Evaporation protons from the low-energy fusion of $^6\text{Li} + ^{58}\text{Ni}$

E F Aguilera$^1$, J J Kolata$^2$, E Martinez-Quiroz$^1$, P Amador-Valenzuela$^1$, D Lizcano$^1$, A Gómez-Camacho$^1$, and A García-Flores$^{1,3}$

$^1$ Departamento de Aceleradores, Instituto Nacional de Investigaciones Nucleares, A. P. 18-1027, C. P. 11801, México, D. F., México
$^2$ Physics Department, University of Notre Dame, Notre Dame IN, 46556-5670, USA
$^3$ Universidad Autónoma del Estado de México, C. P. 50000, Toluca, México

E-mail: eli.aguilera@inin.gob.mx

Abstract. Very recently, fusion cross sections for the weakly-bound proton-rich systems $(^8\text{B},^7\text{Be}) + ^{58}\text{Ni}$ were obtained by using a technique where the protons evaporated after the respective fusion reaction were measured. In the present work, the same technique is applied to get fusion cross sections for the $^6\text{Li} + ^{58}\text{Ni}$ system at sub-barrier energies. Comparison with data reported previously for $^6\text{Li}$ projectiles on similar targets gives consistent results, even though the previous data were obtained with quite different techniques.

1. Introduction

In the present work, the protons that are emitted in the $^6\text{Li} + ^{58}\text{Ni}$ fusion reaction are measured. The fact that $^6\text{Li}$ is a weakly-bound nucleus that can easily break into an alpha particle and a deuteron, makes this system an interesting case to investigate. The study of the interplay between the breakup and the fusion channels in weakly-bound systems is a subject that has attracted much interest lately. This work intends to make a contribution to this general subject, by providing fusion data for this particular system.

Similar measurements for the $(^8\text{B},^7\text{Be}) + ^{58}\text{Ni}$ systems were recently performed [1, 2]. In these experiments, the protons evaporated after the respective fusion reaction were measured and the calculated proton multiplicities were used to deduce the respective fusion cross sections. Somehow aided by the proton excess of the projectiles, the corresponding compound nuclei are close to the proton drip-line, so proton emission is naturally a good signature for fusion in these systems. The two projectiles mentioned above, along with $^6\text{Li}$, are the main components of a mixed beam produced at the radioactive beam facility TwinSol at the University of Notre Dame. The $^6\text{Li}$ projectile does not have a proton excess but, when fused with $^{58}\text{Ni}$, it also produces a compound nucleus which is in the proton-rich region. Because of the high Q value for fusion, it is highly excited and proton emission is still the dominant evaporation channel. Similar to the previous two cases, more than one proton ($\sim 1.5$) is typically produced for each fusion reaction in this system. In the present work, an experiment using the same technique [1, 2] was performed to measure the protons emitted during the $^6\text{Li} + ^{58}\text{Ni}$ fusion reaction at sub-barrier energies.
Only part of the data have been analyzed so far and the respective results are presented in this preliminary report.

In next section, the main experimental details are given while the results are presented and discussed in section 3. Section 4 shows a comparison with fusion data for other two systems having the same projectile and similar targets. Finally, a summary and the conclusions are given in section 5.

2. Experimental details

The experiment was performed using the radioactive-ion-beam facility TwinSol at the University of Notre Dame [3], where a primary beam of $^6\text{Li}$ was used to impinge a primary gas-target of $^3\text{He}$. This beam was bunched so that the respective Time-of-Flight (TOF) could be measured. The reaction products of interest are selected by a first superconducting solenoid which focuses them in a Mid chamber. A second superconducting solenoid further transports the secondary beam, focusing it at the secondary chamber, where the Ni target is placed.

Figure 1 shows an upper view of the experimental set up at the secondary chamber. In order to get an image of the beam, a detector was placed at the target position, lowering the beam rate just enough for the detector to be able to take it. The three main reaction products are generated by the $2p$ and $1p$ pickup reactions (producing $^8\text{B}$ and $^7\text{Be}$, respectively), and by elastic scattering (secondary beam of $^6\text{Li}$). Respective secondary beams that correspond to the same magnetic rigidity are obtained at the secondary-target position. The $^8\text{B}$, $^7\text{Be}$ and $^6\text{Li}$ beams arrive at the target with different times of flight, so they can be selected by placing software windows in the corresponding TOF values. However, each of these beams has its own contaminants that have to be dealt with separately. In the case of $^6\text{Li}$, satellite beams of alphas and deuterons fall on the same time window, so they cannot be separated.

