TRIUMF — RESEARCH PROPOSAL	Experiment no.	Sheet 1 of 15

Title of proposed experiment:

^{18}Ne(α,p)^{21}Na via ^{18}Ne(^{6}Li,d)^{22}Mg* alpha transfer

Name of group: ALPHASPEC

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Members of the group (name, institution, status, per cent of time devoted to experiment)

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T. Davinson	University of Edinburgh	Research Fellow	10%
M. Aliotta	University of Edinburgh	Lecturer	10%
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Start of preparations:	now
Date ready:	End of 2006
Completion date:	Summer 2007

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
28	SCEBT / TUDA II	no

The ^{18}Ne(α,p)^{21}Na reaction is important for the breakout of the hot CNO cycle. In recent experiments, a few resonances in the energy region $E_{\mathrm{c.m.}} = 1.7 - 2.9$ MeV could be identified by a direct measurement [1,2] and their strengths could be measured. However, many levels in the ^{22}Mg compound nucleus could not be uniquely assigned with respect to their widths and angular momenta. Many more states have also been identified before by a measurement of the ^{12}C(^{16}O,^{6}He)^{22}Mg reaction [3] but no spectroscopic factors could be derived, only energy-corrected mirror states in the ^{22}Ne nucleus have been used for the calculation of the stellar reaction rate.

For the previously proposed and approved direct ^{18}Ne(α,p)^{21}Na measurement E870, the needed ^{18}Ne intensity can not be achieved with the currently available ion sources. High intensities would be necessary to reach low energy resonances of astrophysical interest. Even if such yields were available, the lowest energies of astrophysical interest, corresponding to about 500 keV in the center of mass are not likely to be reached and therefore have to be determined by other means.

With the recently commissioned superconducting accelerator at ISAC II, higher energies are available which opens the possibility of an indirect measurement via an α transfer reaction. We therefore propose the measurement of the ^{18}Ne(^{6}Li,d)^{22}Mg* α transfer reaction at ISAC II energies. The cross-section at those energies is much higher and the spectroscopic strength of the α particle in ^{22}Mg can be obtained by comparing the measured cross-section with DWBA calculations. In fact, for small α widths, transfer reactions offer the only possibility of determining spectroscopic factors. With a ^{18}Na intensity of only 5×10^5 pps, a measurement is possible that can be compared with the ambiguous data from [1,2] and [3].

Experimental area

ISAC-II, TUDA II.

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

Primary proton beam from cyclotron

Secondary channel

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

4.5 MeV/u ^{18}Ne ($t_{1/2} = 1.7$ s) beam. An intensity of at least 5×10^5 pps is needed.

TRIUMF SUPPORT:

ISAC RIB production and operational support.

NON-TRIUMF SUPPORT

TUDA chamber, detectors, and data acquisition from U.K. TUDA group (Edinburgh/York).

While the radioactivity is low, the decay product ^{18}F lives rather long ($\approx$ 2 hours) and the usual precautions when opening the chamber will be taken.

1 Scientific Justification

^{18}Ne with its half life of about 1.7 seconds acts as a β^+ waiting point in the second hot CNO cycle (about $T_9 = 0.4$):

$$^{12}\mathrm{C(p,}\gamma)^{13}\mathrm{N(p,}\gamma)^{14}\mathrm{O}(\alpha,\mathrm{p})^{17}\mathrm{F(p,}\gamma)^{18}\mathrm{Ne}(e^+\nu)^{18}\mathrm{F(p,}\alpha)^{15}\mathrm{O}(e^+\nu)^{15}\mathrm{N(p,}\alpha)^{12}\mathrm{C}.$$

At higher temperatures ($T_9 > 0.4$), a breakout from the this CNO cycle via the reaction chain ^{18}Ne(α,p)^{21}Na(p,γ)^{22}Mg(α,p)^{25}Al(p,γ)^{26}Si is possible, from where heavier isotopes can be produced by the rp-process and the rα-process. A corresponding reaction chain can also be ignited by a breakout from the ^{15}O waiting point, starting with α capture on ^{15}O. Due to a poor set of available data, the influence of the inital ^{18}Ne(α,p)^{21}Na on the total CNO leaking rate is not quite clear. The latest published measurement by Groombridge *et al.* [1] stated an enhanced reaction rate by a factor of 50-100 compared with calculations based on statistical Hauser-Feshbach estimation.

