EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-flight experiments Committee

Exploring the X(5) characteristic in the mass A~80 region : Coulomb excitation of ^{78}Sr nucleus.

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Abstract: *We propose to study the low spin collective properties of ^{78}Sr via Coulomb excitation of the radioactive beam at 3.0 MeV/A provided by the REX-ISOLDE facility at CERN. The energy systematics of the ground state band suggest that ^{78}Sr should show X(5) characteristics, similar to those observed in other shape-transitional nucleus like ^{152}Sm. However, this cannot be confirmed due to insufficient data on the transition matrix elements in ^{78}Sr. Measurement of intraband and interband transition strengths between the ground state band and the second 0^+ band to be obtained in the proposed study will provide firm evidence to explore the X(5) nature in ^{78}Sr, the first time proposed in the neutron-deficient A~80 regime. We request a total of 10 days of ^{78}Sr beam with a beam intensity of 5×10^4 particles per second at the Miniball target position and a beam energy of 3.0 MeV/A on a 1 mg/cm^2 thick ^{nat}Ni target. This will allow the second 0+ band to be identified and will allow the reduced electric quadrupole matrix elements corresponding to the interband and intraband transitions between the levels of the ground state and the second 0+ bands to be measured.*

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Introduction:

The spherical harmonic vibrator [U(5)], symmetrically deformed rotor [SU(3)] and the triaxially soft rotor [O(6)] are the three model benchmarks for collective nuclei. However, in reality many nuclei display characteristics which lie in transitional regions between these three limits. Phase transitional behaviour in the evolution of nuclear structure from spherical to deformed shapes has recently been investigated using geometric approaches such as X(5) or E(5).

The X(5) symmetry at the critical point of shape phase transition between a spherical harmonic vibrator [U(5)] and an axially symmetric deformed rotor [SU(3)] was first proposed by Iachello [1-2] and has since then drawn considerable theoretical and experimental attention[3-10]. The X(5) characteristics have been found dominantly in the n-rich nuclei around A~150, specifically in the N~90 isotones. The most effective experimental signature by which one can characterize a nucleus as X(5) is the energy ratio, $R_{4/2}=E(4_1^+)/E(2_1^+)$, between the 4^+ and 2^+ levels in the Yrast band. For an X(5) nucleus, the value of $R_{4/2}$ corresponds to 2.90 which is in between that of a axially deformed rotor ($R_{4/2}$=3.33) and a spherically symmetric harmonic vibrator ($R_{4/2}$=2.0). It must be realized, however, that this is a necessary but not sufficient condition to characterize the X(5) behaviour of a nucleus. The $R_{4/2}$ value corresponding to the shape change from the triaxially deformed γ-soft [O(6)] rotor to the axially deformed rotor [SU(3)] also ranges from 2.5 to 3.33 via 2.90 though no symmetry associated with shape transitional behaviour is expected in this case [11]. Clark *et al*. [12] have shown that many nuclei have displayed the characteristic energy spacing expected for X(5) bahaviour but most of them have failed to fulfill the requirements for interband and intraband transition strengths. Bizzeti *et al.* proposed [13] ^{104}Mo as a probable candidate of X(5) behaviour in A~100 region based on the level energies. But, Hutter *et al.* have shown that the absolute transition probabilities for ^{104}Mo are not in good agreement with X(5) expectations[14]. Therefore, it is important to know both the transition strengths and the level energies before describing any nucleus as an X(5) nucleus.

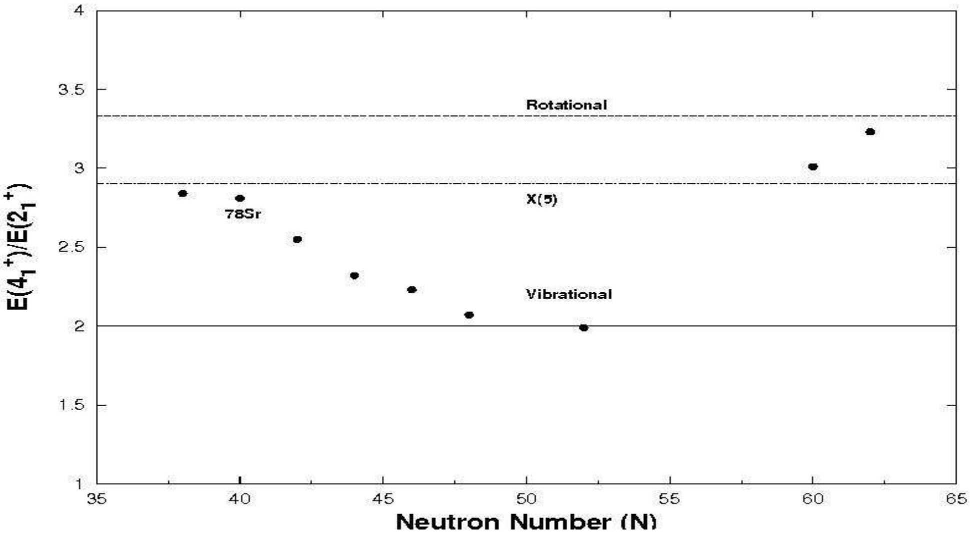

Figure 1: Energy systematics of Sr isotopes. The dashed line indicates the prediction for an axially deformed rotor SU(3), 3.33, the solid line is the prediction for a spherical harmonic vibrator U(5), 2.0, and the dash-dotted line is the prediction for a X(5) nucleus, 2.90, lying between the two limits. The filled circles represent experimental data taken from nuclear data sheets. The data point for ^{78}Sr is labeled.

