TRIUMF – RESEARCH PROPOSAL

Experiment no. E900

Sheet of

Title of proposed experiment: A determinations of the $\alpha + {}^{15}O$ radiative capture rate by a measurement of the ${}^{15}O({}^{6}Li,d){}^{19}Ne$ reaction

Name of group: TUDA

Spokesperson for group: Professor B R Fulton
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Members of group (name, institution, status)

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

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Dr B Greenhalgh	U. of York	RA	30
Mr J Pearson	U. of York	Student	30
Dr D L Watson	U. of York	Senior Lecturer	30
Dr N M Clarke	U. of Birmingham	Senior Lecturer	20
Professor A C Shotter	U. of Edinburgh	Professor	20
Dr T Davinson	U. of Edinburgh	RA	20
Mr N Farrington	U. of Edinburgh	Student	20
Mr P Monroe	U. of Edinburgh	Student	20
Mr C Ruiz	U. of Edinburgh	Student	20
Dr F Sarazin	U. of Edinburgh	RA	20
Dr K Schmidt	U. of Edinburgh	RA	20
Professor P J Woods	U. of Edinburgh	Professor	20
Dr L Buchmann	TRIUMF	Senior Scientist	20
Dr P Walden	TRIUMF	Scientist	20
Professor J D'Auria	SFU	Professor	20

Date for start of preparations: Now

Date ready: April 2001 Dec 2001

Completion date:

Beam time requested

12-hr shifts	Beam line/channel	Polarized primary beam?
22 shifts	ISAC–HE line	unpolarised

SUMMARY

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Do not exceed one page.

The α+^{15}O radiative capture yield remains a key measurement for explosive nuclear astrophysics scenarios. It is thought to be the principle route for break out from the Hot–CNO cycle in novae and X–ray bursters, but until the reaction rate can be pinned down we cannot determine the conditions under which the thermal runaway commences, nor the yield of heavy elements which will be produced in the subsequent rp–process.

A direct measurement of this reaction will be attempted with the DRAGON spectrometer, but achieving this is still some years off. Because of the importance of this reaction, there have been a number of attempts to measure the yield through indirect means. In this proposal we request time for such a measurement, using an alpha transfer reaction onto ^{15}O to determine the alpha decay width of the key states in ^{19}Ne. Uncertainties in the measurement arising from uncertainties in the potentials of the reaction model calculation will be minimised through internal consistency checks.

BEAM REQUIREMENTS

Sheet of

Experimental area

ISAC–HE, TUDA line

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

Protons, 500 MeV, ISAC production target

Secondary channel

HE–ISAC, TUDA beamline

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

^{15}O 1.5 MeV/amu ~10^9 pps

^{15}N 1.5 MeV/amu ~10^9 pps

SUPPORT REQUIREMENTS

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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.

^{15}O and ^{15}N production, bunched beams, data acquisition

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.

The TUDA scattering facility, targets, electronics and detectors will be provided by the UK groups

SAFETY

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Summarize possible hazards associated with the experimental apparatus, precautions to be taken, and other matters that should be brought to the notice of the Safety Officer. Details must be provided separately in a safety report to be prepared by the spokesperson under the guidance of the Safety Report Guide available from the Science Division Office.

Low voltages, standard alpha particle calibration sources.

The physics problem

In this section we highlight the importance of the measurement in the context of current nuclear astrophysics research.

There are a number of astrophysical sites where explosive hydrogen burning is thought to occur [1], supermassive stars, novae, X–ray bursters, accreting neutron stars, supernovae etc. One of the principle reaction chains in these circumstances is the Hot–CNO cycle

$$^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(\beta^+)^{14}N(p,\gamma)^{15}O(\beta^+)^{15}N(p,\alpha)^{12}C$$

which differs from the normal CNO cycle in that the slow ^{13}N β–decay waiting point is bypassed. This is a catalytic process, where the heavy elements are returned at the end of the cycle and the rate (and hence the rate of energy generation) is limited by the ^{15}O β –decay time. However at temperatures above about $0.3T_9$ ($T_9 = 10^9$K) alpha capture onto ^{15}O can occur and the sequence

$$^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$$

leads to breakout of the cycle [2]. Now the CNO elements are no longer conserved, but form seed nuclei for further processing to much heavier elements through the rp–process. This has two important consequences; firstly there is a great increase in energy generation which is what powers these violent objects and secondly, the subsequent rp–process produces many of the heavy elements which we observe in the optical spectra of the remnants of the explosion.