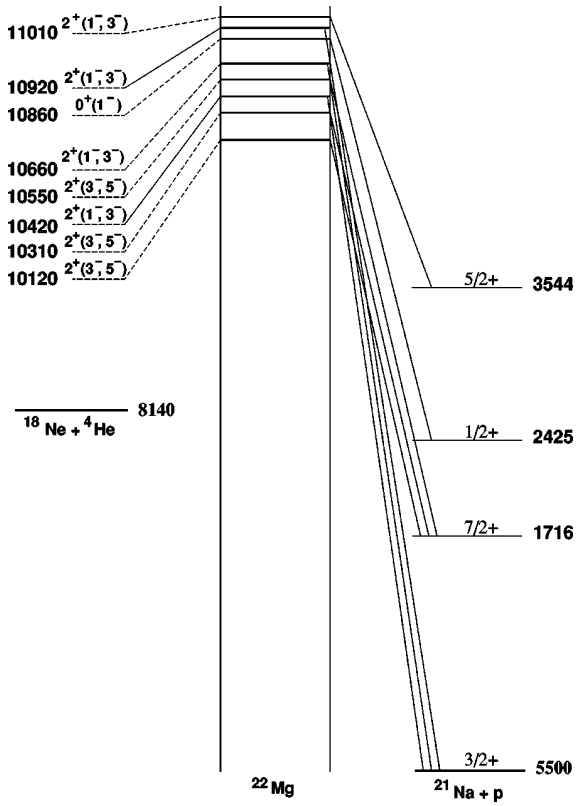

Fig. 1 ^{22}Mg levels of interest, taken from [1].

Fig.1 shows the levels and spin assignments identified by the direct measurement of Groombridge *et al.* [1]. Some resonances could be observed in up to 4 ^{21}Na excited recoil states and in many cases the detected protons could not be uniquely attributed to one of the ^{21}Na levels. For instance, the 10920 resonance could be observed in the p_3 as well as the p_0 channel with almost the same yield. In an indirect measurement by A. Chen *et al.* [3], 23 levels in ^{22}Mg between the α threshold ($E_x = 8.14$ MeV) and $E_x = 11.14$ MeV could be identified, so a level spacing of 130 keV can be expected.

Another ambiguity can be seen in the spin assignment. The angular range was too small to determine the spin, and the recommended 2^+ assigment for most of the levels is more a systematic guessing than a measurement. If the spins can not be assigned uniquely, the angular distribution of the protons is only known vaguely, and therefore, the detector efficiency has a large error.

Therefore, a more precise measurement of the resonance strengths and widths is necessary. Currently, no high intensities of ^{18}Ne can be produced, so a direct measurement is impossible. However, this problem can be compensated by an indirect measurement at higher energies that are now available at TRIUMF. In the proposed measurement of ^{18}Ne(^{6}Li,d)^{22}Mg* at ISAC II energies, many highly excited ^{22}Mg* states become visible in the obtained deuteron spectra. From the angular distributions, the spin of the resonance can be derived. The α width can be obtained from the overall normalization of the cross-section.

2 Description of the Experiment

2.1 Set-up

The aim of the experiment is the determination of the spectroscopic factors of an α particle in excited ($E_x < 12$ MeV) ^{22}Mg nuclei from which the α widths of the different levels can be derived. Since the proton width for the ^{18}Ne(α,p)^{21}Na reaction is large, the cross section is dominated by the α width. Therefore, if the α widths and spins can be determined, the resonance strengths $\omega\gamma$ are also known and the reaction rate can be derived.

The experiment will be performed at the TUDA chamber mounted at the end of the ISAC II beamline. The target will be a 50 μg/cm^2 ^{6}LiF (0.2 μm) layer on a carbon backing where the beam particle lose about 1 MeV. In this energy interval, the cross-section barely changes. The set-up is shown in fig.2.

