Outreach Activity: Liquid Nuclei

The Nuclear Liquid Drop Model

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Binding Blocks Initiative

@BindingBlocks

Activity originally conceived by the Universities of York and Surrey

ICCUB Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU

Binding Blocks Building the Universe one nucleus at a time

Abstract

This document provides an overview of the Liquid Drop Model (LDM) of the atomic nucleus and details the interactive activities designed to explore its concepts. It also includes a step-by-step guide to set up and run the project's local server to visualize the results of the students' activities.

Contents

1 Introduction to the Liquid Drop Model

What holds an atomic nucleus together? The **binding energy** of a nucleus is the answer: it measures the energy gained by coupling neutrons and protons to form a nucleus. For example, if you take the mass of 8 protons and 6 neutrons and compare it to the experimentally measured mass of a ^{14}O (oxygen-14) nucleus, you will find that the nucleus is *lighter* than its parts. This "lost mass" has been converted into a large amount of energy, as described by Einstein's famous formula, $E = mc^2$. This energy is the binding energy.

Although experiments can measure the binding energy of thousands of nuclei, scientists also want to be able to predict these properties without an experiment. This is where scientific models come into play. The **Liquid Drop Model**, conceived by nuclear theorists in the 1930s, is one of the simplest and most successful models for this purpose. It treats the nucleus as if it were a drop of incompressible liquid, like a small water balloon. This analogy works surprisingly well because the strong nuclear force that binds nucleons together is very short-range, much like the forces between molecules in a liquid.

The model allows us to estimate the average binding energy per nucleon (BE/A), a key measure of a nucleus's stability, using the **Semi-Empirical Mass Formula (SEMF)**:

$$\frac{BE}{A} = a_v - a_s A^{-1/3} - a_c \frac{Z(Z-1)}{A^{4/3}} - a_a \frac{(A-2Z)^2}{A^2} + a_p \frac{\delta_0}{A^{1/2}} \tag{1}$$

Where A is the total number of nucleons (protons + neutrons) and Z is the number of protons. Each term represents the contribution per nucleon of a different physical effect:

1. **Volume Term (a_v):** This term provides a constant positive amount to the binding energy. It comes from the idea that each nucleon only interacts with its immediate neighbors due to the short range of the nuclear force.

2. **Surface Term ($-a_s A^{-1/3}$):** This term has a negative sign because the nucleons on the surface have fewer neighbors to interact with, causing them to be less tightly bound. This is similar to surface tension in a real liquid drop.

3. **Coulomb Term ($-a_c \frac{Z(Z-1)}{A^{4/3}}$):** This term accounts for the electrostatic repulsion between positively charged protons. This repulsive force reduces the binding energy and explains why large, stable nuclei need more neutrons than protons to add "binding" without adding more repulsion.

4. **Asymmetry Term ($-a_a \frac{(A-2Z)^2}{A^2}$):** The nucleus is most stable when the number of neutrons and protons is approximately equal ($N \approx Z$). This term introduces an energy penalty for moving away from this symmetry.

5. **Pairing Term ($+a_p \frac{\delta_0}{A^{1/2}}$):** A quantum-mechanical effect where nuclei with an even number of protons and/or an even number of neutrons are systematically more stable than those with odd numbers. The pairing parameter, a_p, sets the magnitude of this correction, where δ_0 is positive for even-even nuclei, negative for odd-odd nuclei, and zero for nuclei with an odd mass number.

This model not only helps us understand the properties of the thousands of known nuclei, nuclear stability, and phenomena like nuclear fission, but it also allows us to predict the properties of nuclei we have not yet discovered and even understand some properties of incredibly dense objects like neutron stars. It is important to remember that this is a scientific model; it is a powerful tool, but it can always be improved or replaced by new data or a revolutionary new theory. Maybe you will be the one to improve it!

2 Description of the Activities

The project includes two main activities designed for you to interactively explore the concepts of the Liquid Drop Model. For each activity, you can select any element from the periodic table and work with the data of its isotopes, provided by the official Atomic Mass Data Center.

The application is focused on Oxygen by default, but we encourage students and teachers to experiment with the other elements of the periodic table. Also, remember that the web server only shows results from O($Z = 8$) to Rb($Z = 37$).

As students make their adjustments, they can send the found values by clicking the **Send** button at the bottom left of the application (see Section 5). The data on the web server will be updated automatically, and a message will show which group has sent the most recent data.

2.1 Activity 1: Adjusting the Liquid Drop Model

In this activity, you will understand how the parameters of the Liquid Drop Model (a_v, a_s, a_c, a_a, a_p) relate to real experimental data through 5 different exercises.

Two graphs will guide your adjustment (see Figure 1):

- **Graph 1:** Shows the binding energy per nucleon (BE/A) versus the mass number (A). The blue dots are the real experimental data, and the red line is the theoretical value of the LDM formula using the parameters you have set with the sliders.
- **Graph 2:** Shows the difference (the error) between the experimental data and your theoretical fit. It also provides the root mean square (RMS).

In some exercises, a vertical green line will indicate the mass number of the symmetric isotope.

Your goal is to adjust the values of the liquid drop model parameters (see Section 5) to make the red line in graph 1 match the blue dots as closely as possible. This is equivalent to making the error in graph 2 as close to zero as possible for all isotopes. Through the 5 exercises, you will determine the optimal fit values for the model parameters in a guided manner.

