Exploring the Dipole Polarizability of $^{11}$Li at REX-ISOLDE

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Dipole polarizability refers to the effect of the excitation to negative parity states through the electric dipole interaction. In nuclear reactions induced by stable beams, dipole polarizability does not play a major role. For nuclei close to the drip lines where the separation energies of neutrons or protons are small, a substantial part of the dipole strength function occurs at low excitation energies. We here propose to investigate this effect by measuring elastic scattering and break-up at energies close to the Coulomb barrier. We have chosen $^{11}$Li as the most suitable candidate for the REX-ISOLDE set-up.

1. Introduction

Halo nuclei are composed by a core nucleus and one or two loosely bound neutrons. Due to the loosely bound structure, they should be easily polarizable. Thus, in the presence of a strong electric field, the nucleus will be distorted, so that, with respect to the centre of mass of the nucleus, the halo neutrons will move opposite to the electric field, while the positively charged core will move in the direction of the field.

The phenomenon of dipole polarizability should affect strongly the elastic scattering of halo nuclei on heavy targets, even at energies below the Coulomb barrier, where the nuclear force should not be important. Two effects are relevant: First, Coulomb break up will reduce the elastic cross sections. Second, the distortion of the wave-function generated by the displacement of the charged core with respect to the centre of mass of the nucleus will reduce the Coulomb repulsion, and with it the elastic cross sections.

A simple way of describing the effect of polarizability is by means of a dipole dynamic polarization potential (DDPP). It has an attractive real part, that describes the reduction of the Coulomb repulsion, and an absorptive imaginary part, which describes the reduction of elastic cross section due to Coulomb break-up. The DDPP can be obtained using a semiclassical derivation [1], and it is such that, given the B(E1) distribution, the projectile and target and the scattering energy, it is completely determined by an analytic expression.

Recently, the experimental values of the B(E1) distribution of $^{11}$Li, measured by Zinser et al [2], have been used to calculate the effect of dipole polarizability on the elastic scattering of $^{11}$Li on $^{208}$Pb at 24 MeV (2.2 MeV/u), which is well below the Coulomb barrier [3]. It is found that there is a strong reduction of the differential cross sections with respect to Rutherford at backward angles, which depends on which values, compatible with
2. Proposed experiment

The experiment proposed consists in measuring the elastic differential cross section of $^{11}\text{Li}$ on $^{208}\text{Pb}$ at 2.2 MeV per nucleon laboratory energy. This will be complemented with the detection of the $^9\text{Li}$ fragments coming from break-up, and from a systematic study of the scattering of the other isotopes $^6,^7,^8,^9\text{Li}$ at the same energy per nucleon. Thus, we expect to see and quantify the reduction of the differential cross sections at backward angles for $^{11}\text{Li}$, compared to the Rutherford cross sections expected for the other isotopes.

The main limiting factor for this experiment is the intensity of the $^{11}\text{Li}$ beam. We will make the conservative assumption that we can achieve an intensity of 125 $^{11}\text{Li}$ per second interacting with the $^{208}\text{Pb}$ target. This estimate assumes a production rate of 10,000 pps, a transmission of 10% through REX-ISOLDE with a cost of 3 half lives due to cooling, breeding, and transport of the $^{11}\text{Li}$ nuclei. To compensate this very small value, we require to have the solid angle of the detector as large as possible, and the target as thick as possible.

We propose to use a detector setup as shown in the figure. It contains four annular detectors, each one of which is a $\Delta E' - E'$ telescope, covering all the azimuthal angles and a range of scattering angles from $\theta = 5$ to 45 degrees (EF), from 50 to 70 degrees (MF), from 110 to 130 degrees (MB) and from $\theta = 135$ to 175 degrees (EB). Uncertainties in the solid angles of the detectors could be avoided determining $\sigma(\text{EF}, R)/\sigma(\text{EB}, R)$ by measuring the ratio of forward to backward counts for an stable isotope such as $^6\text{Li}$,
scattering below the barrier. Further, as the set-up is symmetric, systematic differences in detectors and electronics can be tested by rotating the full detector set-up 180° around the target, and again determining the above mentioned ratio.