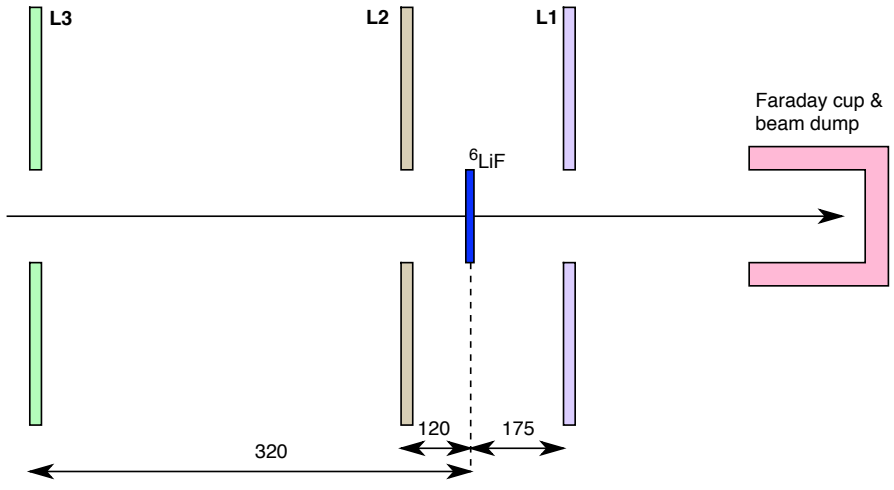

Fig. 2 Proposed set-up with three LEDAs.

One downstream (L1) and two upstream LEDAs cover angular ranges of 16° - 36.5° (L1), 133° - 157° (L2), and 158° - 171° (L3), respectively, divided by 16 angular steps each. The beam will be dumped in a Farady cup where the intensity can be montitored. The bunched beam also enables a TOF measurement.

There are about 30 other levels below the 10 MeV excitation energy leading to peaks at higher energies in the deuteron spectra. They all can be measured simultansously and provide additional information for other reactions like ^{21}Na(p,γ). The following calculations for a direct stripping reaction are important for an estimation of the angular range that needs to be covered and the expected cross-sections for the ^{18}Ne(^{6}Li,d)^{22}Mg* reaction.

