TRIUMF - RESEARCH PROPOSAL

Experiment no.

Sheet 1 **of**

Title of proposed experiment

Study of halo effects in the Scattering of ^{11}Li with heavy targets at energies around the Coulomb Barrier

Name of group

DENEX

Spokesperson for group

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(For each member, include percentage of research time to be devoted to this experiment over the time frame of the experiment)

Name	Institution	Status	Time
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M. Álvarez	University of Sevilla	Research Associate	50 %
M. V. Andres	University of Sevilla	Associate Professor	10%
M.J.G.Borge	IEM/ CSIC	Senior Researcher	50 %
L. Buchmann	TRIUMF	Research Scientist	20 %
W. Catford	University of Surrey	Lecturer	
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M. Turrión	IEM/CSIC	Research Associate	20 %
P.Walden	TRIUMF	Professor	10%

Start of preparations:

Date ready:

Completion date:

Beam time requested:

12-hr shifts	**Beam line/channel**	**Polarized primary beam?**

SUMMARY

The scattering of halo nuclei is strongly affected by coupling to the continuum. At energies below the Coulomb barrier, the dominant effect is that of the dipole Coulomb force that couples the ground state to the low energy continuum. Nuclear effects should also play a role, even at energies below the Coulomb barrier, due to the long range of the halo. A careful analysis of the elastic and break-up cross section of a halo nucleus on a heavy target at energies around the Coulomb barrier should give information on the B(E1) distribution of the halo nucleus, and also about the reaction mechanisms that govern the collisions of halo nuclei.

We here propose to investigate this effect by measuring elastic scattering at energies close to the Coulomb barrier. We have chosen ^{11}Li as the most suitable candidate. We ask for a total of 28 shifts of radioactive beam plus 2 shifts of stable beam.

BEAM and SUPPORT REQUIREMENTS

Experimental area

TUDA facility in the ISAC experimental hall

Primary beam and target (energy, energy spread, intensity, pulse characteristics, emittance)

500 MeV proton beam from TRIUMF cycloton
10 microamp of proton beam on a Ta target

Secondary channel

ISAC-HE

Secondary beam (particle type, momentum range, momentum bite, solid angle, spot size, emittance, intensity, beam purity, target, special characteristics)

ISACII experimental hall need to go to 2.4 -3.1 MeV/u, ask for 10^4 ^{11}Li p/s
Spot size < 0.5 cm

Energy resolution better than 100 keV

TRIUMF SUPPORT:
Summarize all equipment and technical support to be provided by TRIUMF. If new equipment is required, provide cost estimates.

NOTE: Technical Review Forms must also be provided before allocation of beam time.

Continued infrastructure support from TRIUMF for TUDA at ISAC, including assigned personnel, included ISAC-II

Need of Faraday cup at the end of the chamber.

NON-TRIUMF SUPPORT:
Summarize the expected sources of funding for the experiment.
Identify major capital items and their costs that will be provided from these funds.

NSERC TUDA Project Grant (L. Buchmann et al.)
Ref. Proyecto: FPA2005-02379 (Dinámica, estructura y modos de desintegración de núcleos exoticos ligeros)
Spanish Founding agency CICYT from 31 /12 2005 till 30 /12 2007 Responsible: María José García Borge
Ref. Proyecto: FPA2005-04460 (Dispersión de Núcleos Exóticos a energías en torno a la barrera Coulombiana)
Spanish Founding agency CICYT from 31 /12 2005 till 30 /12 2006 Responsible: Joaquín Gómez Camacho
Ref. Proyecto: FPA2003-05958 (Exóticos)
Spanish Founding agency CICYT from 31 /12 2003 till 30 /12 2006 Responsible: Ismael Martel Bravo

SAFETY	**Sheet** 4 **of** 20

The ^{11}Li beam is of very short half-life ($T_{1/2}$ = 8.5 ms) , only one gamma line in the decay of 320 keV and it is produced with very low intensity,.

I would say no safety issues are relevant in this experiment.

1 Scientific Justification

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 B(E1) distribution is a measurement of the importance of polarizability. Large B(E1) values at low excitation energies (close to the break-up threshold) indicate that the nucleus is easily polarizable. In terms of the ground state wavefunction, large B(E1) values at energies close to the break-up threshold indicate a large probability that the halo neutrons are in the extreme asymptotic tail. Recent experimental results by Nakamura et al [NAK05] show, in a preliminary analysis, that the B(E1) values may be considerably larger than those measured by Zinser et al [ZIN97].

