EPJ Web of Conferences **17**, 02003 (2011)
DOI: 10.1051/epjconf/20111702003

Fusion of ^{9,11}Li with ^{208}Pb

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Abstract. The fusion excitation functions for the reaction of ^{9}Li with ^{70}Zn and ^{208}Pb were measured. In the reaction with ^{70}Zn, the evaporation residues (EVRs) were detected by a radiochemical separation of the As and Ge EVRs followed by β-counting. In the reaction with ^{208}Pb, the At EVRs were detected by α-counting. In both systems, one observes substantial sub-barrier fusion enhancement that cannot be explained by coupled channels calculations. The implication of these studies for the study of the ^{11}Li + ^{208}Pb reaction are discussed.

1 Introduction

One of the most active areas of research with radioactive beams is the study of the fusion of weakly bound nuclei, such as the halo nuclei. The central issue is whether the fusion cross section will be enhanced due to the large nuclear size of the halo nucleus or whether fusion-limiting breakup of the weakly bound valence nucleons will lead to a decreased fusion cross section. Most theoretical calculations have dealt with the ^{11}Li + ^{208}Pb reaction, with a wide variety of outcomes. Figure 1 (taken from a review article of Signorini [1]) shows the range of predictions for the sub-barrier fusion cross sections, which span four orders of magnitude. It is clear that a measurement of the fusion excitation function for the ^{11}Li + ^{208}Pb reaction would be valuable in resolving the differences between the various predictions shown in Figure 1.

In this context, the nuclear structure and nuclear reactions of ^{9}Li are of interest for three reasons. (a) It is the core nucleus of the two-neutron halo nucleus ^{11}Li that is of great current interest and an understanding of ^{9}Li is important for an understanding of ^{11}Li. (b) ^{9}Li is itself a very neutron-rich nucleus ($N/Z = 2$) with a significant neutron skin [2] and an understanding of its reactions may be helpful in understanding the interactions of very neutron-rich nuclei. (c) ^{9}Li is a well-characterized nucleus with a simple shell-model structure, which should be helpful in modeling its interactions.

2 Experimental

The measurement of the fusion cross sections for the ^{9}Li + ^{70}Zn (^{9}Li + ^{208}Pb) reaction was carried out at the ISAC (ISAC2) facility at TRIUMF [14]. Proton beams (500 MeV) with intensities ranging from 50–85 μA struck Ta metal production targets. Beams of radioactive ^{9}Li were extracted with energies up to 18.4 keV, mass separated by passage through two dipole magnets and accelerated to their final energy by radiofrequency quadrupole and drift tube linear accelerators. The details of the production of these secondary beams are discussed elsewhere [3,4].

2.1 ^{9}Li + ^{70}Zn

In the ^{9}Li + ^{70}Zn experiment, the beam was delivered to the HEBT straight-through beam line in the ISAC facility. The experiment was carried out in a large-volume (~40 L) scattering chamber, known as the Laval chamber, at the end of this beam line. The beams struck ^{70}Zn targets mounted in the chamber. Targets of ~95% enriched ^{70}Zn (thickness ~0.8–1.1 mg/cm^2) were prepared by electro-deposition on Al backing foils (0.54–0.71 mg/cm^2).Beam intensities were monitored by detecting elastic scattering at ±16.2°, with additional monitoring of the beam by a suppressed Faraday cup at the end of the beam line. Typical beam intensities were 4-6 x 10^6 particles/s. PACE [5] and HIVAP [6] calculations indicated the entire evaporation residue cross section is concentrated in the three isotopes of As, stable ^{75}As, 1.09-day ^{76}As, and 38.8-h ^{77}As. Both simulations show the largest predicted component is ^{76}As.