2.2 Estimation of the cross-section and angular distribution

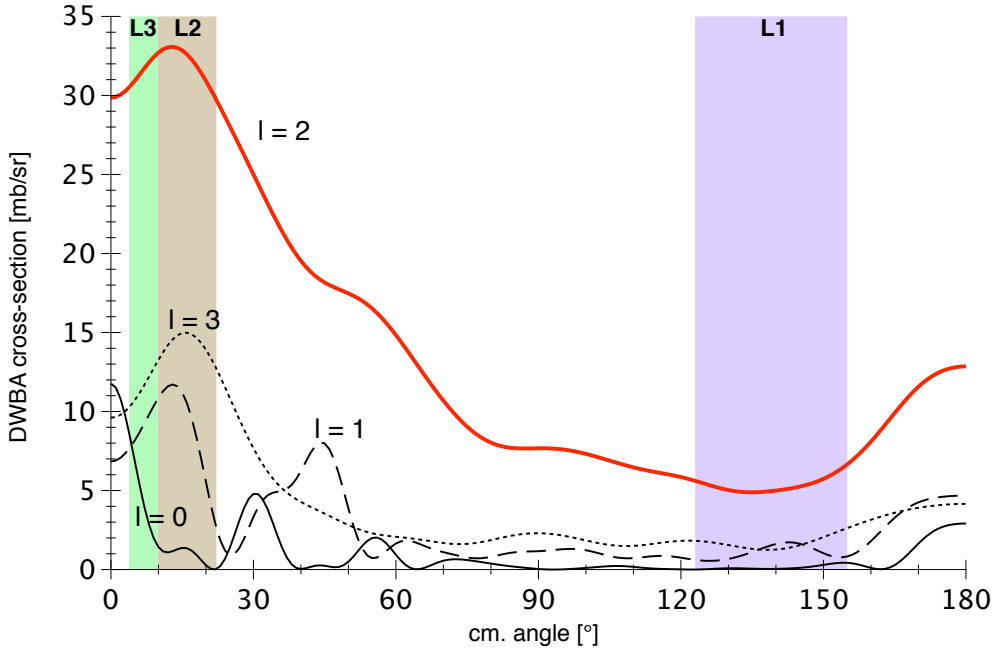

Fig. 3 Calculated angluar distribution in the c.m. system for different angular momentum transfers for the ^{6}Li(^{18}Ne, d)^{22}Mg* reaction (normal kinematics) with $E_{\mathrm{x},^{22}\mathrm{Mg}} = 10.12$ MeV. l is equal to the spin of the resonance. The impact energy is 4.5 MeV/u. The shadowed regions inidicate the angular ranges covered by the three detectors as in the set-up proposed (see above).

The cross-section for a DWBA calculation is an incoherent sum of contributions from different angular momentum transfers, weighted by the spectroscopic factors.

$$\sigma(E) \sim \sum_{lj} \frac{1}{2j+1} |S_{lj}|^2 \sigma_{\mathrm{lj}}(E)$$

Since ^{18}Ne and the α particle both have spin zero and positive parity there is only one possible transfered orbital and total angular momentum (l and j) which is equal to the spin J of the ^{22}Mg* recoil. This greatly simplifies the situation as the spectroscopic

factors can be assigned unambiguously and the angular distribution is a direct indicator of the spin of the excited ^{22}Mg recoil.

The cross-section and angular distribution of a transfer reaction is also determined by the optical potential for all configurations. A Distorted Wave Born Approximation should provide sufficient accuracy for an estimation. Furthermore, the zero-range approximation for the α+d =^{6}Li state is also well fulfilled which reduces the problem to finding an optical potential for the entrance channel, the exit channel, and for ^{18}Ne + α configuration.

Fig. 3 shows the angluar distribution for different spins of the ^{22}Mg recoil excited to 10.12 MeV at an impact energy of E_{lab} = 4.5 MeV/u. The calculations have been performed with the code DWUCK4 [4], employing potentials from [5], [6], and [7] for ^{6}Li+^{18}Ne, d+^{22}Mg, and α+^{18}Ne, respectively. Clearly, the l = 2 transfer is the largest one, which is also the most likely spin assigment of all the states in this energy region found so far [1]. With a good angular resolution, remaining spin ambiguities can be probably resolved in the set-up proposed here.

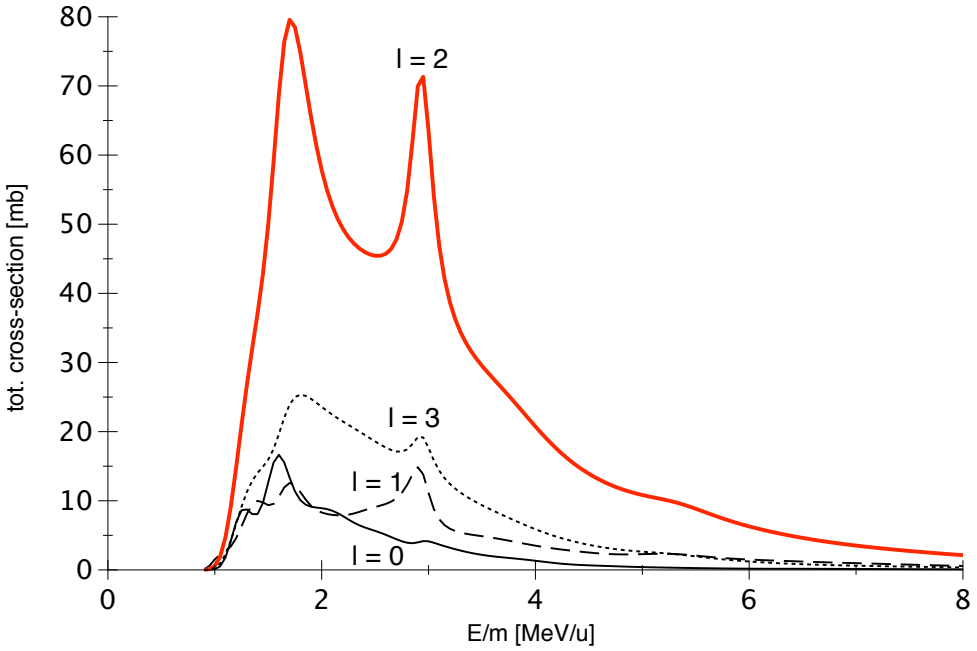

Fig. 4 Excitation curves, calculated with DWBA zero-range.