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). This potential 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 [AND94], and it is completely determined by an analytical expression in terms of the B(E1) distribution, the projectile and target and the scattering energy. When the DDPP, along with the standard Coulomb and nuclear potentials, is used in an optical model calculation, the results of the elastic cross sections are very close to those of a full coupled channels calculations including explicitly the dipole Coulomb excitation [AND97].

We made use of the experimental values of the B(E1) distribution of ^{11}Li, measured by Zinser et al [ZIN97] 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 [AND99]. We found that there is a strong reduction of the cross sections with respect to Rutherford at backward angles, and a smaller reduction at forward angles. This reduction depends on which values, compatible with the experimental uncertainties, are taken for the B(E1) distribution. For the central values of this distribution, we predict a 30% reduction around 150 degrees, 25% around 120 degrees and 8% reduction around 60 degrees. However the measurement of Zinser et al. [ZIN97] were not very sensitive to the B(E1) values very close to the break-up threshold. recent measurements by Nakamura et al., [NAK05] show that B(E1)-values close to the break-up threshold are very important. if we take the values of [NAK05] for the B(E1) distribution, we find that the reduction is much more important, about 20% at 60 degrees. Thus, we can conclude that a measurement of this reaction can be of interest, since it would allow to determine the values of the DDPP, and, from it, it would allow to reduce the uncertainties in the B(E1) distribution of ^{11}Li.

Furthermore, we have performed explicit coupled channels calculations that take into account the coupling to the continuum. These calculations take into account the fact that the most relevant degree of freedom of ^{11}Li, when colliding with a heavy target at energies around or below the Coulomb barrier, is the coordinate between the ^{9}Li core and the centre of mass of the neutrons. Hence, a di-neutron model is used for ^{11}Li. As it is well known, the di-neutron model overestimates the B(E1) distribution. So, in our calculations the B(E1) strength is renormalized to be in agreement with the experimental B(E1) distribution measured by Nakamura [NAK05]. Our calculations, take into account both Coulomb and nuclear coupling (CDCC Coulomb + Nuclear). The results, shown in Fig. 1, predict a strong reduction in the elastic cross sections, in accordance to our previous results using polarization potentials. We also present a coupled channel calculation including only Coulomb dipole excitation (CDCC Bare + Dipole Coulomb), and an optical model calculation using the dipole Coulomb polarization potential (Bare + Coulomb DPP). The calculations using dipole Coulomb polarization potential take into account only the effect of Coulomb dipole excitation. All these calculations are in agreement for small angles.

Our calculations, shown in Fig. 1, indicate that at forward angles (θ < 60º for E=24 MeV, θ < 45º for E=28 MeV, θ < 40º for E=30 MeV), Coulomb dipole excitation is the dominant excitation mechanism, and nuclear coupling does not play any role. Therefore, a careful measurement of the reduction of the elastic cross section, along with the energy distribution of the break-up fragments, will allow to obtain information on the B(E1) distribution, which allows to differentiate between the measurements of Nakamura [NAK05] and Zinser [ZIN97].