![Figure 1. Upper view of the secondary chamber showing the experimental setup.](image)

To measure the evaporated protons after the fusion reaction, four telescope detectors were placed at backward angles and two additional telescope detectors at forward angles served to monitor the beam for normalization purposes (see Fig. 1). During the experiment, the Ni target was placed at the center of the chamber. The satellite beams of alphas and deuterons were of some concern because the protons produced by them in reactions with the Ni target could not be separated from those produced by $^6\text{Li}$. However, by looking at the respective cross sections reported earlier for these reactions [4, 5], the corresponding contributions could be estimated as less than 0.3\% in both cases, so they could be safely neglected. The experiment was performed in three stages covering a total of six energies of $^6\text{Li}$, between 10 and 14.1 MeV in the laboratory frame of reference. In the present preliminary report only the results corresponding to one of the stages, including three of the six energies ($E_{\text{lab}} = 10.9, 12.2, 13.2$ MeV), are presented.
3. Results and discussion

Figure 2 shows the proton angular distribution obtained for each of the three energies. The respective PACE2 [6] predictions are indicated with the solid curves, which were integrated over the whole solid angle to get the total proton cross sections $\sigma_p$. These cross sections can be mapped into $\sigma_{\text{fus}}$ by using the respective proton multiplicities, $M_p$, calculated also with the code PACE2. The possible contribution of incomplete fusion to the data was estimated to be small.

![Figure 2. Proton angular distributions for three experimental energies. The curves correspond to respective PACE2 predictions.](image)

![Figure 3. Deduced fusion cross sections for $^6\text{Li} + ^{58}\text{Ni}$. The curves are explained in the text.](image)

The resulting fusion excitation function is shown in Fig. 3 with solid squares and, for comparison purposes, the total reaction cross sections that were obtained previously by our group [7] are also shown, with empty squares. It can be observed that the fusion cross section practically saturates the total reaction cross section, especially at the lowest energies. The dashed curve corresponds to a Barrier-Penetration-Model (BPM) calculation using Wong’s formula [8]:

$$\sigma_{\text{Wong}} = \frac{\hbar \omega_0 R_B^2}{2E} \left[ 1 + e^{\left(\frac{E-V_B}{\hbar \omega_0}\right)} \right]$$  \hspace{1cm} (1)

The respective barrier parameters $V_B, R_B, \hbar \omega_0$ were obtained from the Sao Paulo potential (SPP) [9], which is a double-folding potential that has been shown to provide a realistic bare potential for many systems. In the SPP calculation, default values were used for the respective nuclear densities. The potential is shown with the solid line in figure 4, and the respective barrier leads to the values $V_B = 12.4 \text{ MeV}$, $R_B = 9.02 \text{ fm}$, and $\hbar \omega_0 = 3.63 \text{ MeV}$ for the height, the radius, and the barrier curvature parameter, respectively. With respect to Wong’s predictions, the fusion data show a considerable enhancement, but the actual enhancement is in fact even larger, as explained in the following paragraph.

In the sub-barrier region, Wong’s formula is inaccurate for systems as light as the one considered in the present work, actually overpredicting the results of more accurate BPM calculations. To account for this, an optical potential model (OPM) calculation was done for this system by using the respective SPP for the real part and an interior imaginary potential of Woods-Saxon form, with parameters $W_0 = 50 \text{ MeV}$, $r_W = 1.06 \text{ fm}$, $a_W = 0.2 \text{ fm}$ (dashed line in figure 4). The absorption in this potential effectively simulates an incoming wave boundary condition, thus providing a good estimation for fusion. The obtained result, $\sigma_{\text{OPM}}$, is indicated
with the solid curve in Fig. 3. The actual fusion enhancement should be considered with respect to this curve.

![Figure 4](image1.png)

**Figure 4.** Real (solid line) and imaginary (dashed line) potentials used to calculate both the barrier parameters and the $\sigma_{\text{OPM}}$ curve of Fig. 3.