Figure 1. displays the observable $R_{4/2}=E(4_1^+)/E(2_1^+)$ over the range of Sr nuclei. The dashed line indicates the value of 3.33 for an axially deformed rotor and solid line indicates the value of 2.0 applicable for a spherical harmonic vibrator. For transitional nuclei X(5), this value corresponds to 2.90 and lies in between the values for axially deformed rotor and spherical harmonic vibrator as shown by the dot-dashed line in Figure 1. The filled circles indicate values obtained for different Sr isotopes. For the neutron-deficient nucleus ^{78}Sr, the $R_{4/2}$ value corresponds to ~ 2.81 which is very close to the expected value of 2.90 for the X(5) symmetry and hence presents ^{78}Sr as a promising candidate for testing the features of X(5).

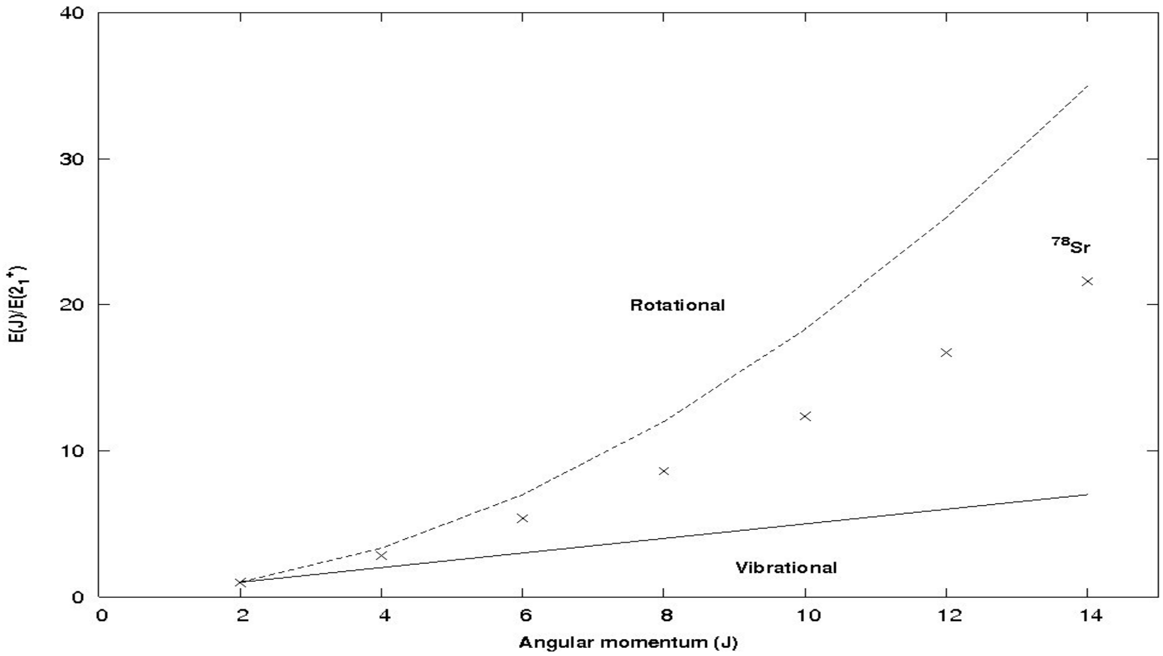

Figure 2: Excited state angular momentum, J, versus the ratio of the energies of the excited states to that of the 2_1^+ state, $E(J)/E(2_1^+)$ plot for ^{78}Sr nucleus. The dotted line shows the predictions for the axially deformed rotor SU(3), the points are data for ^{78}Sr from NNDC [17] and the solid line presents the predictions for harmonic vibrator U(5).

Figure 2 shows the detailed plot of the energy ratio $[E(J)/E(2_1^+)]$ for ^{78}Sr with the angular momentum J. In the figure, the dotted line displays the predictions for an axially deformed rotational nucleus, the solid line displays the predictions for a spherical harmonic vibrational nucleus and the points are the data obtained for ^{78}Sr nucleus, which consistently lie between these rotational and vibrational limits up to angular momentum $14\hbar$ and agree well with the X(5) predictions[15] as calculated by Brenner *et al*.

Another phenomenological guide to identify the X(5) symmetry in the transitional region is the P factor defined as $P=N_pN_n/(N_p+N_n)$ [16], where N_p and N_n represent the numbers of the valence protons and neutrons particles or holes respectively, and scales as the integrated valence proton neutron interaction strength. For an X(5) nucleus this value corresponds to ~5. Considering ^{100}Sn as the core, ^{78}Sr has 12 valence proton holes and 10 valence neutron holes giving the value of P factor ~5. In fact, considering the valence proton neutron interaction strength represented by the P factor, there are only four nuclei, ^{76,78}Sr and ^{78,80}Zr, in the region A<100 which we can expect to display the X(5) symmetry. Here, we propose to study ^{78}Sr. Following the success of this measurement, we would like to explore the other neutron deficient Sr and Zr nuclei in the near future.