Measurements of the $^{19}Ne(p,\gamma)^{20}Na$ reaction [3,4] have shown that under the conditions expected in explosive hydrogen burning, this rate is always faster than the preceding capture rate, so the overall rate is controlled by the $^{15}O(a,\gamma)^{19}Ne$ reaction. Hence there is great interest in determining this rate accurately, in order to pin down the conditions under which explosive burning can occur.

Ultimately it will be necessary to make a direct measurement of this process and this is one of the long term goals of the DRAGON project (E813). However this will be an immensely difficult experiment and will not be undertaken for a number of years, until the performance of the spectrometer is understood in detail and an intense ^{15}O beam has been developed. In view of the importance of knowing this yield, several indirect methods for obtaining the information are being attempted. The yield for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is dominated by resonant capture to a few key levels close to threshold. If the resonances are narrow and well separated, and the partial widths of these states are known, the reaction rate (R) can be calculated accurately using the narrow resonance formalism

$$R = N_a N_b (2\pi/\mu kT)^{3/2}\, h^2(\omega\gamma)\, \exp(-E_{cm}/kT)$$

where N_a and N_b are the number densities of the reactants, μ is the reduced mass, $\omega = (2J_T+1)/(2J_a+1)(2J_b+1)$ with J_a, J_b and J_T the spins of the two nuclei and the resonance, $\gamma = \Gamma_i\Gamma_f/\Gamma_T$ where Γ_i and Γ_f are the partial widths of the resonance in the incoming and outgoing channels and Γ_T the total resonance width, E_{cm} is the resonance energy and T is the temperature. Hence the calculation requires a knowledge of the excitation energy, spin and decay widths for the relevant states in ^{19}Ne.

Figure 1 shows the spectrum of states in ^{19}Ne above the alpha threshold, along with the spectrum of ^{19}F with the known analogue assignments indicated [5]. The crucial state for α+^{15}O capture at the temperature range of interest, around 0.3 T_9, is the first above threshold, at E_x = 4.033 MeV. At higher temperatures the E_x = 4.379, 4.549, 4.600, 4.712 and 4.783 MeV states will increasingly play a role, but the E_x = 4.140, 4.197 and 4.635 MeV states are thought to be less important as the increased angular momentum barrier between the α and ^{15}O will inhibit the capture. Neither the total or partial widths are known for any of the ^{19}Ne states, although an upper limit for the E_x = 4.033 MeV state has recently been published based on an intermediate energy Coulomb excitation measurement [6]. By contrast, for the much better studied ^{19}F nucleus, widths have been measured for most of the relevant states.

In the absence of a direct measurement of the partial widths of states in ^{19}Ne, a number of authors have used the widths from the mirror states in ^{19}F to determine the reaction rates [7,8]. The crucially important 4.033 MeV state in ^{19}Ne has its analogue at 3.908 MeV in ^{19}F (a bound state) and the only published alpha width for this state in ^{19}F comes from an analysis of the ^{15}N(^{6}Li,d)^{19}F alpha transfer reaction [9] (an explanation of how the alpha width can be extracted from a measurement of the alpha transfer strength is given in the next section). For the higher states in ^{19}F, direct measurements of the alpha width have been reported [10]. However, as pointed out in a recent paper by de Oliveira et al. [11], the assumption that the alpha widths will be the same for the mirror states is highly questionable, casting doubts on yield calculations which rely on this approach.