Assuming that the incident beam is pure $^{11}$Li, after the collision with the target one will get elastically scattered $^{11}$Li, as well as break-up fragments. From them, the most important fragment will be $^9$Li coming from the removal of the halo neutrons. It is very important that $^{11}$Li events are separated from $^9$Li events. This can be done considering that, while the backward scattered $^{12}$Li would have an energy of about 20 MeV, the $^9$Li, having lost the neutrons, would have an energy of about 17 MeV. The separation of $^9$Li and $^{11}$Li events puts a limit on the target thickness. We will take $2 \text{mg/cm}^2$ in our calculations. With this value, $^9$Li events can be separated from $^{11}$Li events in all the detectors except in the MF detector.

The expected count rate for the different detectors, assuming different values of the dipole polarizability, is shown in table 1. As example, one would need 119 hours (15 shifts), to obtain 100 events in the end-backward detector assuming that the cross section is Rutherford. Taking the end-forward counts for normalisation purposes, this would allow to measure average cross sections in the end-backward, middle backward and midde-forward detectors with statistical accuracies of 10%, 8% and 2.5%, which are sufficient to observe the predicted effects of dipole polarizability.

The number of break-up events gives a complementary information to the elastic cross sections, to determine the break-up mechanism. A very rough estimate is to assume that the break-up events observed in each detector will just be the difference of Rutherford events to the actual elastic events observed. Using the numbers of table 1 shows that break-up cross section can be measured in the experiment with 10-20% accuracy.

It is useful to define ratios which are independent from geometric factors, and which only depend on the polarizability. If we scatter $^6$Li from $^{208}$Pb below the barrier, we expect to find pure Rutherford scattering. For the Li isotopes, we can define the following ratios, where $D$ is the detector (MF, MB, EB), and $\Lambda$ represents the mass of each measured isotope $\Lambda = 7, 8, 9, 11$:

$$R(D, \Lambda) = \frac{N(D, \Lambda)N(EF, 6)}{N(EF, A)N(D, 6)}$$

Note that in this ratio, any uncertainty associated to the solid angle, the efficiency of the detector or the intensity of the beams disappear. For the isotopes $^{7,8,9}$Li, the value of this ratio should be 1, showing that the effect of dipole polarizability is small, at all scattering angles. However, for $^{11}$Li, the ratio should be significantly smaller than one,
and thus one will see a systematic change in the behavior of $^{11}$Li with respect to the rest of the isotopes, which is yet another manifestation of the halo structure of this nucleus.

3. Interpretation of the results

We will consider an experimental situation as previously described. Consider that we have run the experiment for 119 hours, or for the necessary time to obtain 305700 counts in the end-forward detector. By doing this measurement, we expect to achieve the following objectives:

a) To observe that, in contrast to what happens for all normal nuclei, for which the elastic cross sections at energies below the barrier is accurately given by the Rutherford formula, $^{11}$Li behaves differently, due to its large polarizability, and gives elastic cross sections which are considerably smaller. This would be achieved measuring the number of elastic events, for $^{11}$Li, and finding that they are significantly smaller than the values expressed in the first row of table 1 for the MF, MB and EB detectors. This also could be seen by finding break-up events in those detectors, and also by finding that the ratios $R(D, 11)$ for those detectors are significantly smaller than one.

b) To quantify the reduction of the elastic cross sections, and thus obtain information, complementary to the distribution measured by Zinser et al, that allows to determine more accurately the B(E1) distribution at energies close to the break-up threshold. This can be achieved comparing the number of observed elastic events, and comparing them with the predictions in table 1. These results could be confirmed by looking at the break-up cross sections, which should be proportional to the B(E1) values. Also, the deviation of $R(D, 11)$ from unity depends on the size of the polarizability.

c) To see whether the DDPP is sufficient to describe the elastic differential cross section distribution, or, on the contrary, a more accurate treatment of the reaction mechanism is required. It should be considered that, even if the nuclear potential by itself is unimportant at energies so much below the barrier, coulomb-nuclear interference effects may play a significant role. We expect that the effect of these coulomb-nuclear interference terms will lead to a further reduction of the elastic cross sections at backward angles. So, if the ratios of the number of counts in the EB detector to the MF or MB detectors is not consistent with the patterns shown in table 1 it would be an indication of nuclear coulomb interference playing a role. This would be confirmed with a larger number of break-up events in the backward detector, or a value of the ratio $R(EB, 11)$ smaller than expected.

REFERENCES