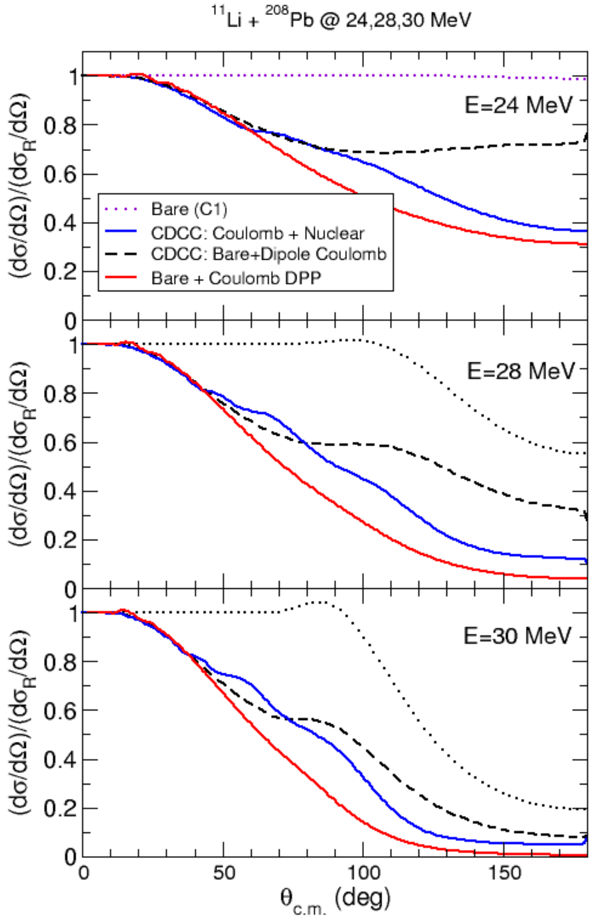

Figure 1: Elastic cross section of ^{11}Li on ^{208}Pb divided by the Rutherford cross section at 24, 28 and 30 MeV. The dotted line indicates the calculation with a bare potential, where the halo effect is not considered. The red line indicates the halo effect approximated through a dipole coulomb polarization potential. The dashed line indicates the halo effect calculated considering the coupling to the continuum due to the dipole coulomb force. The blue line indicates the halo effect including both coulomb and nuclear coupling to the continuum.

At larger angles, nuclear forces play an important role. The study of the elastic and break-up cross sections, performed at several collision energies, will allow understanding the role of the nuclear and Coulomb interaction in the collision of a weakly bound nucleus such as ^{11}Li on ^{208}Pb. We will also learn the role of the continuum of ^{11}Li in the scattering process, in particular, which partial waves play a role, which break-up energies are more important, and if the 3-body nature of ^{11}Li has a special significance in this collision.

1.1. **Systematic of Li isotopes**.

It should be stressed that the strong effect of dipole polarizability in ^{11}Li scattering is a consequence of the low break-up threshold. Other Li isotopes, such as ^{6}Li, ^{7}Li, ^{8}Li and ^{9}Li, will not show the reduction in Rutherford cross sections at energies below the barrier. In fact, the scattering of ^{6}Li and ^{7}Li on ^{208}Pb at energies around and below the barrier has been studied in detail at Daresbury Laboratory using unpolarized [KEE93] and polarized beams [MAR94]. The effect of dipole polarizability for the elastic scattering of ^{7}Li on ^{208}Pb at 27 MeV was investigated [MAR98], and found that the reduction on the elastic cross sections is about 1%, much smaller than for ^{11}Li.

A systematic study of the cross sections of Li isotopes could be illuminating. At energies well below the Coulomb barrier (24 MeV), the scattering cross sections for ^{6}Li, ^{7}Li, ^{8}Li and ^{9}Li should be accurately described by the Rutherford formula, while that of ^{11}Li should display an important reduction in the cross sections at backward angles.

1.2. **Inclusive break-up cross sections of ^{11}Li.**

The reduction in the elastic cross sections of ^{11}Li at backward angles is due to the combined effect of the real, attractive part of the dynamic polarization potential, which generates a reduction of the Coulomb repulsion, and the absorption which is due to the effect of the Coulomb and nuclear break-up. This latter effect can be investigated by looking at the fragments of ^{11}Li, in particular to the ^{9}Li. This fragment can be differentiated from the ^{11}Li nuclei just by taking into account that they will have approximately 9/11 of the energy of ^{11}Li. Thus, the ratio of ^{9}Li to ^{11}Li events will be a complementary measurement of the effect of coupling to break-up channels. It depends on the break-up cross sections, while the reduction in the elastic cross sections of ^{11}Li depends on the coupling through the dynamic polarization effects.

2. **Previous experience**.

Two experiments very similar to the one proposed here were performed at the CRC at Louvain la Neuve (PH189. PH215) [SAN05-SAN05a]. We measured the elastic scattering cross section of ^{6}He on ^{208}Pb at several energies around the Coulomb barrier. From the analysis of the elastic scattering data, clear evidence for a long range absorption in the ^{6}He – ^{208}Pb optical potential were found. This was partly due to the effect of Coulomb dipole polarizability. However, the effect of nuclear break-up did also play a major role, as it was shown by coupled channels calculations that took into account both effects of Coulomb and nuclear coupling to the continuum.