There have been a number of recent attempts to obtain more accurate information on the partial width of the relevant ^{19}Ne states. The Edinburgh group have made two attempts, using the d(^{18}Ne,^{19}Ne)p [12] and ^{20}Ne(^{3}He,α)^{19}Ne [13] reactions to populate the excited states in ^{19}Ne and then observing the coincident alpha decays. Such a measurement can give a measure of the quantity Γ_α/Γ_T. A parallel measurement of the total width (Γ_T) through a doppler shift measurement of the gamma decay is in progress. In principle the combination of these two measurements would allow Γ_γ to be determined, since for the crucial 4.033 MeV state the width is dominated by the gamma decay and so $\Gamma_T \sim \Gamma_\gamma$. However, to date neither of the transfer–breakup measurements has had the sensitivity to detect the 4.033 MeV state. A further attempt at such a measurement, using the d(^{18}Ne,^{15}Nα)p reaction, is planned at TRIUMF (E874).

Z=+11 initial Z=7+2+1=10 final ^{15}N should be ^{15}O maybe thinking of ^{15}O → e^+ ^{15}N ν_e

In this proposal we request time to make a measurement of the ^{15}O(^{6}Li,d)^{19}Ne alpha transfer reaction, from which the alpha width of the astrophysically relevant states in ^{15}O can be inferred. This measurement should be possible with low intensity ^{15}O beams, available during the early operation of ISAC–I.

low intensity
DRAGON requires
high intensity.

The methodology of the proposed measurement

In this section we describe how a measurement of the alpha transfer cross section on ^{15}O can be used to extract the partial width of states in ^{19}Ne, from which the radiative capture cross section can be calculated. The approach relies on the fact that the spectroscopic factor measured in the transfer reaction can be related directly to the reduced alpha width of the state.

The idea that the alpha width of states can be determined from a measurement of the alpha transfer cross section is not new. The first measurements of this type were carried out by DeVries et al.[14] in the 1970s. They studied alpha transfer onto ^{208}Pb, using the (^{16}O,^{12}C) reaction, to the ground and first excited states in ^{212}Po. By comparing the measured yields to DWBA calculations of the reaction, they extracted a ratio for the spectroscopic factors for the two states, which was in agreement with the ratio of widths calculated from their lifetimes. In subsequent work Davies et al. [15] made a measurement of alpha transfer cross sections to alpha decaying states in ^{208}Po, ^{211}Po, ^{212}Po and ^{213}At. The absolute reduced widths extracted from the alpha transfer measurements and those obtained from the alpha decay lifetimes, were in good agreement.

More recently de Oliviera et al. [8] determined the alpha widths of states in ^{19}F relevant to fluorine nucleosynthesis through a measurement of the $^{15}N(^{7}Li,t)^{19}F$ reaction. Through a careful analysis of the uncertainties in the reaction model calculations, they determined an alpha width for the main level of astrophysical relevance (E_x = 4.378 MeV) of $\Gamma_\alpha = 1.5 \times 10^{-9}$ eV, a value 60 times smaller than the commonly used one. This value was questioned by Wilmes et al. [7] who had performed direct alpha capture measurements (although their experimental sensitivity was not sufficient to get down in energy to the 4.378 MeV state). However, in a subsequent joint paper [11] the authors confirmed the de Oliviera value, lending weight to the belief that accurate alpha widths can be obtained from alpha transfer measurements, providing the state is not too far above threshold and providing care is taken to control the uncertainties in the reaction model calculation.

The present measurement is a straightforward (ignoring for the moment the experimental difficulties of using a radioactive beam) extension of this approach to measuring the alpha decay widths of the astrophysically relevant states in ^{19}Ne. The (^{6}Li,d) reaction will be used rather than the (^{7}Li,t) reaction used by de Oliviera et al, since (a) it is better understood and suffers less from two–step contributions and (b) the reaction Q–values are more favourable (this is a factor since the maximum beam energy at ISAC–I limits us to low energies). The principle weakness in the alpha transfer reaction approach is that the extraction of the reduced width from the alpha transfer cross section relies on the accuracy of the reaction model calculation. The yield is sensitive to the choice of the distorting potentials and of the coupling potentials used for the transition. There is also the question as to whether two–step reactions can contribute, or whether the yield is affected by couplings to other channels. Fortunately, there have been great strides in the development of accurate reaction models and as de Oliveira et al. have shown, these can be dealt with if care is taken with the calculations. We are fortunate to have the expertise of Dr M N Clarke who has spent some two decades studying transfer reactions and developing reaction model codes. Through the use of his ZAFRA approximation [16], finite range effects can be incorporated into reaction calculations of alpha transfers, and through his experience in coupled reaction channels codes such as FRESCO [17] we can explore the sensitivity of the calculations to second order effects. With this background knowledge and experience we believe we can reduce the uncertainties in the model calculations to a small level.