For an X(5) nucleus, the B(E2) strengths of the transitions between the Yrast and non-

Yrast positive parity states have very characteristic signatures. The interband reduced electric quadrupole transition strengths between the Yrast states, B(E2;J→J-2), should increase with angular momentum J at a rate between that of rotor and vibrator and should be higher compared to the similar interband transitions between the non-Yrast states build on second 0+ state. The energy of the 0_2^+ state should be 5.65 times that of the energy of the 2_1^+ state. The non-Yrast states based on 0_2^+ band should have larger energy spacing than that of the Yrast band. The only neutron deficient nucleus which has been proposed to exhibit X(5) characteristics considering energy systematics is ^{122}Ba [18]. But even in this case, no informations has been obtained for the B(E2) values.

As mentioned before, to confirm the X(5) assignment, it is important to measure the reduced electric quadrupole transition strengths [B(E2)] between the levels which are yet to be known for ^{78}Sr in any detail. The B(E2) values are known only for the first two transitions and agree well with X(5) systematics as shown in figure 3. The level scheme on the left in figure 3 displays the X(5) predictions as calculated by Brenner *et al.* [15] whereas the level scheme on the right displays the experimental data for ^{78}Sr [17]. From the figure, it is evident that the energy spacing of the Yrast band and the B[E2] strength of the first two transitions in ^{78}Sr agree well with the X(5) predictions. Figure 4 displays the systematics of B(E2) values over Sr isotopes indicating the collective nature of ^{78}Sr.

^{78}Sr nucleus was first studied by Lister *et al.* [19] using fusion-evaporation reaction, with 100 MeV ^{24}Mg beam on ^{58}Ni target. Levels up to 10$\hbar$ and the lifetimes of first two excited states were measured in this experiment. Gross *et al*. [20,21] have measured ^{78}Sr using fusion-evaporation reaction with 110 MeV ^{24}Mg beam on ^{58}Ni target and 128 MeV ^{40}Ca beam on ^{40}Ca target and have extended the Yrast band up to 22$\hbar$. ^{78}Sr has also been studied using a fusion-evaporation reaction by Rudolph *et al.* [22] with 130 MeV ^{28}Si beam on ^{58}Ni target. Surprisingly, only a few negative parity bands and no positive parity band beside the ground state band have been observed in this reaction. It is difficult to study ^{78}Sr nucleus using fusion-evaporation reactions due to small cross sections and a lack of good stable target and beam combinations.

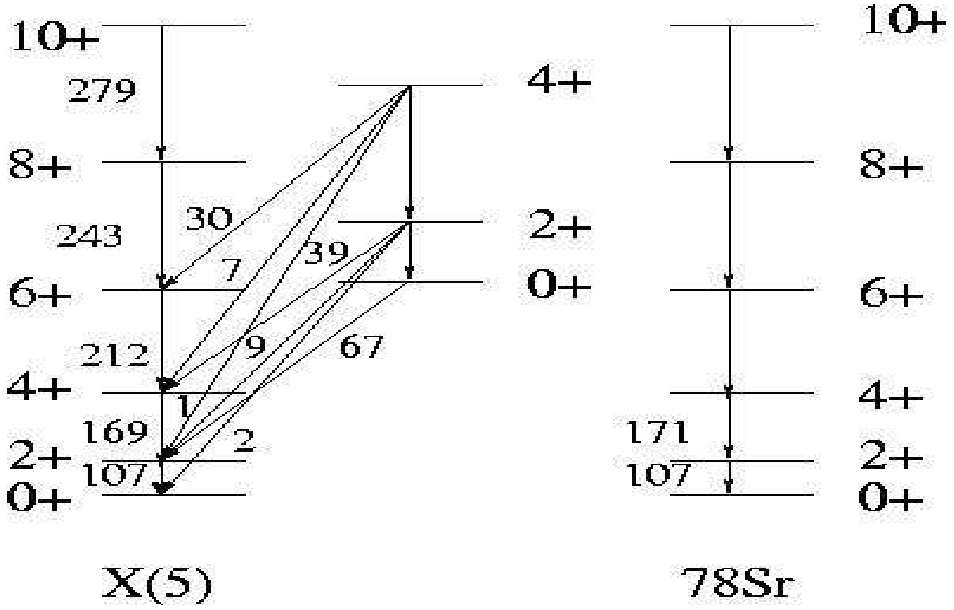

Figure 3: Comparison of X(5) predictions of energy levels and reduced transition matrix elements with experimental data in ^{78}Sr. Energy spacing in the Yrast band and the first two transition strengths agree very well with the X(5) predictions (D. Brenner et al. [15]).