The ^{4}He fragments, coming from break-up, were also detected making use of a set of telescopes allowing mass and charge identification. From the detection of these fragments, we found that break up was indeed the major reaction channel, and that the coupling to the continuum was indeed responsible of the long range absorption observed in elastic scattering. Dipole polarizability, which was due to the effect of dipole Coulomb coupling to the continuum, was a part of the dynamical effect of Coulomb and nuclear coupling to the break-up channels that affected strongly the scattering of ^{6}He.

3. Description of the experiment.

The experiment proposed consists in measuring the elastic differential cross section of ^{11}Li on ^{208}Pb at 2.2 to 3.0 MeV/u laboratory energy. We expect to observe and quantify the reduction of the differential cross sections at backward angles compared to the Rutherford cross section. By doing this measurement, we expect to achieve the following objectives:

a) To observe that, ^{11}Li behaves differently to all normal nuclei, for which the elastic cross sections at energies below the barrier is accurately given by the Rutherford formula. This is due to its large polarizability, and results in elastic cross sections which are considerably smaller.

b) To quantify the reduction of the elastic cross sections, and thus obtain information, complementary to the distributions measured by Zinser et al [ZIN97] and Nakamura et al [NAK05]. This will allow to determine more accurately the B(E1) distribution at energies close to the break-up threshold.

c) To see whether the dipole polarization potential is sufficient to describe the elastic differential cross section distribution, or, on the contrary, a more accurate treatment of the reaction mechanism is required, including explicitly the coupling to the continuum.

3.1. Intensity

The main limiting factor for this experiment is the intensity of the ^{11}Li beam. We will make the conservative assumption that a yield of 10000 ^{11}Li per second interacting in our target can be obtained. To compensate this relatively small value, we optimize the solid angle of the detector system to a maximum coverage and the target thickness.

3.2. Energy

The energy of the ^{11}Li beam should be sufficient so that the backscattered ions (both from elastic scattering and from break-up) are able to go through the Delta-E detector of the telescope. According to our simulations (see an example in Fig. 2) , energies from 2.2 to 3 MeV per nucleon are required.

3.3. Resolution

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 by the telescope as it is shown in Fig. 2.

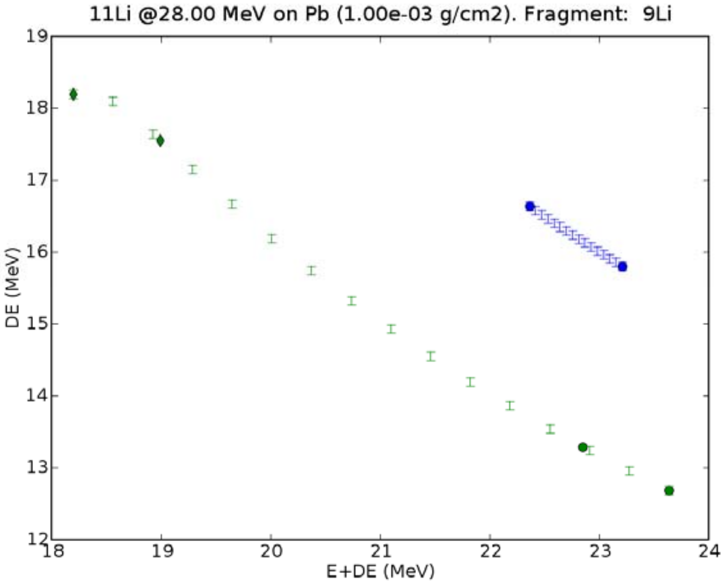

Figure 2: Simulation of the telescope response (thickness of 40 µm and 500 µm) at 150º degrees for the scattering of ^{11}Li beam of 28 MeV on a 1mg/cm^{2} ^{208}Pb target. The blue points correspond to ^{11}Li elastic events scattered along the thickness of the target. The green points correspond to ^{9}Li break-up fragments. The detector resolution (better than 50 keV) as well the energy dispersion (< 100 keV) of the incoming beam are not considered in the calculations. This effect are small compared to the 2.5 MeV difference between the ^{11}Li scattered beam and the ^{9}Li break-up fragment.

