.

An excited 0^+ state in ^{80}Sr at 1.0±0.1 MeV – with a strong 15% population of the ground state – has been observed by Alford and collaborators from a study of the ^{78}Kr(^{3}He,n) reaction at 25.4 MeV [5]. The work by Alford and co-workers is shown in Fig. 2, and suggests a more solid ground for the 0^+ assignment from both the neutron time-of-flight spectrum at 0° (left panel) and the similar angular distributions for the ground and excited 0^+ states, consistent with $L = 0$ transfer (right panel). In more detail, the angular-distributions for the ground state and excited 0^+ states present small errors, even compared with other angular distributions in the same paper [5], and similar trends. DWBA calculations assuming an $L = 0$-transfer and a simple $p^2_{3/2}$ form factor for the transferred particles reproduce the angular distributions nicely. It is important to note that during these measurements, the ^{78}Kr target was enriched to 92.3%. With a 0.35% isotopic abundance for ^{78}Kr, it is hard to envision a similar (^{3}He,n) measurement in the near future. Alternative ways that can shed some light into the existence of this 0^+ state are the β decay measurement proposed here and the Coulomb-excitation of ^{80}Sr, a proposal approved with high priority at TRIUMF.

It is interesting to note that this excited 0^+ state at 1.0(1) MeV in ^{80}Sr is given as tentative (0^+) in the NNDC because of the following three reasons [6]:

1) The ENSDF policy about (^{3}He,n) reaction mentions validity of $S = 0$ state for the two protons for observed strong groups.
2) This state has not been observed in any previous experiment, in particular the β decay of ^{80}Y [2].
3) Comparison with theoretical predictions was not found satisfactory. Particularly, the relatively strong transition to a state of 1.0(1) MeV in ^{80}Sr is in disagreement with the simple pairing model [5].

Experimentally, the current ambiguity in the assignment of the 0^+ state in ^{80}Sr clearly demands additional experimental studies. A strong motivation for doing a more dedicated β-decay measurement at IDS/ISOLDE is provided above. Theoretically, Alford and collaborators quoted that:

"It seems likely that this transition arises as a consequence of coexisting deformed and spherical states in this mass region, a possibility which is not encompassed in the model calculations. In ^{80}Sr, a strong $L = 0$ transition to a state at 1 MeV excitation supports the suggestion of coexisting spherical and deformed states in this mass region."

This scenario was investigated in the current work and beyond mean-field calculations in ^{80}Sr were performed by Tomás Rodríguez and presented during the last INTC meeting in November 2020. Such calculations supported a largely prolate ground-state band and a slightly deformed oblate shape for the second 0^+_2 state predicted at 1.19 MeV, although presenting, as shown in the collective wavefunction in Fig. 3, mixed configurations with components of different shapes; a possibility not considered in the pairing-model calculations of Alford and collaborators.

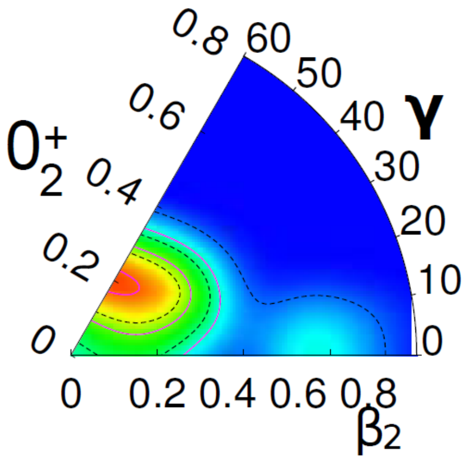

Figure 3: The collective wavefunction of the excited 0_2^+ state in ^{80}Sr predicted at 1.19 MeV clearly presents mixed configurations with components of oblate and prolate shapes.

3 Reply to the beam production and estimates

The proposed β-decay experiment is described in detail in our original proposal. Relevant to this Letter of Clarification, the target group was addressed and confirmed that neutron-deficient Y beams were produced at the PSB as YF_2^+ molecular beams using both surface and plasma ion sources. Estimation of these yields will be provided at the TAC in order to re-evaluate the shift request in this light. A written response with the new beam time estimates will then be provided upon request. In the meantime, kindly refer to the table with our original estimates.

Isotope	Half-life	Yield [ions/s]	β-γ_{Ge}-γ_{Ge} [counts/shift]	β-γ_{Ge}-γ_{LaBr} [counts/shift]	$0_2^+ \rightarrow 0_1^+$ K $E0$ e^- [counts/shift]	$2_\gamma^+ \rightarrow 2_1^+$ K $E0$ e^- [counts/shift]	# of shifts
^{80}Y	4.8(3) s	1 x 10^4	$\sim$ 2 x 10^2	$\sim$ 1 x 10^2	40	3 x 10^3	9
^{82}Y	8.3(2) s	1 x 10^5	4 x 10^4	1 x 10^4	140	9 x 10^4	6

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