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Addendum to the Proposal INTC/P-130
(Experiment IS 389 – Status report and beam time request)

**Measurement of Moments and Radii of Light Nuclei
by Collinear Fast-Beam Laser Spectroscopy
and β -NMR Spectroscopy**

M. Kowalska, R. Neugart
Institut für Physik, Universität Mainz, D-55099 Mainz, Germany

D. Borremans, D. Balabanski, P. Himpe, S. Mallion, G. Neyens, D. Yordanov
Instituut voor Kern- en Stralingsfysica, K.U. Leuven, B-3001 Leuven, Belgium

P. Lievens
Laboratorium voor Vaste-Stoffysica en Magnetisme, K.U. Leuven, B-3001 Leuven,
Belgium

K. Blaum
Department of Physics, CERN, CH-1211 Geneva 23, Switzerland

Spokesperson: R. Neugart
Contactperson: M. Kowalska

1. Introduction

The proposal P 130 for experiment IS 389, submitted in August 2000, contained two high-priority items for which the allocated 30 shifts of beam time were used:

1. Very sensitive laser spectroscopy measurements on neon isotopes using collisional ionization and β -activity detection were completed. The results include new and accurate nuclear moments of ^{17}Ne , ^{23}Ne and ^{25}Ne and the development of mean square charge radii between ^{17}Ne and ^{28}Ne .
2. Following the recommendation of the INTC we have then concentrated our effort on a considerably improved measurement of the quadrupole moments of ^{11}Li in comparison to ^9Li , for which a first result had been obtained in the last period of ISOLDE-2 running [1].

The proposal was based on improvements in the production of ^{11}Li at ISOLDE and in the polarization of lithium beams. The latter was mainly a result of careful investigation how to optimize the optical pumping conditions and to rotate the spins from longitudinal into the transversal direction of the NMR field, performed during the extensive work on neutron-rich sodium isotopes [2]. Also a better NMR magnet with improved field homogeneity had been introduced.

Given these conditions, a conservative estimate could be based on an increase by a factor of 2 in both the yield and in the β -decay asymmetry, compared to the earlier experiment. From this the hope was to improve the earlier result $Q(^{11}\text{Li})/Q(^9\text{Li}) = 1.14(16)$ by a factor of 3 to 5. This accuracy would most probably reveal a significant difference between the quadrupole moments of both nuclei and thus give a solid experimental result for the polarization effect of the two halo neutrons in ^{11}Li on the ^9Li core.

Here we report on the progress we have achieved and on the reason why we ask for an additional beam time allocation of **10 shifts**.

2. Status of the Experiment

A first test run on ^8Li and ^9Li in late 2001 had very promising results. As alternatives to the previously used LiNbO_3 crystal we tested LiTaO_3 and a metallic single crystal of Zn. For both of them the resolution of the quadrupole splitting of the NMR signal was superior to previous results obtained for LiNbO_3 . In LiTaO_3 the electric field gradient is somewhat larger, and in Zn even the smaller field gradient gives a gain in resolution by a factor of 5 because of the much smaller line width.

The sensitivity required for a measurement on ^{11}Li with half-life 8.5 ms can only be achieved by employing a multi-rf technique where (for spin $I = 3/2$) three equidistant frequencies: ν_L , $\nu_L + \nu_Q$, $\nu_L - \nu_Q$ are applied as a function of the unknown splitting ν_Q . The Larmor frequency ν_L has to be determined beforehand. This is done by measuring the resonance in a cubic crystal, and for a sufficient precision one needs at least the same resolution as for the measurement of the resonances including quadrupole interaction. For this purpose a Si single crystal has been found to be an excellent choice.

Summarizing the situation we have now for the Larmor frequency measurement as well as for the quadrupole spectra typical linewidths of 1-2 kHz (depending on the rf power), whereas in the previous experiments these widths were of the order 5-10 kHz. This is a decisive improvement even beyond the expectations of our proposal, and a full order of magnitude appears to be a realistic goal for the gain in accuracy of the quadrupole moment ratio $Q(^{11}\text{Li})/Q(^9\text{Li})$.