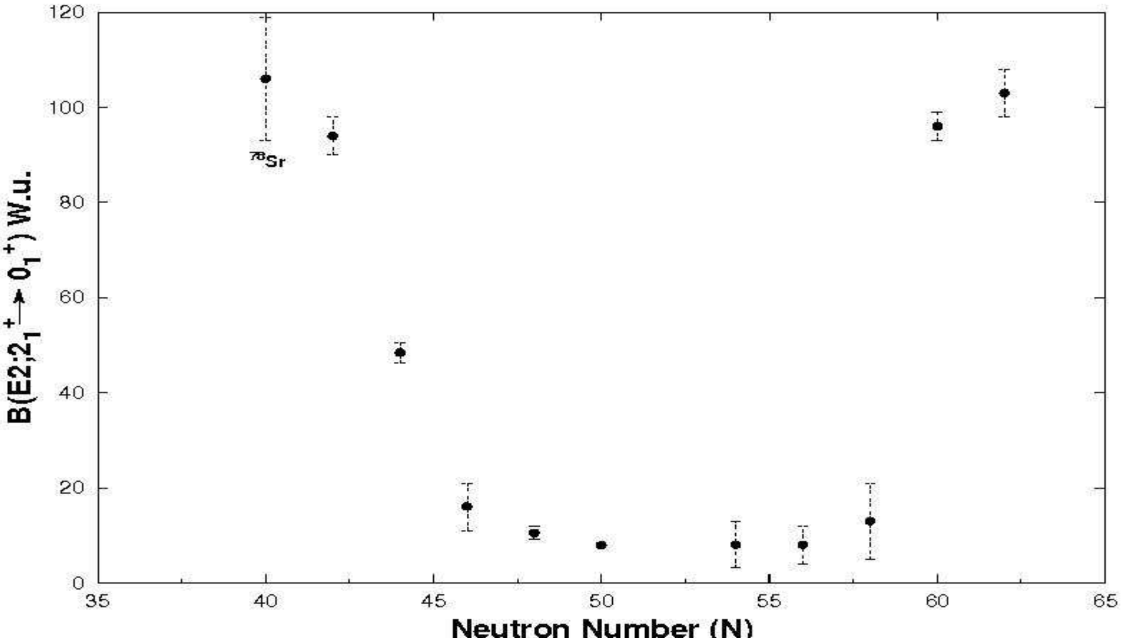

Figure 4: Systematics of $B(E2;\ 2_1^+\rightarrow 0_1^+)$ values in W.u. for Sr isotopes.

Hence, the physics goals of this proposal are two fold. Firstly, we would like to explore the second 0^+ band and secondly, we would like to measure the strengths of the interband and intraband transitions between the levels of the ground state and the second 0^+ bands. This will be explored by populating the states of interest via Coulomb excitation of ^{78}Sr beam below the Coulomb barrier to obtain model independent results.

Experimental Method

^{78}Sr will be studied using γ-spectroscopy techniques via Coulomb excitation of the radioactive ions impinging upon a ^{nat}Ni target. The setup consists of the Miniball array to detect γ-rays following Coulomb excitation and the CD detector in the forward direction to detect scattered beam particles for coincidence requirements. The CD detector is a double-sided segmented Si detector which covers angles in the range of 15°-50° in laboratory frame. Having four quadrants, each of which is segmented in 16 annular stripe on the front (θ coordinate) and in 12 radial segments (ϕ coordinate) on the back, the CD detector helps to determine the reaction kinematics and hence enables better Doppler correction of the γ-rays. Considering that the lighter targets give smaller excitation probabilities and heavier targets increase the elastic scattering in the particle detector as well as destroy kinematic focusing obtained through the use of inverse kinematics, ^{nat}Ni is optimal as evident from figure 5. It has been also found that in this case, for all scattering angles the condition for “safe” Coulomb excitation will be fulfilled.

Figure 6 displays the Rutherford scattering cross section for this reaction in the center of mass frame. The CD detector has an angular acceptance of 15°-50° in laboratory frame which will correspond to ~ 30°-175° in the center of mass frame [Figure 7]. Figure 8 displays the kinematics of this reaction. From the figure it is apparent that most of the angular range of the scattered particles will be covered by the CD detector (15°-50°) to give maximum particle detection efficiency.