However, a key approach in this proposal is that we hope we can remove any remaining model uncertainties by carrying out an internal consistency check. For this we propose to carry out, under the same experimental conditions, a measurement of the $^{15}N(^{6}Li,d)^{19}F$ reaction. This would be done to the mirror states in ^{19}F to the states of interest in ^{19}Ne, where the alpha widths are known [7–11]. As the reaction is to states which have the same structure, the coupling potentials should be the same. The diagonal potentials should only differ in the Coulomb terms, and these are treated exactly in the calculations. Hence we would expect the ratio of reduced widths as extracted from the alpha transfer measurements of the two states to be relatively insensitive to any remaining uncertainty in the reaction model calculations. Hence we can calibrate to the known widths of the ^{19}F states.

In the context of internal consistency checks, we also note that our data set will contain the cross sections to higher lying states in ^{19}Ne, in particular the $E_x = 4.600$ and 4.712 MeV states. If we take a ratio of the yield to the $E_x = 4.033$ MeV state to the yield to these higher states, this enables us to determine the ratio of alpha widths to high accuracy, since any uncertainties in the experimental normalisation cancel in the ratio, as do many of the uncertainties in the reaction model (for example the distorting potentials). If we have the ratio, and since the higher energy state width is known, we can determine the width of the 4.033 MeV state. The ratio Γ_α/Γ_T has been measured for these states [18] so if measurements of the total width become available, we can determine the alpha widths for the higher states, and hence from the ratio measurement the width for the 4.033 MeV state. A gamma ray study of the ^{19}Ne nucleus using the immense power of the Gammasphere array has been proposed at Berkeley and it is possible the required widths may be obtained from this experiment.

One potential problem in this measurement is the contribution of compound nucleus reaction yield. Ideally we would wish to measure at a high beam energy where such processes are reduced compared to the direct transfer component, but we are limited by the 1.5MeV/amu limit of ISAC–I. We will measure the cross sections to large angles (near to 180°) in order to determine the magnitude of any compound nucleus contribution (this will be symmetric about 90°, while the direct component will be forward peaked). In addition we have standard Hauser Feshbach codes available which are known to reproduce the compound nucleus yield of such systems accurately.

The experimental setup

In this section we outline the TUDA system on which the experiment would be carried out. The expected energy and angular resolution is compared to that required for the measurement.

TUDA (Triumf UK Detector Array) has been funded by a grant to the University of Edinburgh from the UK Engineering and Physical Sciences Research Council. It comprises a chamber to house a detector array and the electronics and data acquisition system to read out the detector signals. Various designs of silicon strip detectors are used, matched to the needs of particular experiments. The chamber and electronics were installed in September, the data acquisition has recently been tested and in November the detector and preamps will be tested in the chamber to leave the full system ready for experiments.

The setup used for the current experiment is outlined in figure 2 and is similar to setups which have been used successfully in previous experiments with radioactive beams at the Louvain–la–Neuve laboratory in Belgium. In this type of inverse kinematics reaction, the forward angles in the centre of mass, which we want to measure, correspond to the duterons emerging at backward angles in the laboratory. Hence the detectors cover the back angle region, which has the experimental advantage that they do not see the flux of heavy ions. The small angles (roughly 167–150°) are covered by a LEDA design detector placed about 20 cm from the target. This comprises 8 sectors, each of which comprise 16 separate strips arranged as arcs on the silicon. Hence the strips provide information on the scattering angle. The wider angle region (roughly 150–130°) is covered by 8 segments of a LEDA detector, again placed about 20 cm from the target, but this time in a fan–shaped arrangement. The performance of the detectors and electronics is known from the Louvain–la–Neuve experiments and we expect an energy resolution of 20–25 keV for 5.5 MeV alphas, a time resolution of 1–2 ns and a low energy threshold at about 200 keV. The angular resolution is dictated by the 4 mm strip width, which for a target to detector distance of 20 cm is about 1°. A forward angle LEDA detector provides detection of deuterons from scattering angles near 180° in the centre of mass, from which the contribution of any compound nucleus reaction background can be measured.