For a measurement on ^{11}Li all experimental conditions (optical pumping efficiency, quality of crystals and observed β -asymmetries, rf power and resonance width, and the magnetic field calibration) have to be tested and optimized on ^8Li and ^9Li . Thus, in the preparation phases of two scheduled runs, we have considerably improved the earlier results on the magnetic moments of ^9Li and ^{11}Li [3] and on the quadrupole moments of ^8Li and ^9Li [4]. These results will be published independently [5].

However, for a final quadrupole moment measurement on ^{11}Li we had bad luck with the ISOLDE performance. A first run in 2002 suffered from a problem in the target heating, and when this was settled it turned out that the HRS could not be calibrated accurately enough to transmit an acceptable amount of ^{11}Li . Therefore, the second run in 2003 was scheduled for the GPS. After we had spent the usual 4 shifts of testing and optimization we had to realize that the ^{11}Li yield had already dropped and continued to drop. Presumably even at very low electrical target heating the Ta foils were destroyed by a too intense proton beam. Heating more gave only short-term improvements. We also think that the very irregular proton pulse structure¹ was destructive for the target.

Nevertheless for some time the conditions were acceptable to try a measurement in the Zn host crystal. The result of 10 hours of data taking (not including necessary intermittent re-optimizations) is shown in the lower left-hand part of Figure 1. The β -decay asymmetry is plotted as a function of the distance of the three-frequency quadrupole-shifted resonance from the Larmor frequency. For comparison, the upper part shows the corresponding spectrum for ^9Li , taken at half the rf strength which is insufficient to saturate the transitions for the very short-lived ^{11}Li .

On the right-hand side we have reproduced the corresponding plots of the ISOLDE-2 measurement in a LiNbO_3 crystal published in 1992 [1]. As the measuring times are comparable, it is directly obvious that the statistics is poorer for the new measurement than for the old one. The big progress is in the resolution (note the scale difference on the horizontal axis between left and right). Naive fitting of the resonance positions with a Gaussian curve yields the new result $Q(^{11}\text{Li})/Q(^9\text{Li}) = 1.11(7)$ in very good consistency with the old one, $Q(^9\text{Li})/Q(^9\text{Li}) = 1.14(16)$. However, the situation is more complex. In addition to the three-frequency one-photon resonance there has to be a two-frequency two-photon resonance with a strength depending critically on the rf power at half the distance to the Larmor frequency. As this is not clearly visible, one has to over-simplify the fit. In principle one has to model also the relevant three-frequency resonance, because the line shape arises from the interplay of three transitions, but the statistics of the spectrum does not allow meaningful fitting using a more complex resonance structure.

¹For some reason the supercycle consisted of 36 pulses of which we could use about 50 % only by accepting longer breaks and groups of consecutive pulses. This also gives big fluctuations in the yield per pulse. Usually we have tried to take the pulse structure as regular as possible.