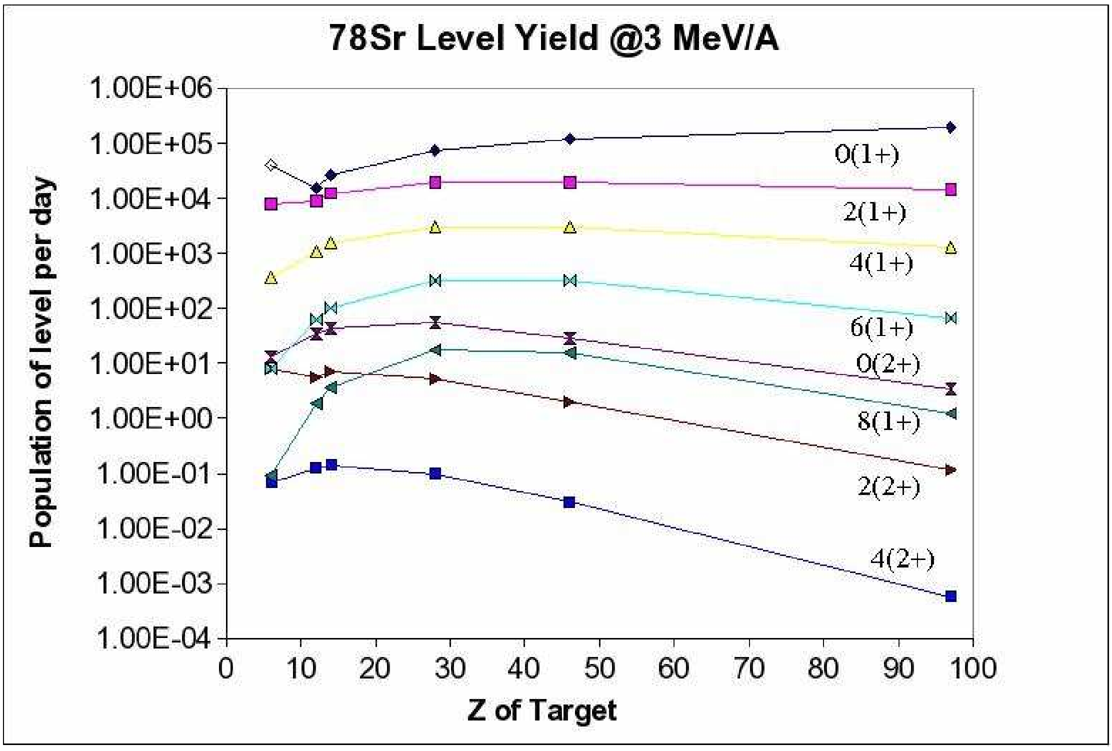

Figure 5: Yield of different excited levels as calculated using the Coulomb excitation code "CLX" [23] for different targets considering a γ-ray photopeak efficiency of 10% for Miniball, a beam intensity of 5x10^{4} ions/s, the CD particle acceptance range of 15^{o}-50^{o} in the laboratory frame, and a 1 mg/cm^{2} ^{nat}Ni target. Lines are to guide the eye.

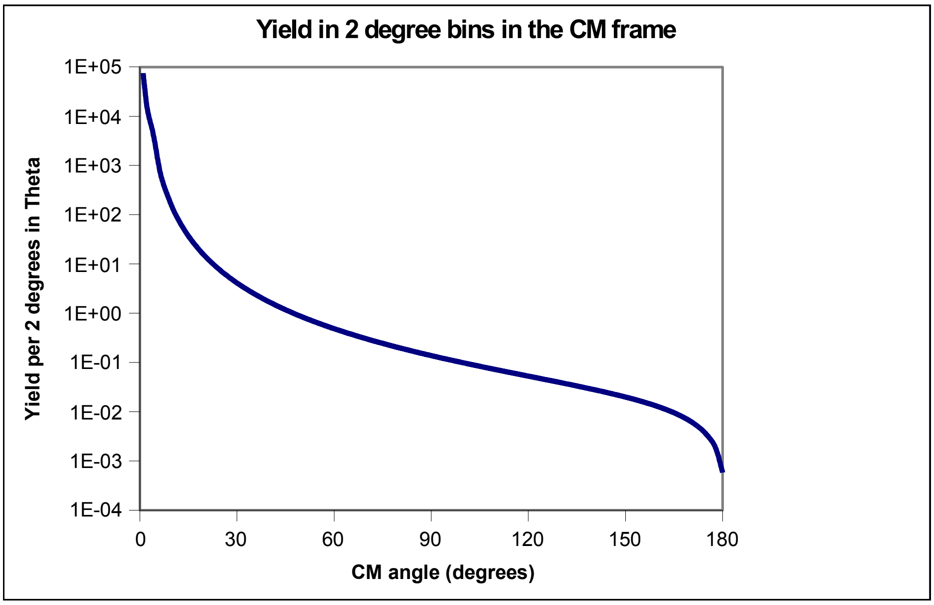

Figure 6: Rutherford scattering cross sections in centre of mass frame for ^{78}Sr (3.0 MeV/A) on ^{nat}Ni.