The measurement will be carried out at the maximum available from ISAC–I, of 22.5 MeV (1.5 MeV/amu). The target will be a Li_2O foil, made from isotopically enriched ^{6}Li. The ^{16}O content of this target will contribute a flux of elastically scattered ^{15}O, but should not contribute any reaction products as the collision is below barrier (E_{cm} = 11.6 MeV while V_{CB} = 12.8 MeV). In fact this elastic scattering flux can provide a useful means of measuring the beam current exposure in the experiment. However there will be a considerable differential energy loss in the target between reactions which occur at the front and rear of the target. Energy loss calculations suggest this will be of the order of 7 keV/μg.cm^{-2}, so limiting the target thickness to about 10 μg.cm^{-2} in order not to compromise the separation of the states in the deuteron energy spectrum (separation arround 100 keV).

The kinematics of the reaction, coupled with the energy detection threshold, show that the scattered deuterons can be detected over the full angular range. The inner detectors will cover the centre of mass angular range from about 5–20° and the outer detectors from about 20–30°. The deuterons will be identified from other reaction products through a measurement of the time of flight. In the backward angle detector the energies are limited to less than 2 MeV, which implies a separation between the p, d and t ions of over 3 ns, which will be separable with the expected time resolution (note that HEBT beam energy calculations show the beam time structure will be better than 1 ns at this beam station). In the forward angle detector the energies are higher, up to 10 MeV, but the longer flight path more than compensates for this.

Expected yields and beamtime estimate

In this section we present calculations of the expected alpha transfer yields, which allows us to estimate the beamtime required for the measurement

Figure 3 shows the result of a DWBA calculation for the state at 4.033 MeV, indicating an expected cross section arround 100 μb/sr in the angular region covered by the detection system. The two curves shown are a zero range calculation using the zafra approximation in the CHUCK code and a full finite range calculation using the FRUCK code. Both calculations use the same published optical potentials [19]. The zero range calculation uses the normalisation of D0 = –275 MeV.fm$^{3/2}$ and a spectroscopic amplitude of sqrt(0.49) = 0.7 for the (^{6}Li,d) vertex, while the finite range calculations assumes a spectroscopic factor of S = 1.0. Hence the curve labelled EFR in figure 3 should be scaled by a factor of 0.7, which brings it almost exactly into line with the zero range calculation (labelled zafra) in the crucial forward angle region. This exact agreement of the two reaction codes lends added support to our belief that we can extract accurate spectroscopic factors.

A spectroscopic factor of $S_\alpha = 1.0$ has been assumed for the α+^{15}O vertex, since this is unknown (and indeed is the quantity which we wish to determine in the experiment). The magnitude of the calculated cross sections will scale with S_α , so a normalisation of the calculated yield to the experimental data allows us to determine S_α . For the purposes of estimating the yield in the following, we will take a value of $S_\alpha = 0.04$. This is based on the values of $S_\alpha = 0.04$ [9] and < 0.07 [11] quoted for the analogue state at 3.908 MeV in ^{19}F. Mao et al. calculate that their measured $S_\alpha = 0.04$ gives a value of $\Gamma_\alpha \sim 10$ μeV, so this is also consistent with the estimate of $\Gamma_\alpha/\Gamma_T \sim 10^{-4}$ [20] for the ^{19}Ne state if we use as the total width the measured width of $9^{+}/_{-}5$ fs (73 meV) for the analogue state. The recently reported upper limit for the ^{19}Ne state of $\Gamma\gamma < 430$ meV [6] is also consistent with these assumed values.