A zero-range paramter of D_0^2 = 7.6 × fm^{2}MeV^3 and a spectroscopic factor of 1 has been assumed in the calculations. The real spectroscopic factor can be estimated by comparing the α widths measured by [1] (assuming a large proton width, $\Gamma_p/\Gamma \approx 1$) with the one-particle α width. The values are in the same order of magnitude, so we can expect spectroscopic factors between 0.1 and 1. However, nearly nothing is known about the strengths of the states in the astrophysically important region below E_x = 10 MeV.

The excitation curve in Fig. 4 clearly shows two single particle resonances. However, strength and position sensitively depends on the optical potential used, so it would be useful to measure at different energies to determine the highest cross-section but also to reveal possible resonant contributions in the ^{24}Al compound nucleus. The d + ^{22}Mg

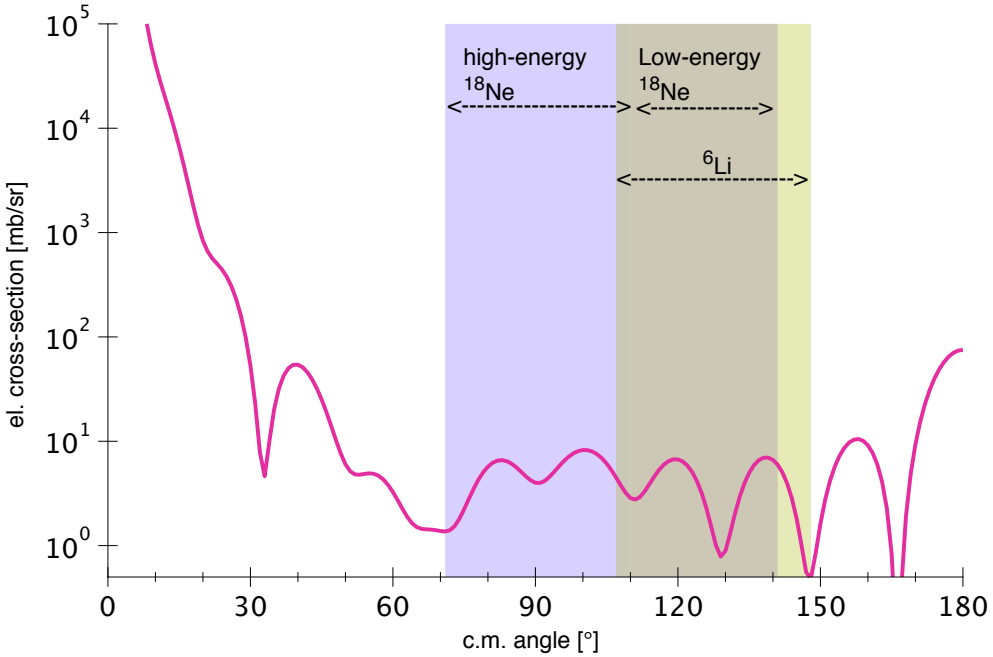

Fig. 5 DWBA cross-section for ^{6}Li on ^{18}Ne elastic scattering in the c.m. system (normal kinematics).

potential was derived from a global fit for all d+X potentials [6] and has been proved to be reliable in many other reactions. For the α + ^{18}Ne configuration, the potential is merely used to find a wave function of the bound or scattering state by variation of the potential depth, so the potential has not to be known exactly but there also exist good global fits [7]. For the ^{6}Li + ^{18}Ne potential, the situation is more difficult and it would be desirable to measure the potential by elastic scattering at the same energies.