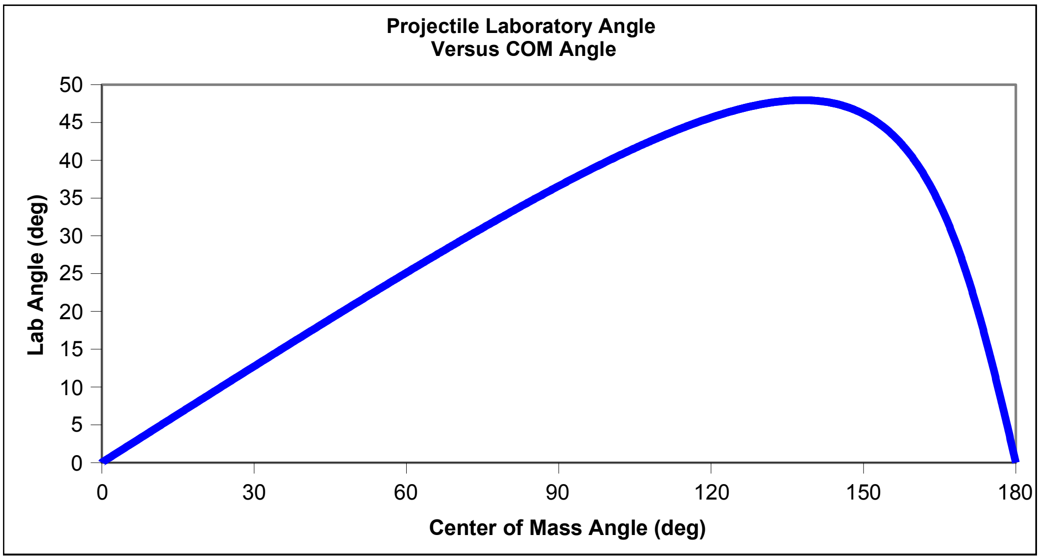

Figure 7: Projectile center of mass angle versus the laboratory angle.

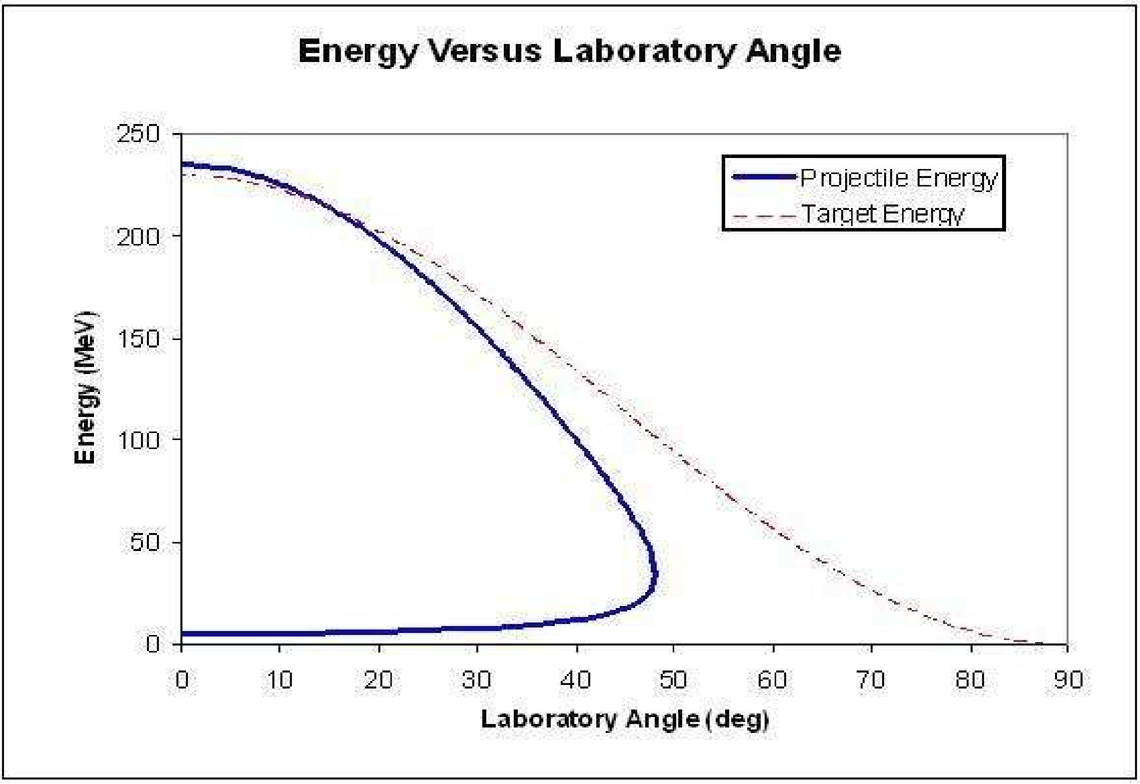

Figure 8: Beam particle scattering angle versus energy and target particle recoil angle versus energy in the laboratory frame.