For each of the ^{9}Li energies studied, a fresh ^{70}Zn target was installed in the scattering chamber and it was irradiated for 1–3 days. The irradiated target foil was counted with a Ge γ -ray spectrometer for about 1 day prior to commencing a radiochemical analysis of the target. Following γ –ray spectroscopy, the irradiated

Article available at http://www.epj-conferences.org or http://dx.doi.org/10.1051/epjconf/20111702003

target foil and backing material were dissolved in acid and the As and Ge residues were separated by standard radiochemical separations [7]. Then the As and Ge fractions were assayed using a Tennelec LB1000 Low Background Beta Counter (efficiency ~52.5%) and the decay of the sample was followed for several days. The yields of the As chemical separation ranged from 27 to 100% (average yield = 63%), whereas the yields of the Ge separations ranged from 3 to 32% (average yield = 22%). (These yields were determined by post irradiation neutron activation analysis of the samples.) The residue nuclei were identified by their atomic number (established by chemistry) and their observed decay half-life. The only detected activity in any irradiation was ^{76}As. Upper limits (2σ) for the production of ^{77}Ge and ^{77}As were ~ 0.1 mb. After correction for chemical yields, branching ratios, detector efficiency, temporal variation of the beam intensity during the irradiations, etc., the production cross sections for the residue nuclei were calculated.

2.2 ^{9}Li + ^{208}Pb

The measurement of the fusion cross section for the ^{9}Li +^{208}Pb reaction was carried out at the ISAC2 facility at TRIUMF [15]. The experiment was setup on the straight-through beam line of the ISAC2 facility. The experiment was carried out in a large (~ 35L) thin-walled spherical scattering chamber mounted on this beam line. The ^{9}Li (^{7}Li) beams struck ^{208}Pb (^{209}Bi) targets mounted at the center of the chamber. Beam intensities were monitored by detecting elastic scattering at ± 16 ° with additional monitoring of the beam by a suppressed Faraday cup at the end of the beam line. (A 0.008 m^3 5% boron-loaded paraffin shield was used to reduce the neutron emission from the Faraday cup to acceptable levels (1μSv/h at 3m). ^{9}Li is a 178 ms β-emitter with a Q_β ~ 13.6 MeV with ~ 50% of the decays resulting in neutron emission.) The average on-target ^{9}Li intensity was 10^7/s and the average on-target ^{7}Li intensity was $2.5\text{x}10^9$/s. Both beams were pulsed with the beam being on for 172 ns, then off for 172 ns. The ^{208}Pb target was 0.903 mg/cm^2 thick and the ^{209}Bi target was 0.465 mg/cm^2 thick. An array of 18 (300 mm^2) Si detectors surrounding the target was used to detect decay -particles emitted from evaporation residues (EVRs) that stopped in the Pb/Bi targets in the beam-off period. The geometrical efficiency of the array for detecting decay -particles emitted by the EVRs that stopped in the targets was evaluated by a Monte Carlo simulation to be 20%. To check this estimate, we also measured the yield of the evaporation residues ^{212,213}Rn formed in the reaction of 34.95 MeV ^{7}Li with ^{209}Bi and compared our results to the previous measurement of Dasgupta, et al. [8] The agreement was excellent indicating we are able to reproduce known information about similar reactions.

In both reactions, one expects a negligible rate for the fusion-fission reaction (HIVAP) and the EVR cross section is taken as the fusion cross section. In the ^{9}Li + ^{70}Zn reaction, the observed ^{76}As cross section was multiplied by 1.2-1.4 (depending on beam energy) to represent the fusion cross section (PACE, HIVAP). In the ^{9}Li + ^{208}Pb reaction, the observed cross sections ($^{211-214}$At) were used to compute the fusion cross section. This technique was checked with measurements of the known fusion cross sections for the ^{7}Li + ^{209}Bi reaction.