Fortunately, the elastic scattering is a by-product of the reaction measurement and can be simultaneously determined by a detector placed in forward direction. Fig. 5 shows the elastic scattering cross-section in the c.m. system at 4.5 MeV/u and the angular regions covered by the detectors (see set-up above). The corresponding angular distributions in the lab. frame as well es the energies are shown in Fig. 6. The elastic cross-section exhibits characterisitc maxima and minima with a period of about 10°. The set-up can be extended by another forward detector to cover also the region around the first minimum. However, in the first place it serves only as a check of the optical potential for ^{6}Li and should be sufficient to fix the optical potential parameters.

Finally, the angular distribution of the reaction products and their energies are shown in fig.7. The flat end of the deuteron distribution is actually not flat but has a prominent peak (see fig.3) that is nearly balanced by kinematic effects. The excited ^{22}Mg recoils immediately decay to ^{21}Na + p, again with different end states, depending on the ^{21}Ne excitation energy (see fig. 1). For the ^{21}Na ground state transition, the maximum angle is $\approx 60°$ for the protons and $\approx 20°$ for ^{21}Na. However, the energy of the protons is too high to stop them in the detector. At least, they produce a signal that can be detected in coincidence with ^{21}Na as well as the backwards emitted deuterons. A more detailed

kinematic analysis will show whether this can improve the efficiency of the set-up.

The high energy deuterons emitted in forward direction can not be stopped in the L1 detector either. However, they will not disturb the measurement of the elastically scattered ^{6}Li and ^{18}Ne since they lose only a few MeV. In backwards direction at L2 and L3, the energy is about 3 MeV and the expected level spacing is about 60 keV (130 keV in the c.m. system). Assuming a negligible energy straggling for the deuterons leaving the target, the levels can be still resolved in the spectrum.

The reaction cross-section for all detectors is about 10 mb/sr. Therefore, with 5×10^{6} ^{18}Ne beam particles per second and the target density given above, we can expect 4 deuterons / min / sr for each ^{22}Mg level. Roughly estimated, the total solid angle of L1, L2, and L3 is 3 sr. Since we have 48 angles, we roughly expect 14 deuterons / hour / angle and 10% statistics is reached after 7 hours.

2.3 Particle discrimination and other by-products

Elastically scattererd carbon, fluorine, and ^{18}Ne (from scattering on C and F) can be energetically differentiated from elastically scattered ^{6}Li and ^{18}Ne (on ^{6}Li) and/or by TOF measurement.

3 Experimental Equipment

The experiment needs the TUDA scattering chamber at ISAC II, TUDA II.
LEDA detectors are available at Lothar Buchmann's group.

4 Readiness

TUDA II will be available 2006.

5 Beam Time required

As estimated, a 7-hour run is required for 10% statistical error at each angle. The cross-section will be presumably smaller since the calculations are based on a spectroscopic factor of 1. To be on a safe side and also to gain a statistical error better than 10%, 24 hours are proposed for each energy. Since we also want to scan an energy region between 1.7 and 4.5 MeV/u in order to find the two single particle resonances (see fig.4), we propose about 200 keV/u steps, resulting in 14 days or

28 12-hour shifts

It should be noted that an energy change is an additional help to gain more reliable data for the optical potentials involved. As mentioned previously, spectroscopic factors for

the lower lying ^{22}Mg states close to the α threshold have a large error or are completely unknown. Another uncertainty is the actual ^{18}Ne intensity that can be delivered to TUDA II. If both, the intensity and the spectroscopic factors are low we just reduce the number of energies but still have good chance for a successful experiment.

6 Data Analysis

Only standard analysis tools are required. However, since the α widths are derived by a comparision with model calculations, some theoretical study for a careful selection of the model parameters is needed.