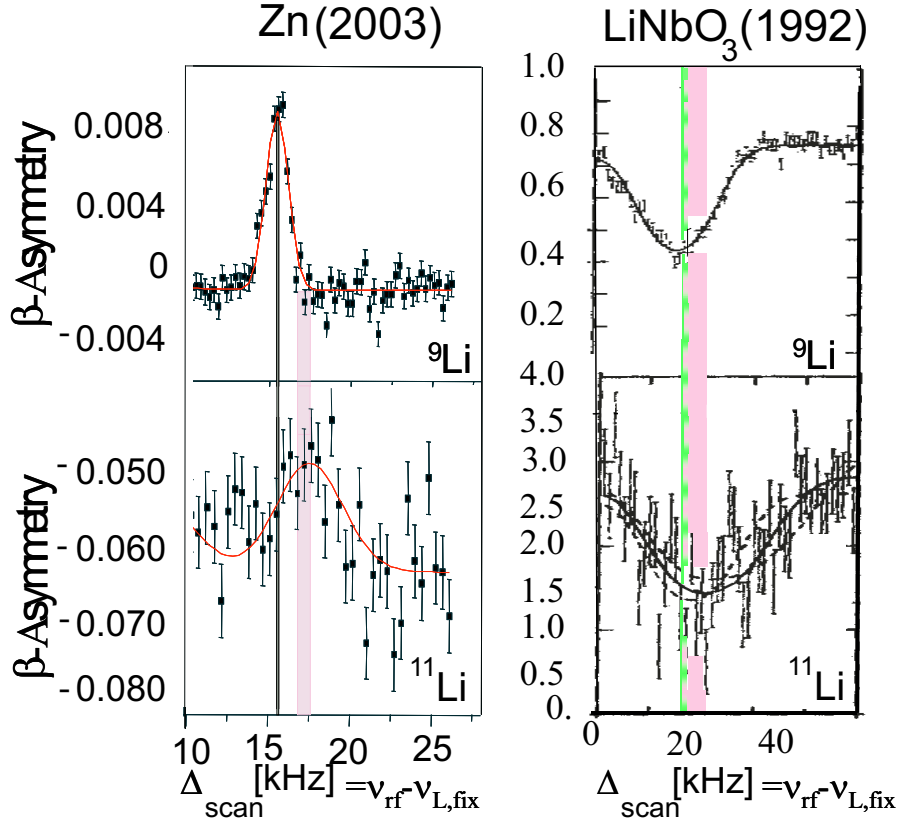


Figure 1: Spectra of measurements of the quadrupole moment of ^{11}Li in comparison to ^9Li (left: result of 2003, right: published result of 1992).

This leaves us in an uncomfortable situation: The idea of the proposal was to use the improvements in yield and in optical beam polarization for an accurate measurement with good statistics. The polarization was as expected, but the yield was considerably lower than at ISOLDE-2. Using practically the same arrangement we had about 100 counts per proton pulse compared to the previous 200 counts per second. In counts per time unit or in counts per μC this difference corresponds to a factor of 4. Taking into account our transmission and detection solid angle of nearly 5 % the quoted count rate corresponds to a yield of about 500 ^{11}Li atoms per μC of protons. This is below all standard yield numbers of the last few years.

3. Additional beam time request

As we have used all our allocated beam time, we ask for an additional allocation of 10 shifts, in order to be able to produce a high-quality measurement that removes the ambiguities of the spectrum shown in Figure 1 and at the same time improves the statistics. This should be no problem with the standard yields of 2000 to 4000 atoms per μC that were reported by other users, even if the proton number per pulse has to be limited.

As an alternative to the thin-foil Ta target we consider to use the UC_2 target that will also produce the neutron-rich Mg isotopes (our new Proposal P 185). This target was

used earlier for our tests on the Li isotopes, and it gave about 200 counts per full-intensity proton pulse on ^{11}Li , more than the other targets that were intended to give high yields. Albeit the yield is modest one could take advantage of the reliability and stable operation of the UC_2 target over longer periods of time.

We see a possible scenario in the combination of such a ^{11}Li run with a Mg run that we expect to be scheduled for P 185 this year. The magnetic field calibration on ^8Li for the β -NMR measurements on ^{29}Mg and ^{31}Mg will anyway require a changeover of the laser and the apparatus for running on neutral Li atoms instead of Mg^+ ions. This can be achieved within 1 day. In the initial phase of the magnesium run we could check the ^{11}Li yield and already decide 3 days in advance whether or not we can use it for the measurement on ^{11}Li . With a bit of flexibility of another user this might be arranged without loss of beam time.

Of course, an independent run with a thin-foil Ta target giving yields as reported by other users would be better. This could still be envisaged, if our scenario fails or if it is better understood how to reach a good and stable performance of the thin-foil Ta target over at least 2 days.

In summary we request an additional beam time allocation of **10 shifts** for the completion of IS 389, more precisely for a final good measurement of the quadrupole moment of ^{11}Li . This request is for one run of which the first 4 shifts are to be used to optimize and calibrate the experimental conditions on ^8Li and ^9Li and 6 shifts are devoted to ^{11}Li .

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