3 Results and Discussion

3.1 ^{9}Li + ^{70}Zn

We show the fusion excitation function for the ^{9}Li + ^{70}Zn reaction in Figure 2 along with predictions of a coupled channels calculation. We used the code CCFULL [9] to make this calculation. We included the inelastic excitation of the first vibrational 2+ and 3− states in ^{70}Zn [10] and the rotational states in ^{9}Li [10]. We assumed a potential with V_0 = 105 MeV, r_0 = 1.12 fm and a diffuseness parameter a = 0.65 fm. There is a large sub-barrier fusion enhancement that is not described by the coupled-channels calculation.Zagrebaev et al. [11] found that standard coupled channels calculations along with neutron transfer were not able to describe the observed sub-barrier fusion and postulated "di-neutron transfer" to account for the observed data. Balantekin and Kocak [12] also found that coupled channels calculations including inelastic excitation and one-neutron transfer failed to reproduce the data and suggested the possible formation of a molecular bond accompanied by two-neutron transfer to account for the observed behavior. In this approach, the neutron-rich ^{70}Zn contributes two neutrons to form the ^{11}Li halo structure in the nuclei at contact, which enhances the fusion cross section. The data are well represented by this model (Figure 3).

3.2 ^{9}Li + ^{208}Pb

In Figure 4, we compare the measured fusion excitation function for the ^{9}Li + ^{208}Pb reaction with coupled channels calculations for this reaction. As with the ^{70}Zn reaction, the coupled channels calculations were done with CCFULL [9] with the same parameters for the ^{9}Li and the interaction as before. We included the first vibrational 3^- state in ^{208}Pb at 2.615 MeV, B (E3; $0^+\rightarrow3^-$) =0.611 e^2b^3 [10]. We also included a simple one-dimensional barrier penetration calculation with no coupled channels. The measured excitation function shows evidence for enhanced sub-barrier fusion and suppression of fusion above the barrier relative to the coupled channels predictions.

What are the implications of these studies for studies of the fusion of ^{11}Li with ^{208}Pb (Figure 1)? Clearly fusion of the "core" ^{9}Li nucleus is complicated and has features that are not readily explainable with conventional ideas about fusion. The use of α-counting of short-lived EVRs can be carried out with reasonable efficiency in between ISAC2 beam bursts and can, using stacked targets, be used as a basis for studying the $^{11}Li + ^{208}Pb$ reaction [13].

4 Future Work

The stage is now set for our attempt to measure the « Holy Grail of Fusion Reactions », the fusion excitation function for the $^{11}Li + ^{208}Pb$ reaction. We were scheduled to make this measurement in the summer of 2010 but a failure of the high power targets prevented the attempt. We are now tentatively scheduled to do this in June, 2011.

The key issue will be the intensity of the ^{11}Li beam. We will run a single energy of ^{11}Li (46 MeV) which will be degraded, in steps, to 25 MeV. (We will not have the beam intensity to measure sub-barrier cross sections). Recent experiments with ^{11}Li have had on-target beam intensities of 1000-5000/s. (Since we pulse the beam (172 ns on, 172 ns off) the effective beam intensities will be one-half this, i.e., 500-2500 p/s)

The target/detector array is shown schematically in Figure 5 with detailed pictures of the four detectors, the target-detector geometry and the overall apparatus in Figures 6 and 7. The beam intensity will be monitored upstream of the cube array using elastic scattering from a thin Au foil and downstream in a shielded Faraday cup. In each cube, the incoming beam passes through a 1 mg/cm^2 ^{208}Pb target, backed with a 4.0 mg/cm^2 Al foil that acts as a catcher/degrader. The α-decay of the stopped EVRs will be detected in 4 α-detectors in each cube. The geometrical efficiency of detection of the decay α-particles has been calculated to be ~ 20%. The center of target beam energies are stepped from 46 to 25 MeV throughout the array.

To estimate the expected counting rates, we consider two extreme possibilities, complete fusion of ^{11}Li with ^{208}Pb and breakup of ^{11}Li to ^{9}Li with fusion of ^{9}Li with ^{208}Pb. We have measured the latter cross sections and based upon our experience with ^{9}Li, we estimate the former cross sections using HIVAP. (We are not sensitive to the breakup/transfer reactions producing ^{210}Pb and ^{212}Pb.