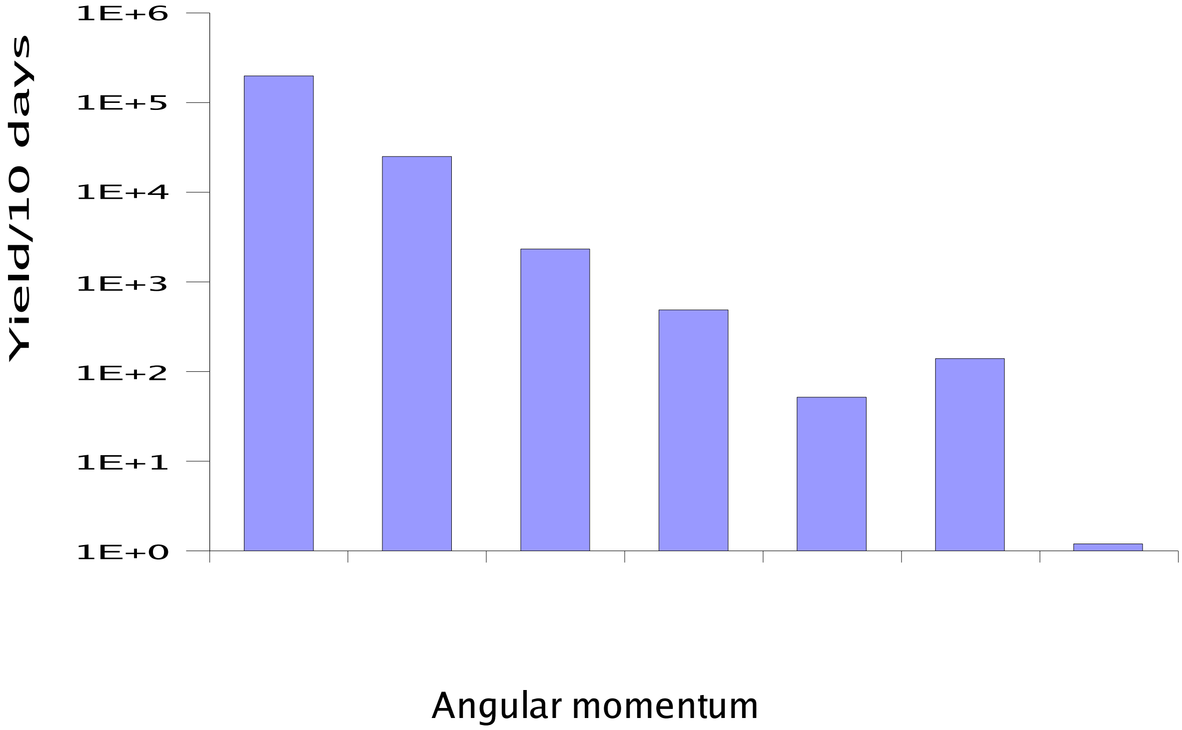

Figure 9: Predictions of the Coulomb excitation code GOSIA for the total yield of different levels in ^{78}Sr in 10 days. See text for details.

Figure 9 displays the yield of different levels in 10 days calculated using the code GOSIA for Coulomb excitation of the projectile with 3.0 MeV/A ^{78}Sr beam on ^{nat}Ni. The matrix elements assumed in the calculations have been taken from the X(5) predictions as shown in figure 3. No transitions have been considered between $0_2^+ \rightarrow 2_2^+$ and $2_2^+ \rightarrow 4_2^+$ levels. These states can be populated via two paths of excitation and may be enhanced or minimized according to the interference of the excitation probability. Integration over the angular range of 15^o-50^o covered by the CD detector have been performed in the calculations. As apparent from the previous discussion, the B(E2) values need to be measured with sufficient statistics to reduce the uncertainty and to obtain a precise value to differentiate from the rotor and vibrator limits.

The half life of the radioactive nucleus ^{78}Sr has been found as 2.5 min [17]. At REX-ISOLDE, ^{78}Sr has been produced in the focal plane of the separator with an intensity of $2.2 \mathrm{x} 10^6$ s^{-1} by bombarding 1 μA proton beams of energy 600 MeV from CERN SC on 50 gm/cm^2 Nb metal powder primary target. Since no data is available of ^{78}Sr beam with PSB+EBIS we have used the existing data from CERN SC for yield calculations. It is expected that the beam of interest will be contaminated by ^{78}Rb which will exceed the intensity of ^{78}Sr by two or three order of magnitude. Addressing this reality is critical to the success of our proposed experiment. A recent measurement at the CERN-ISOLDE facility with neutron deficient Sr isotopes [24] successfully used CF_4 gas at the ion source to form molecules of SrF+ with high efficiency. No RbF+ contaminant was found at this molecular mass region. Building upon this success, the electron beam ion source (EBIS) will be used to break up the SrF+ beam and charge breed the resulting ionized Sr. The resulting beam of Sr will then be a pure beam with A/q of ~4 and will be injected into REX. With an overall efficiency of 2% of $2.2 \mathrm{x} 10^6$ intense beam, considering REX and transfer line transmission efficiency, charge breeding efficiency, and a 50% efficiency for creating SrF+, we assume a ^{78}Sr beam of intensity 5x10^4 s^{-1} at the Miniball target position containing the ^{nat}Ni.

The calculations suggest that with a ^{78}Sr beam of intensity 5x10^4 s^{-1}, impinging on 1 mg/cm^2 thick ^{nat}Ni target, 10 days of beam time are required to obtain reasonable statistics for 0_2^+ band. This request assumes that the Miniball array will have at least a 10% γ-ray photopeak detection efficiency for the transitions of interest and that the CD detector covers the range of 15°-50° in the laboratory frame. We estimate that the detected rate of decay from the 2_1^+ state will be ~ 2x10^4 counts per day and that the total decay from the 0_2^+ state will be 60 counts per day, compared with the decay from the 2_2^+ of about 5 counts per day. This allows us to make a measurement of the B(E2;$0_2^+ \rightarrow 2_1^+$) strength relative to that of the B(E2;$2_1^+ \rightarrow 0_1^+$), which is known, to within 20% and compare the measurement to X(5) model predictions. We also calculate that we should have sufficient population of Yrast levels to obtain additional B(E2)s such as B(E2;$8_1^+ \rightarrow 6_1^+$) and B(E2;$6_1^+ \rightarrow 4_1^+$).