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A ^{15}O beam intensity of 10^{11}pps has been assumed for experiment E813 and this will require extensive target development work. For this proposal we will assume a much more modest value of 10^9 pps, which should be available in the early operation of ISAC. As noted earlier, the thickest target we can use to achieve the required energy resolution is 10 $\mu g/cm^2$. Although we will wish to measure the yield over a wide angular range of the detectors to check the shape of the angular distribution predicted by the model calculation, the spectroscopic factor will be determined by the normalisation to the forward angle points where the cross section is expected to be about 4 $\mu b.sr^{-2}$ (assuming a spectroscopic factor of 0.04 as discussed above). Hence we expect a count rate of 1.2×10^3 pps in a typical angular bin of 5° in the centre os mass, so that to achieve a statistical accuracy of 5% on the cross section measurement we would require 92 hours of beamtime (a 5% uncertainty on the cross section would translate into a 5% uncertainty on the reduced alpha width). A further 2 shifts would be required to measure the elastic scattering angular distribution, which is necessary to enable us to check the optical potential for the entrance channel. In addition we require 2 shifts to set up and calibrate the detectors. Hence we estimate the ^{15}O beam measurement would require 12 shifts.

The ^{15}N measurement involves a stable (although low abundance) beam isotope and so could be run when the radioactive target is not in operation. The beam intensity is not known, but should be higher than the ^{15}O beam. We estimate that we would require 8 shifts for this aspect of the measurement.

We note that these beam time estimates do not include any time for the tuning of the beam and optimising the timing performance.

The ^{15}O and ^{15}N measurements do not require to run at the same time, although this would be helpful since the same setup will be used for both measurements and the system could be running with the stable beam while the proton target ion source was being tuned.