![Figure 5](image2.png)

**Figure 5.** Comparison of reduced fusion cross sections for $^6\text{Li}$ on targets of $^{58}\text{Ni}$ (present work), $^{59}\text{Co}$ (Ref. [12]) and $^{64}\text{Zn}$ (Ref. [13]). The curve is to guide the eye.

4. **Comparison with similar systems**

A comparison of our results was made with data for other systems having the same projectile but targets of $^{59}\text{Co}$ [12] and $^{64}\text{Zn}$ [13]. To make the comparison, the data must be properly scaled, so the cross sections and energies were reduced according to the expressions $\sigma_{\text{red}} = \sigma/(A_p^{1/3} + A_t^{1/3})^2$, $E_{\text{cm}}^{\text{red}} = E_{\text{cm}}/[Z_pZ_t/(A_p^{1/3} + A_t^{1/3})]$. This reduction of data is expected to eliminate trivial effects of size and charge without washing out other important effects [10, 11], thus making data for different systems directly comparable to each other. Intuitively, one would expect this reduction to work better for similar systems, in particular for systems whose respective barrier curvatures have close values. Such curvatures are estimated to differ by less than 2% for the three systems compared, thus justifying the method. Compared to other existing prescriptions for data reduction, this method has the great advantage of being completely model independent.

Figure 5 shows the reduced fusion data for the $^6\text{Li} + (^{58}\text{Ni},^{59}\text{Co},^{64}\text{Zn})$ systems. It can be seen that, in the overlapping region, our data are quite consistent with the data for the other two systems. This in spite that the experimental techniques were completely different in the three cases. In the work of Beck et al. ($^6\text{Li} + ^{59}\text{Co}$) [12], the gamma rays emitted by the evaporation residues were measured. For the $^6\text{Li} + ^{64}\text{Zn}$ system [13], the cross sections for heavy residue production were measured using an activation technique, detecting off-line the characteristic X-rays emitted in the electron capture decay of the reaction products. It is thus very encouraging to have such a good consistency with our data, where the normal experimental difficulties are very much increased by the fact that they were actually obtained as part of a multi-beam experiment, using only secondary beams. In a way, we could say that the observed consistency further supports the reliability of our technique.

5. **Conclusions**

Evaporated protons were measured for the $^6\text{Li} + ^{58}\text{Ni}$ system at sub-barrier energies and the respective fusion excitation function was deduced by using calculated proton multiplicities. It
was observed that the fusion cross sections nearly saturate the previously measured total reaction cross sections. The data show a big fusion enhancement with respect to the predictions of the one dimensional barrier penetration model using a realistic bare potential. Good agreement was observed with previous fusion data for the $^6$Li + ($^{59}$Co, $^{64}$Zn) systems even though the experimental techniques used in the three cases were quite different.

Acknowledgments
This work has been partially supported by CONACYT (México) and by the NSF (USA) under Grant No. 09-69456.

References
[1] Aguilera E F et al. 2011 Phys. Rev. Lett. 107 092701
[2] Martínez-Quiroz E et al. 2014 Phys. Rev. C 90 014616
[3] M. Y. Lee, et al., Nucl. Instrum. Methods A 422, 536 (1999)
[4] Vlieks A E, Morgan J F, and Blatt S L, 1974 Nucl. Phys. A 224 492
[5] Pavlenko Y N et al. 2012 Bulletin of Russian Academy of Sciences: Physics 76 888
[6] Gavron A 1980 Phys. Rev. C 21 230
[7] Aguilera E F et al. 2009 Phys. Rev. C 79 021601(R)
[8] Wong C Y 1973 Phys. Rev. Lett. 31 766
[9] Chamon L C, Carlson B V, Gasques L R, Pereira D, De Conti C, Alvarez M A G, Hussein M S, Cândido Ribeiro M A, Rossi Jr. E S and Silva C P 2002 Phys. Rev. C 66 014610
[10] Prasad N V S V, Vinodkumar A M, Sinha A K, Varier K M, Sastry D L, Madhavan N, Sugathan P, Kataria D O, and Das J J 1996 Nucl. Phys. A 603 176
[11] Gomes P R S, Lubian J, Padron I, and Anjos R M 2005 Phys. Rev. C 71 017601
[12] Beck C et al. 2003 Phys. Rev. C 67 054602
[13] DiPietro A et al. 2013 Phys. Rev. C 87 064614