Assuming complete fusion, a pulsed 11Li beam intensity of 1000/s, a 208Pb target thickness of 1 mg/cm2, a detection efficiency of 20%, and HIVAP cross sections, we estimate detecting 800 events at 46 MeV and 150 events at 25 MeV in our one week experiment. A similar number of events are projected for breakup/fusion.

5 Conclusions

What have we learned from this study?

(1) We have used radiochemical techniques to measure evaporation residue cross sections in reactions induced by radioactive beams, thus enabling studies of the fusion of weakly bound nuclei.

(2) In both reactions we have observed substantial sub-barrier fusion that is not accounted for by conventional coupled channels calculations. For the case of the $^{9}Li + ^{70}Zn$ reaction, the best explanation of the data involves the unusual concept of the formation of the molecular bond to enhance two neutron transfers.

(3) Extension of these measurements to the study of the $^{11}Li + ^{208}Pb$ reaction seems feasible.

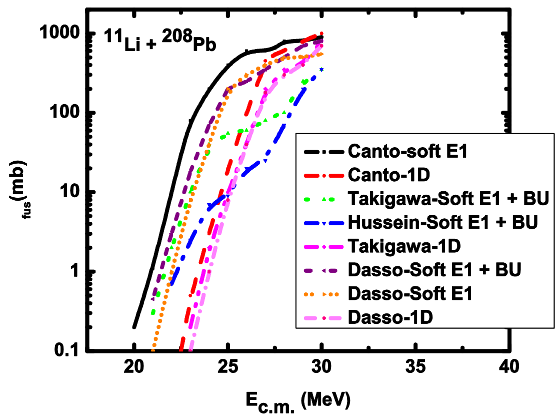

Fig. 1. Various theoretical predictions for the sub-barrier fusion cross sections for the $^{11}Li + ^{208}Pb$ reaction. See [1] for the details of the various predictions.

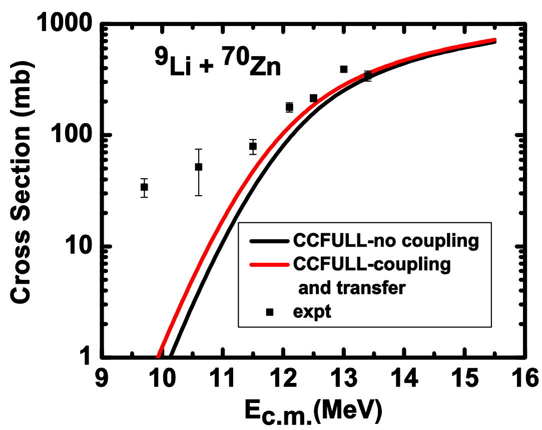

Fig. 2. Comparison of the fusion excitation function for the ^{9}Li + ^{70}Zn reaction with coupled channel calculations [9]

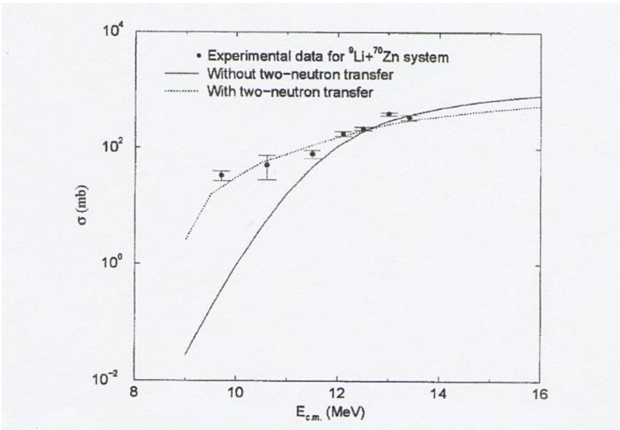

Fig. 3. The fusion excitation function for the ^{9}Li + ^{70}Zn reaction showing the effect of molecular bonding (dashed line) and coupled channels calculations (solid line).