References

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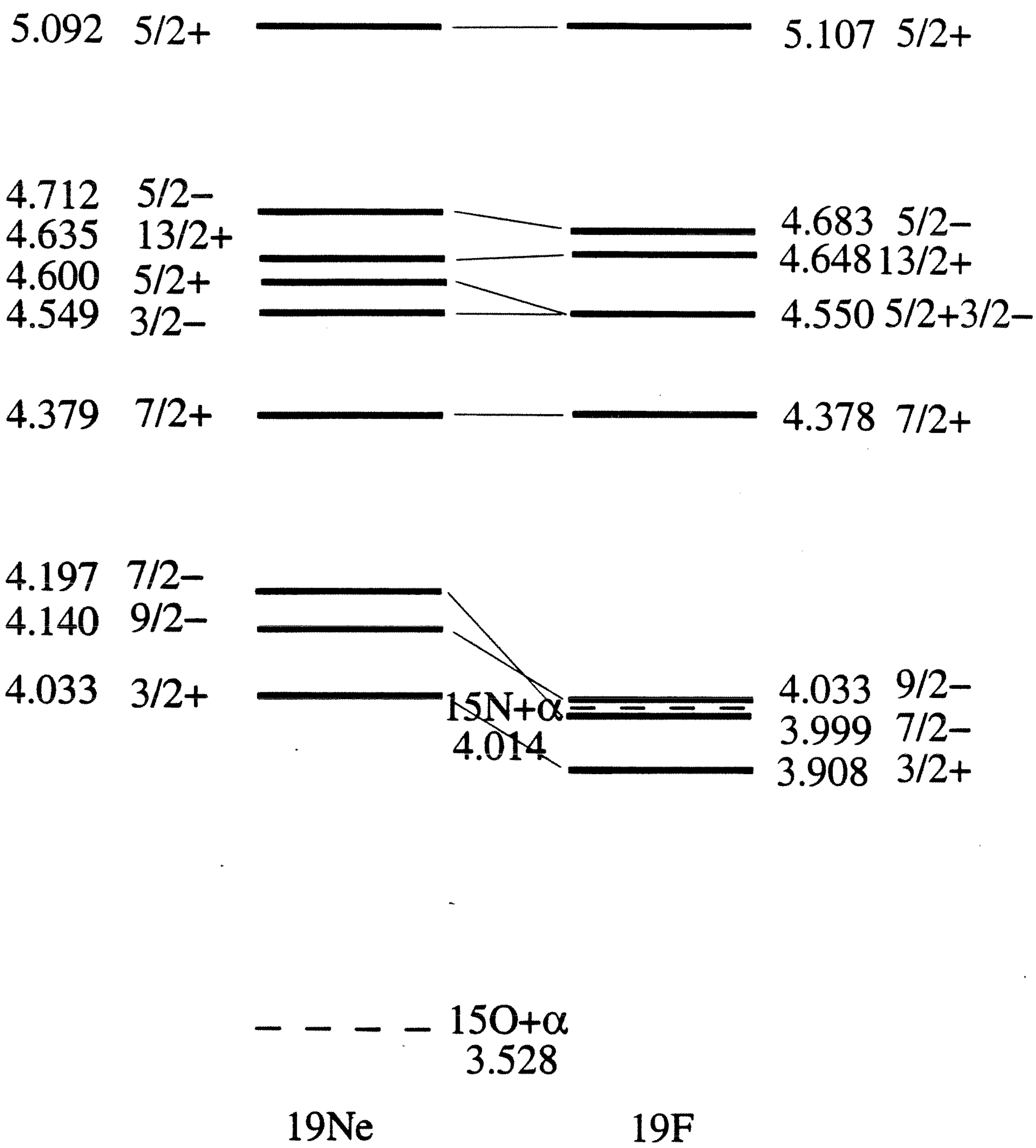
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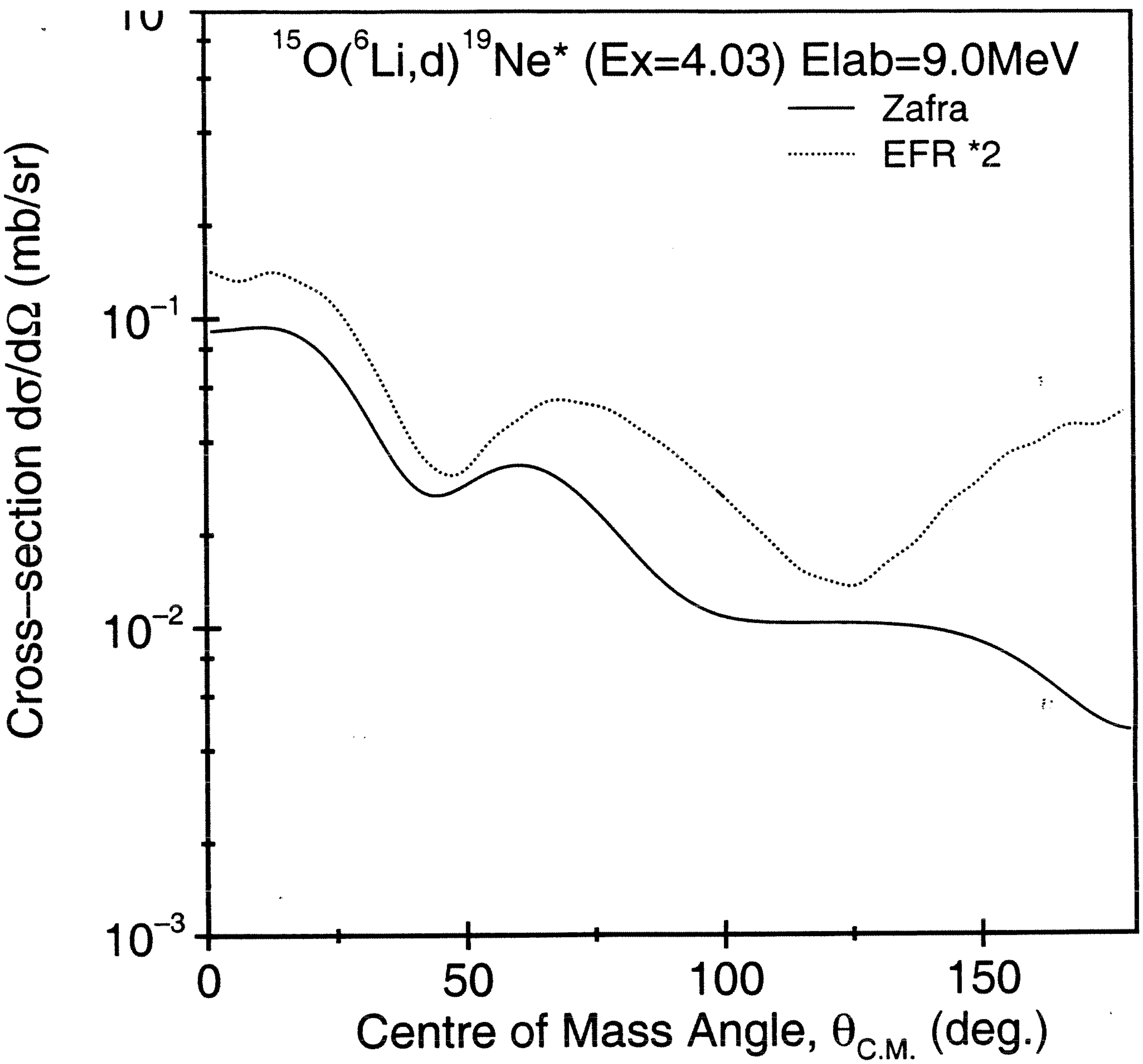