References

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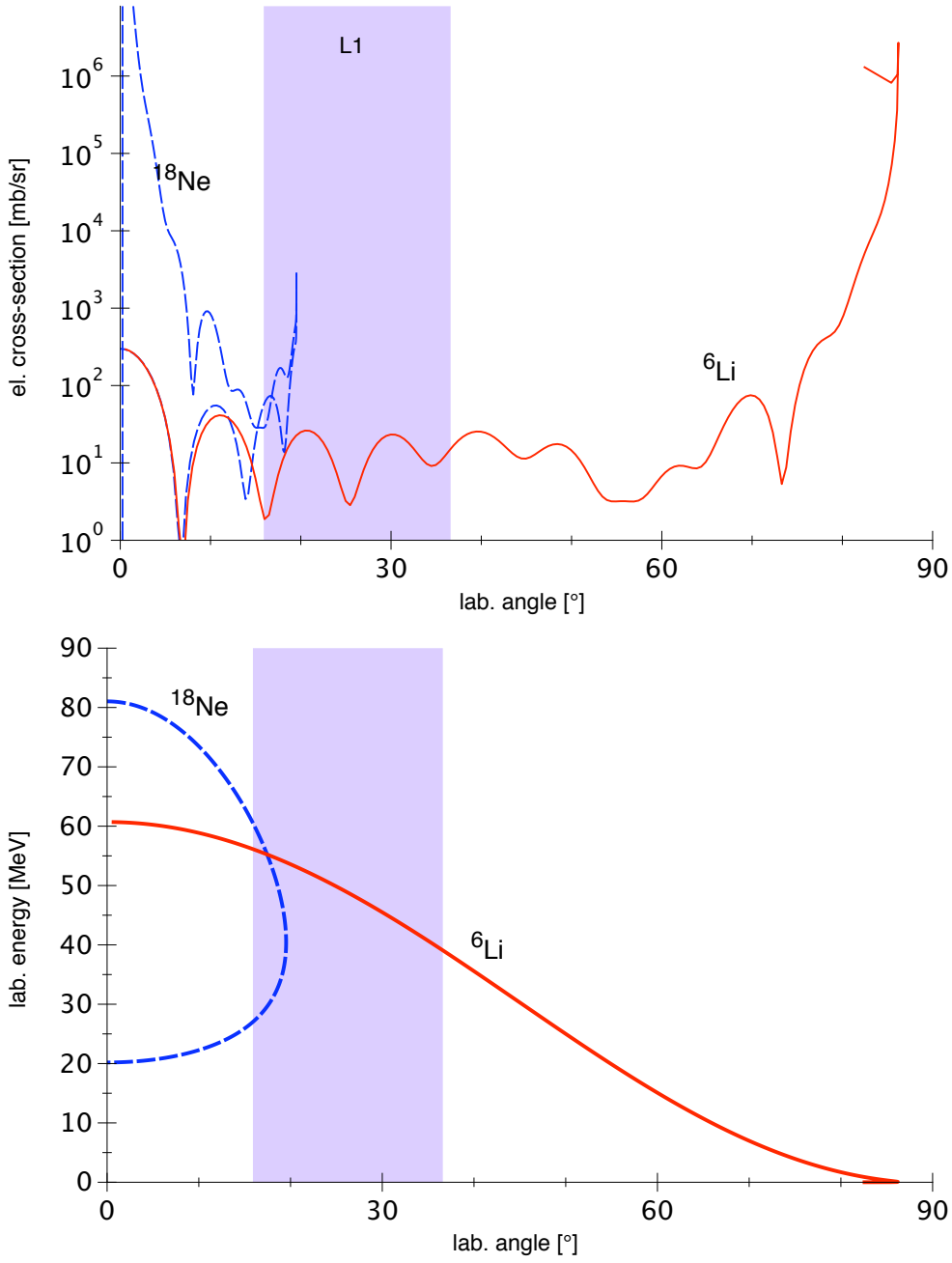

Fig. 6 Top: DWBA cross-section for ^{18}Ne on ^{6}Li elastic scattering at 4.5 MeV/u in the lab. system (inverse kinematics, compare with fig. 5). Bottom: Energies in the lab. system