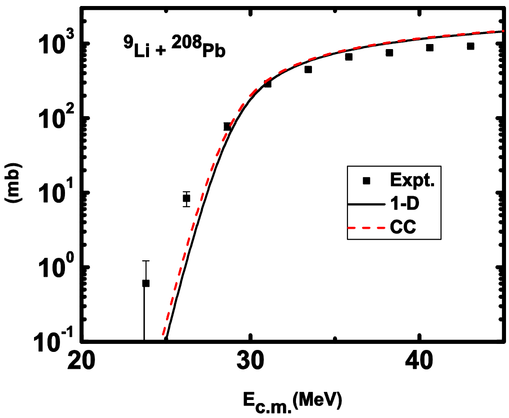

Fig. 4. The fusion excitation function for the ^{9}Li + ^{208}Pb reaction showing coupled channels calculations .

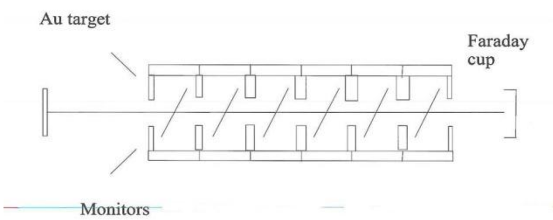

Fig. 5. Schematic drawing of experimental apparatus.

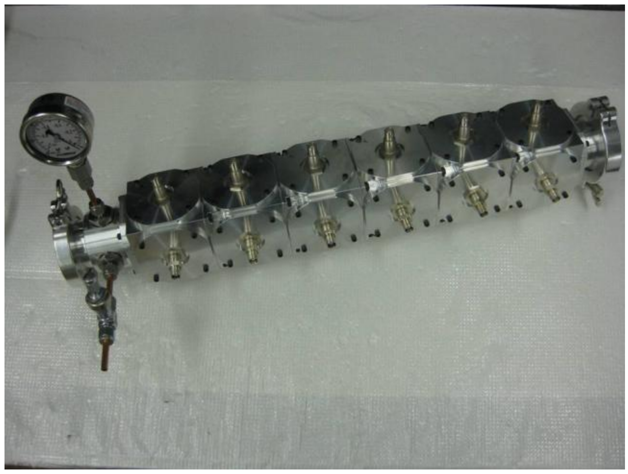

Fig. 6. Array of detector cubes.

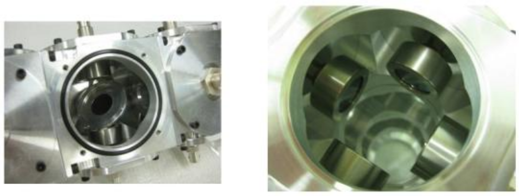

Fig. 7. Details of cubes with and without target installed.

Acknowledgements

I want to acknowledge the participation of R. Yanez, A.M. Vinodkumar, R. S. Naik, P.Sprunger, B. Matteson, L. Prisbey, J. Neeway, M. Trinczek, M. Dombsky, P. Machule, D. Ottewell, D. Cross, K. Gagnon, W. Mills, J.J. Kolata and A. Roberts in this work. We thank the operations staff of the cyclotron and ISAC, and Marco Marchetti and Robert Laxdal for providing the ^{9}Li beams. This work was supported, in part, by the Office of High Energy and Nuclear Physics, Nuclear Physics Division, U.S. Dept. of Energy, under Grant DE-FG06-97ER41026 and TRIUMF and the Natural Sciences and Engineering Research Council of Canada and the U.S. National Science Foundation under Grant PHY06-52591.

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Note added in proof. The study of the fusion of ^{11}Li with ^{208}Pb was carried out at TRIUMF in June, 2011. The chopped ^{11}Li beam intensity was 1000 p/s. While data analysis is ongoing, there is preliminary evidence for the complete fusion of ^{11}Li with ^{208}Pb.