The calculated count rate of 60 counts per day for the 0_2^+ state depends upon a beam intensity of 5x10^4 ^{78}Sr nuclei/s. Since the 0_2^+ level has not yet been experimentally observed, a γ-γ coincidence measurement using Miniball must be performed to make the correct transition assignment. This coincidence assignment can be made upon the total of 60 counts in the 0_2^+ to 2_1^+ transition gating upon the 2_1^+ to 0_1^+ transition that we expect to occur in the γ-γ matrix. This can be successfully performed since the Miniball particle-γ-γ matrix should be very clean with little background.

Our estimates from the SC yield (scaled with a proton current of 1 μA assuming 3 pulses from the PSB to ISOLDE) and assuming a 2% total efficiency to transmit the pure ^{78}Sr beam to the Miniball target position are subject to change. If the 2% total efficiency to produce and transfer ^{78}Sr is too optimistic, a factor of 2 gain in production rate can be obtained by taking 6 of the 12 pulses from the PSB to ISOLDE. If our matrix element estimates based upon the X(5) predictions are too large, meaningful limits can be obtained to constrain the B(E2) from the 0_2^+ state. If we get 100 counts or fewer in the 0_2^+ to 2_1^+ transition, we will not be able to verify the assignment of the level via a γ-γ coincidence measurement.

If the overall beam intensity is lower than a pure beam of 5x10^4 ^{78}Sr per second on the Miniball target for 10 days, we can still obtain meaningful data on other transitions in ^{78}Sr. Using the calculated intensity of 3000 counts in the photopeak after 10 days for the $6_1^+ \rightarrow 4_1^+$ transition, we could still add to our knowledge of this nucleus and comparing the results to the X(5) model by measuring this transition even with a factor of 5 less beam over 10 days of measurement. At this lower beam intensity, though, we expect to observe only 100 counts from the 0_2^+ state and less than 30 counts from the $8_1^+ \rightarrow 6_1^+$ transition.

If the beam is not pure, then care must be taken to correctly identify the transitions that are observed. The transitions in ^{78}Sr can still be measured in a relative way since the lifetime of the 2_1^+ and 4_1^+ states are known. Although an absolute measurement of the reduced transition probabilities is preferred since it may have less uncertainty and the lifetime measurements could be verified, the relative B(E2)s would still provide useful information for the comparison with X(5) predictions.

Due to the experimental challenges of maintaining high beam intensities of ^{78}Sr on the Miniball target for 10 days it may be beneficial to have the beam time separated into different runs so that the maximum yield and maximum number of proton pulses can be utilized. Such an arrangement should not be detrimental.

Beam	Min intensity	Target Material	Ion Source	Beam time
^{78}Sr	5 x 10^4	Nb metal powder of 50 gm/cm^2.	EBIS with CF_4 gas.	10 days

References

[1] Iachello F, Phys. Rev. Lett. **87**, 052502 (2001).
[2] Iachello F, Phys. Rev. Lett. **85**, 3580 (2000).
[3] Krucken R *et al*., Phys. Rev. Lett. **88**, 232501 (2002).
[4] Casten R F *et al.*, Phys. Rev. Lett. **87**, 052503 (2001).
[5] Caprio M A *et al.*, Phys. Rev. C **66**, 054310 (2002).
[6] Tonev D *et al.*, Phys. Rev. C **69**, 034334 (2004).
[7] Dewald A *et al.*, Phys. Jour. **G 31**, S1427(2005).
[8] Rosensteel G *et al.*, Nucl. Phys. **759A**, 92 (2005).
[9] Bonatsos D *et al.*, Phys. Lett **584B**, 40 (2004).
[10] Bonatsos D *et al.*, Phys. Lett **632B**, 238 (2006).
[11] Dieperink A E L *et al.*, Phys. Rev. Lett. **44**, 1747 (1980).
[12] Clark R M *et al.*, Phys. Rev. C **68**,037301 (2003).
[13] Bizzeti P G *et al.*, Phys. Rev. C **66**, 031301 (2002).
[14] Hutter C *et al.*, Phys. Rev. C **67**, 054315 (2003).
[15] Brenner D S, AIP Conf. Proc. **638**, 223 (2002).
[16] McCutchan E A *et al.*, Pys. Rev. C **69**, 024308 (2004).
[17] Rab S, Nucl. Data Sheets **63**, 1 (1991).
[18] Fransen C *et al.*, Phys. Rev C **69**, 014313 (2004).
[19] Lister C J *et al.*, Phys. Rev. Lett. **49**, 308 (1982).
[20] Gross C J *et al.*, Phys. Rev. C **39**, 1780 (1989).
[21] Gross C J *et al.*, Phys. Rev. C **49**, R580 (1994).
[22] Rudolph D *et al.*, Phys. Rev. C **56**, 98 (1997).
[23] H. Ower, computer program CLX.
[24] Sikler G et al., Nucl. Phy. **763A**, 45 (2005).