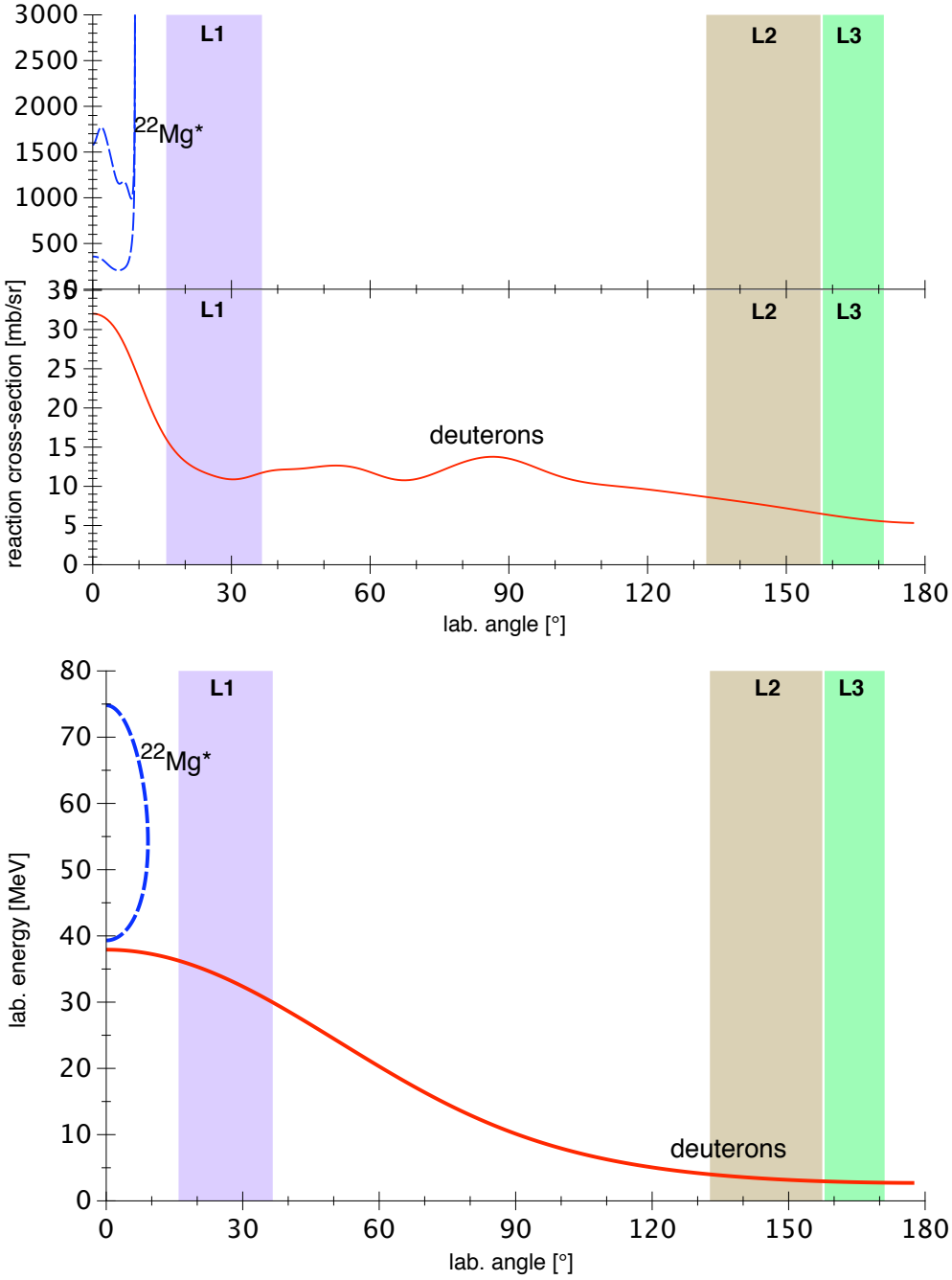

Fig. 7 Top: DWBA cross-section for the ^{6}Li(^{18}Ne, d)^{22}Mg* reaction at 4.5 MeV/u in the lab. system (inverse kinematics, compare with fig. 3). Bottom: Energies in the lab. system. Note that the deuterons are actually backward-peaked but the distribution is strongly skewed by kinematics.

Include publications in refereed journal over at least the previous 5 years.

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