3.4. Detectors

We plan to use the DINEX detector array, which was used for the experiments at Louvain la Neuve. It consists on two annular telescope arrays (CD), which are placed at forward and backward angles. They consist of four 90º Si telescopes of thickness 40 µm front and 500 µm back (see left hand side of Fig. 3). To cover intermediate angles the setup is complemented by other DSSSD-Si telescopes of equivalent thickness. A schematic cartoon of the setup is display on the right hand side of fig. 3. The setup covers large scattering angles (from 15-40º and 140-165º with DINEX and from 55-125º with the DSSSD) relevant for the calculations, see Fig. 1. These detectors could have concentric strips, which allow getting information on the scattering angle.

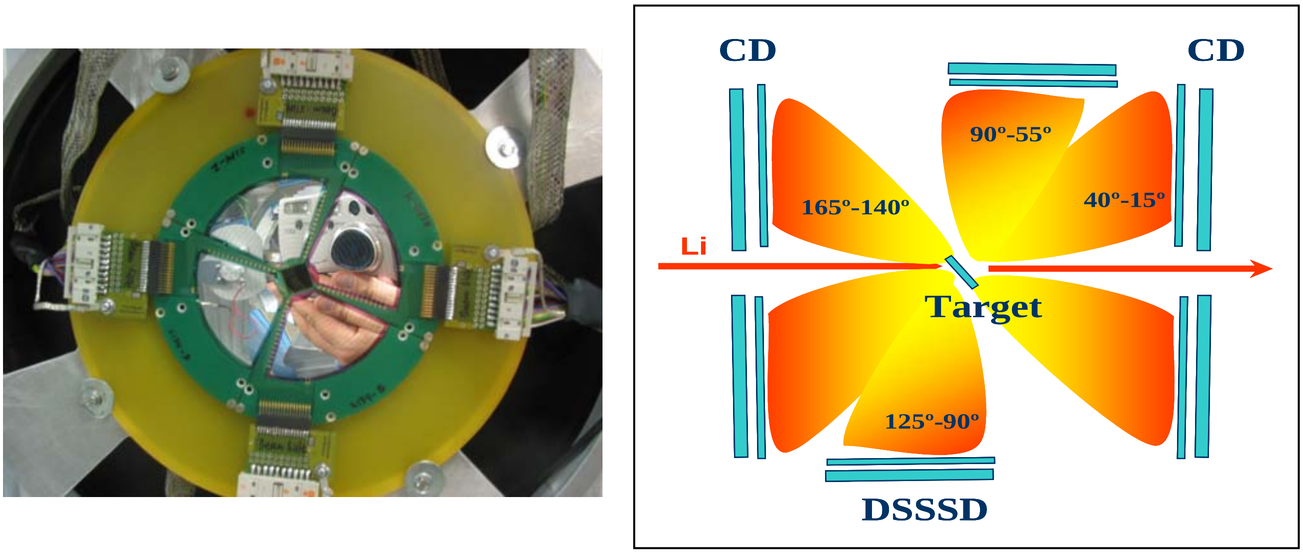

Figure 3: On the left, view of one of the two annular DINEX detector array. In each quadrant there are 16 strips for the Delta-E detector. On the right, a schematic display of the setup with the angles subtended by the combined system of DINEX plus DSSSD.

Uncertainties in the solid angles of the detectors will be reduced measuring the ratio of forward to backward number of counts for a stable isotope, such as ^{7}Li, at energies below the Coulomb barrier and compare with the Rutherford values. In this way, the ratio of the cross sections for the ^{11}Li projectile, and those of the ^{7}Li projectile will be given by the corresponding ratio of the number of counts, and systematic errors in the solid angles of the strips and in the efficiency of the electronic chain could be avoided. Further, as the set-up is symmetric, systematic differences in detectors and electronics can be tested by rotating the full detector set-up 180 degrees around the target, and again determining the above mentioned ratio.

3.4 Target thickness.

The stopping power of a ^{11}Li beam at 28 MeV on a ^{208}Pb target is 0.4 MeV per mg/cm². Taking into account that some backward scattered particles have to cross the target twice, and in order to maintain the energy separation of ^{11}Li and ^{9}Li, this thickness should not be larger than 2.5 mg/cm². We will take 1 mg/cm².

