Fusion measurements for the $^7\text{Li}+^{51}\text{V}$ system at energies around the Coulomb barrier

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Abstract. We present the experimental fusion cross sections for the $^7\text{Li}+^{51}\text{V}$ system measured using the EN Tandem Van de Graaff Accelerator facility at National Institute of Nuclear Research (ININ), in Mexico. The study was focused on energies around the Coulomb barrier, $B = 10.33 \text{ MeV}$ ($B_{\text{lab}} = 11.75 \text{ MeV}$), in the interval from 10.0 MeV to 13.5 MeV in steps of 0.5 MeV, in the laboratory frame. In order to complement this study, the experimental results were compared with a fusion-evaporation analysis using the PACE2, LILITA and CASCADE codes, in the same interval of energies. We found that the $xn$ and $xn\alpha$ are the most relevant evaporation channels, leading to $^{55}\text{Fe}$, $^{56}\text{Fe}$, $^{52}\text{Cr}$ and $^{53}\text{Cr}$ as residual nuclei.

1. Introduction
In recent years, the Heavy Ion Group of the National Institute of Nuclear Research (ININ), has incorporated into its research interest the study of nuclear reactions using stable beams on different targets using the EN Tandem Van de Graaff Accelerator facility at ININ, in Mexico. The main goal of these studies is to compare and complement the information on the behavior and nuclear structure of radioactive beams, such as $^7\text{Be}$ and $^8\text{B}$. For this, the elastic scattering angular distributions of the $^9\text{Be}+^{51}\text{V}$ and $^7\text{Li}+^{58}\text{Ni}$ systems have already been measured around the respective Coulomb barrier energies $[1, 2]$. Recently, several theoretical and experimental analyzes have been carried out to study the fusion mechanisms of $^7\text{Li}$ on different targets by various research groups around the world $[3, 4, 5, 6, 7, 8]$. Following this reasoning we aimed to measure, by using the $\gamma$-ray technique $[4, 9, 10]$, the fusion cross sections for the $^7\text{Li}+^{51}\text{V}$ system at energies between $E_{\text{lab}} = 10.0$ and 13.5 MeV.

In order to compare our experimental data, we performed an evaporation-fusion analysis by using the PACE2 $[11]$, LILITA $[12]$ and CASCADE $[13, 14]$ codes. Calculations made with these codes usually involve the selection of multiple sets of input parameters which may have a wide range of reasonable variation, sometimes leading to important sensitivity in the final results. Examples of the latter are the level density and optical parameters. For this reason, it is necessary to choose an appropriate set of input parameters to assess the compatibility of the corresponding physical calculations that permits a reliable comparison of the fusion cross section deduced for the different codes.
2. Experimental setup
The experiment was carried out at the Accelerator facility at ININ, in Mexico. The $^7$Li beam was produced with the 6MV EN Tandem Van de Graaff Accelerator. The experimental arrangement consisted of a natural composition Vanadium thick target, a Surface Silicon-Barrier detector (SSB) and a Hiperpure Germanium detector (HpGe). The SSB detector was used to measure the back-scattered charged particles, while the HpGe detector was used to measure the $\gamma$-rays produced by the residual nuclei formed during the reaction. These detectors were placed at 150 and 125 degrees with respect to the beam axis, as shown in figure 1. The energies considered in this study were $E_{\text{lab}} = 10.0, 10.5, 11.0, 11.5, 11.75, 12.0, 12.5, 13.0$ and 13.5 MeV.

3. Results and discussion
The selected $\gamma$-ray spectra measured are shown in figure 2 for indicated energies. Also, background spectrum is shown for comparison. To determine the fusion cross section, only the $\gamma$-rays produced by decays to ground state, were considered.

The experimental fusion cross sections, $\sigma_{\text{fus}}$, were determined by the relationship:
\[ N_\gamma = \epsilon N_p \int_0^{E_0} \frac{\sigma_{fus} dE}{S(E)}, \]  

where \( N_\gamma \) is the number of \( \gamma \)-ray detected (for a specific energy), \( \epsilon \) is the absolute efficiency of the detection system, \( N_p \) is the number of incident projectiles and \( S(E) \) is the stopping power in the target.

The comparison of the data (symbols) with our calculation using the PACE2 code is shown in figure 3, for most important residual nuclei. In most cases, the calculations show some significant differences while in others there are not. In particular, the \( ^{52}\text{Cr}(2n\alpha) \) and \( ^{53}\text{V}(p\alpha) \) isotopes productions turned out to be larger than those predicted by the code. We suppose that there might be some other processes present, such as transfer, breakup and/or incomplete fusion, that are not considered by the code. It is necessary to make a wide analysis by using the CDCC and CRC methods. The same figure shows the experimental total fusion excitation function measured in this study (black circles). It turned out that the \( xn \) and \( xn\alpha \) are the most relevant evaporation channels leading to residual nuclei \( ^{55}\text{Fe}, ^{56}\text{Fe}, ^{52}\text{Cr} \) and \( ^{53}\text{Cr} \), which represent approximately 85% of the total fusion cross section. The points shown here only include the statistical errors, therefore, the error bars are not visible in the experimental data.

![Figure 3](color online) Comparison of the fusion cross sections measured for every residual nuclei with the PACE2 code for the \( ^7\text{Li}+^{51}\text{V} \) system. The black circles represent the sum of the partial cross sections.

On the other hand, in figures 4(a,b), the fusion cross sections predicted by the PACE2 (solid lines), LILITA (dotted lines) and CASCADE (dash-dot lines) codes are shown for the most significant residual nuclei \( (^{55}\text{Fe}, ^{56}\text{Fe}, ^{52}\text{Cr} \) and \(^{53}\text{Cr} \)). One reason of the differences is the way each code does the calculation. According to the three codes, the evaporation of neutrons is the most important process through which the composite nucleus \( (^{58}\text{Fe}) \) releases its exceeding energy. Therefore, the most expected residual nuclei to be produced are \( ^{56}\text{Fe}(2n) \) and \(^{55}\text{Fe}(3n) \).

We use a well-known data reduction procedure in order to make direct comparisons with similar systems to our study, as proposed in Ref. [15]. For this, we used the data previously reported for \( ^7\text{Li}+^{59}\text{Co} [5] \) and \( ^7\text{Li}+^{64}\text{Zn} [8] \) systems, which have the same projectile. This comparison is shown in figure 5, where our experimental data seem to be located between the two regions formed by the data of these systems.
4. Summary
We performed an experiment to measure the fusion at several energies around the Coulomb barrier for the $^7$Li+$^{51}$V system. A theoretical analysis to compare the predictions for the residual nuclei produced in the fusion of the system, by using the PACE2, LILITA and CASCADE codes, was made. The obtained results show a larger production of the $^{52}$Cr($2n\alpha$) and $^{53}$V($p\alpha$) residual nuclei than those predicted by the fusion-evaporation codes. We suppose that these differences may result from transfer, breakup and/or incomplete fusion processes. It is necessary to perform the corresponding calculations to confirm or refute such hypothesis. It turned out that the $x\alpha$ and $xn\alpha$ are the most relevant evaporation channels leading to residual nuclei $^{55}$Fe, $^{56}$Fe, $^{52}$Cr and $^{53}$Cr.
Acknowledgments
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