Multiple Coulomb Ordered Strings of Ions in the ESR

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In a recent paper, Radon *et al.* [1] reported on high precision mass measurements with Schottky mass spectrometry of about 100 new isotopes with a high resolving power. In that experiment fully stripped isotopes were produced by fragmentation of a $^{209}Bi^{67+}$ beam at 930 MeV/u, separated in the fragment separator, and stored and cooled in the ESR. For fixed magnetic rigidity each species of the beam has its own frequency $f_i = v/C_i$, where C_i is the length of its trajectory close to the circumference of the ESR, C=108.4 m. Neighboring masses Δm run on slightly different trajectories due to their different rigidities and, thus, have different frequencies. Typical deviations were found from the measured frequencies of known isotopes as compared to the known calibration curve. If there are at least two masses so close to each other that their difference in frequencies is smaller than about 80...90 Hz on the average, the lower (higher) one is shifted characteristically to a higher (lower) value. This anomalous effect limits the mass resolution to about 20 μu and such masses then have to be discarded from the results.

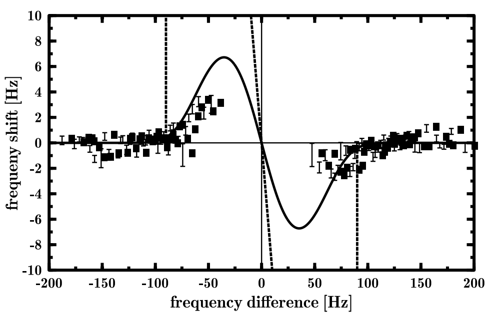

Figure 1: Average anomalous frequency shifts of neighboring isotopes *vs.* difference between their measured frequencies. (after Ref.[1]) with the result of the model calculation included (full line). The dashed sawtooth curve would result without folding over their thermal overlap volume.

In the present work we explain and make a model for the origin of these anomalous frequency shifts on the basis of the anticipation that the ions run on strongly correlated trajectories. The parameters here are of the same order of magnitude as the ones of the machine experiments on the anomalous jump to very low momentum spreads in the ESR [2] and in the SIS [3]. There it has been shown [4] that under the experimental conditions intra-beam scattering is strongly suppressed and that the ions cannot pass each other any more and, thus, run on strings.

Nuclides with different masses but with the same velocity run on different trajectories which are horizontally displaced so that, apart fom thermal fluctuations, $v = Cf$ remains constant, thus $\Delta C/C = -\Delta f/f$. This difference in length of trajectory transforms into the horizontal displacement $-\Delta x = (C/2\pi)\Delta f/f = 17\,\mathrm{m}\times\Delta f/f$. This fact leads to the model that if the displacement is larger than the thermal diameter, the two (or more) strings run on well separated trajectories yielding two (or more) distinct peaks in the Schottky spectrum which lie at the correct positions. The result of Fig. 1 is obtained assuming that this locking is not instantaneous if the clouds start to overlap, but that there is a smooth transition with a probability proportional to the overlap region of the clouds due to the averaging procedure over the experimental data, and folding this probability together with the experimental resolution of 15 Hz into the sawtooth curve of shifts (the dashed lines in Fig. 1). The dashed sawtooth line would result if the strings were always captured if their thermal radii start to overlap. Note that apart from the uncertainty coming from the assumed capture probability this model has no free parameters and that the result agrees nicely with the experiment.

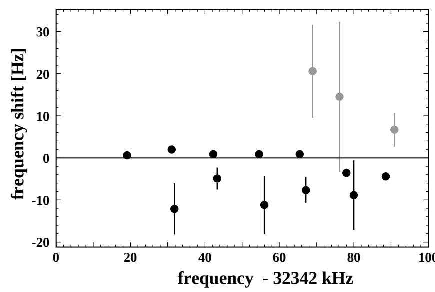

Figure 2: Measured anomalous frequency shifts in a relatively warm beam. The dots with nearly zero shifts belong to isotopes of the primary beam, others are nearby fragment nuclides. The gray dots are questionable by the lack of intensity (after Ref.[5]).

There is indication that the effect of locking or capture is not restricted to the existence of ultra-cold chains. During the preparation of the precision mass experiments similar anomalous frequency shifts have been observed in Ref. [5] in an experiment with a bare gold beam at 295 MeV/u. Its isotopes and other strongly populated fragments had velocity spreads of about 10^{-5} and thermal widths of about 4 mm. By cooling and scraping the beam radius the velocity spread decreased by one order of magnitude. Nearby fragment nuclides with slightly larger masses then acquired anomalous negative frequency shifts of the order of a few Hz, see Fig. 2.

Evidently, the low intensity fragment isotopes (with negative shifts and error bars) and masses slightly larger than the mass of the primary beam (with nearly zero shifts and no error bars) have been absorbed into the cloud of the primary beam itself, thereby reducing their frequencies slightly. The observed positive frequency shifts are statistically irrelevant.

References

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