4 Readiness

We plan to use the ISACII Facility when operative. Detector system, electronics and DAQ are already available.

5 Beam time required

We have evaluated the expected number of counts for the scattering of ^{11}Li in our setup. This number of counts correspond to the total number of events (elastic and break-up), seen in typical strips which are placed at forward (θ =30) as well as backward (θ =150) scattering angles. It should be noticed that our setup has four sectors, each one with sixteen strips corresponding to different scattering angles. The number of counts given in the table corresponds to four strips, constituting one ring, for the given scattering angle. These estimations assume a beam with 10000 pps of ^{11}Li

Counts per hour for ^{11}Li	***N(θ=30)***	***N(θ=150)***
E=2.2 MeV/u	1620	8,4
E=2.6 MeV/u	1132	5,8
E=3.0 MeV/u	852	4,4

Rutherford cross sections were assumed as an estimate of the total (^{11}Li + ^{9}Li) number of events in the detectors. To carry out this experiment, a estimated beam time of 48 hours for the energy of 2.2 MeV/u, 72 hours for 2.6 MeV/u, and 96 hours for 3.0 MeV/u is needed. Thus, this corresponds to 18 shifts of 12 hours. These 18 shifts will allow to obtain cross sections with accuracies on the order of 10% at backward angles, and 1% at forward angles. This accuracy refers to the elastic cross sections, which are estimated to be between 40 % and 10% of the total number of events at backward angles. Besides, it is very important to have measurements at the same velocities of the scattering of ^{9}Li, to determine the optical potentials accurately, because this is an essential ingredient in the coupled channels calculation. Considering that the intensity of ^{9}Li should be much larger than that of ^{11}Li, we will dedicate one day of beam time per energy of ^{9}Li. This corresponds to 6 shifts.

Also, we need an accurate reference measurement with a stable isotope of Li, such as ^{7}Li. This would correspond to one day of beam time. We add two more shifts with a pilot beam for alignment of the setup and adjust the electronics. This makes a total of 28 shifts.

6 Data analysis

In order to account for uncertainties in the target thickness, solid angle of the strips, etc, we will determine the ratios of the number of counts to a reference beam, at energies below the Coulomb barrier, for which we can safely assume that cross sections will be determined by the Rutherford expression. This reference beam will be taken as ^{6}Li, at the energy of 18 MeV. Hence, N(R,θ) is the number of counts obtained in a certain time, in a given detector which is placed at an scattering angle θ. This number will be proportional to the Rutherford cross section, multiplied by the adequate factor solid angle and efficiency factor F(θ) , and the factor associated to target thickness and beam intensity I(R). So,

$$\sigma_{Ruth}(R,\theta) = N(R,\theta)\, I(R)\, F(\theta)$$

For the radioactive isotopes of Li, we will obtain the number of counts N(E,A,θ) , which correspond to the isotope of mass A (where A=9 or A=11), the beam energy E, and the scattering angle θ. This number determines the elastic differential cross section, including the adequate factor solid angle and efficiency factor $F(\theta)$, and the factor associated to target thickness and beam intensity $I(E,A)$.

$$\sigma(E,A,\theta) = N(E,A,\theta)\, I(E,A)\, F(\theta)$$

For very small values of the scattering angle θ, the cross sections are proportional to the Rutherford cross section, that has the same angular dependence (in the centre of mass frame), independently on the energy, or mass of the projectile. Hence, if we take θ_R as a small reference angle, we obtain that the double ratio

$$R(E,A,\theta) = (N(E,A,\theta) / N(E,A,\theta_R)) / (N(R,\theta) / N(R,\theta_R)) = \sigma(E,A,\theta) / \sigma_{Ruth}(E, \theta)$$

gives directly the ratio of the differential cross section to Rutherford. We have made use of the fact that the angular dependence of the Rutherford cross sections is the same, independently on the energy or the projectile mass. Note that in this double ratio all the uncertainties associated to solid angles or beam intensities in the different runs cancel. However, there may be effects associated to changes over time of the efficiencies of the electronic chain, which can be corrected using the information of the Pulser, as shown in [SAN05a]. Also, one should take into account small corrections to pass from centre of mass angles to laboratory angles.

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