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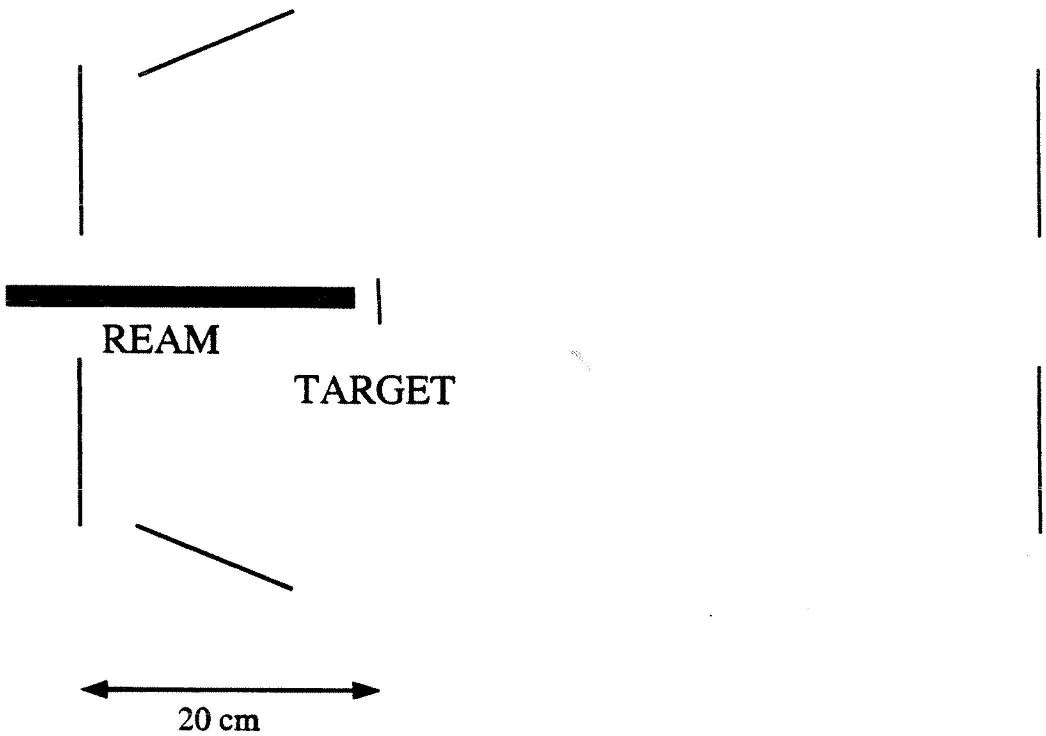

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