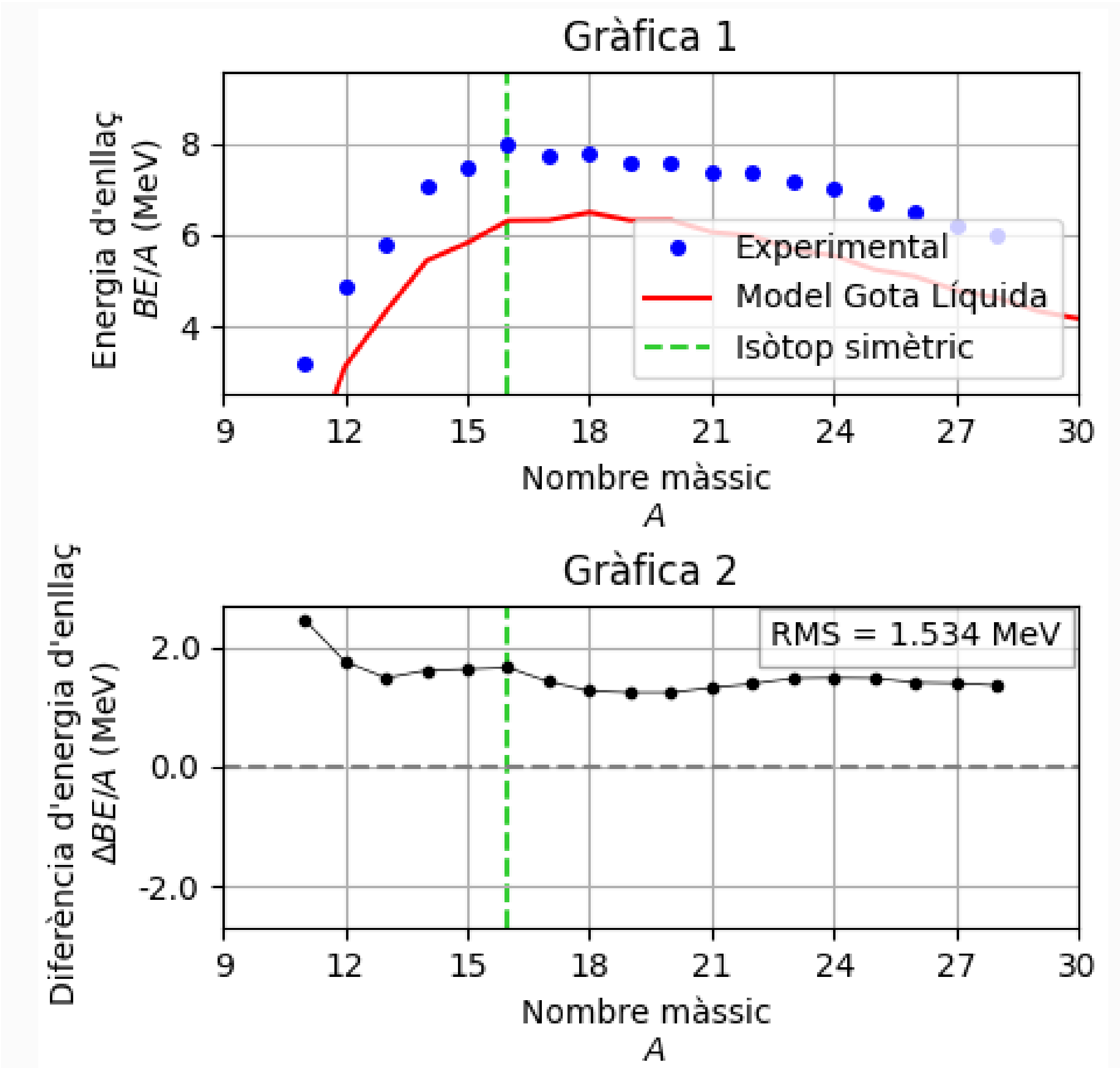

Figure 1: Activity 1 Graphs.

2.2 Activity 2: Predicting the Heaviest Isotope

In this activity, you will use the parameters of the liquid drop model found in Activity 1 to predict the heaviest isotope of an element in the periodic table. Remember that an isotope can only exist if its binding energy is positive (BE/A > 0). If the binding energy were zero or negative, the nucleus would spontaneously disintegrate.

You can monitor the fit of your parameters in Graph 1 shown in Figure 2. If the model is well-adjusted, the theoretical red line should match (almost) all the experimental blue dots. The heaviest isotope is indicated by a vertical green line, which varies depending on the parameters of your model.

Your goal is to understand how the uncertainty in the model parameters can affect the prediction of the heaviest isotope, for a given element, by varying the asymmetry and volume parameters. This will give you a range of possible mass numbers (A) for the limit of the nuclear existence of the isotope.

To visualize the uncertainty range (green area), you can use the cells below the graph. You can enter the minimum (A_{min}) and maximum (A_{max}) atomic number values manually, or by clicking the **Set** button. If you click the **Set** button, you will enter the value indicated by the vertical green line. Remember that $A_{min} < A_{max}$.

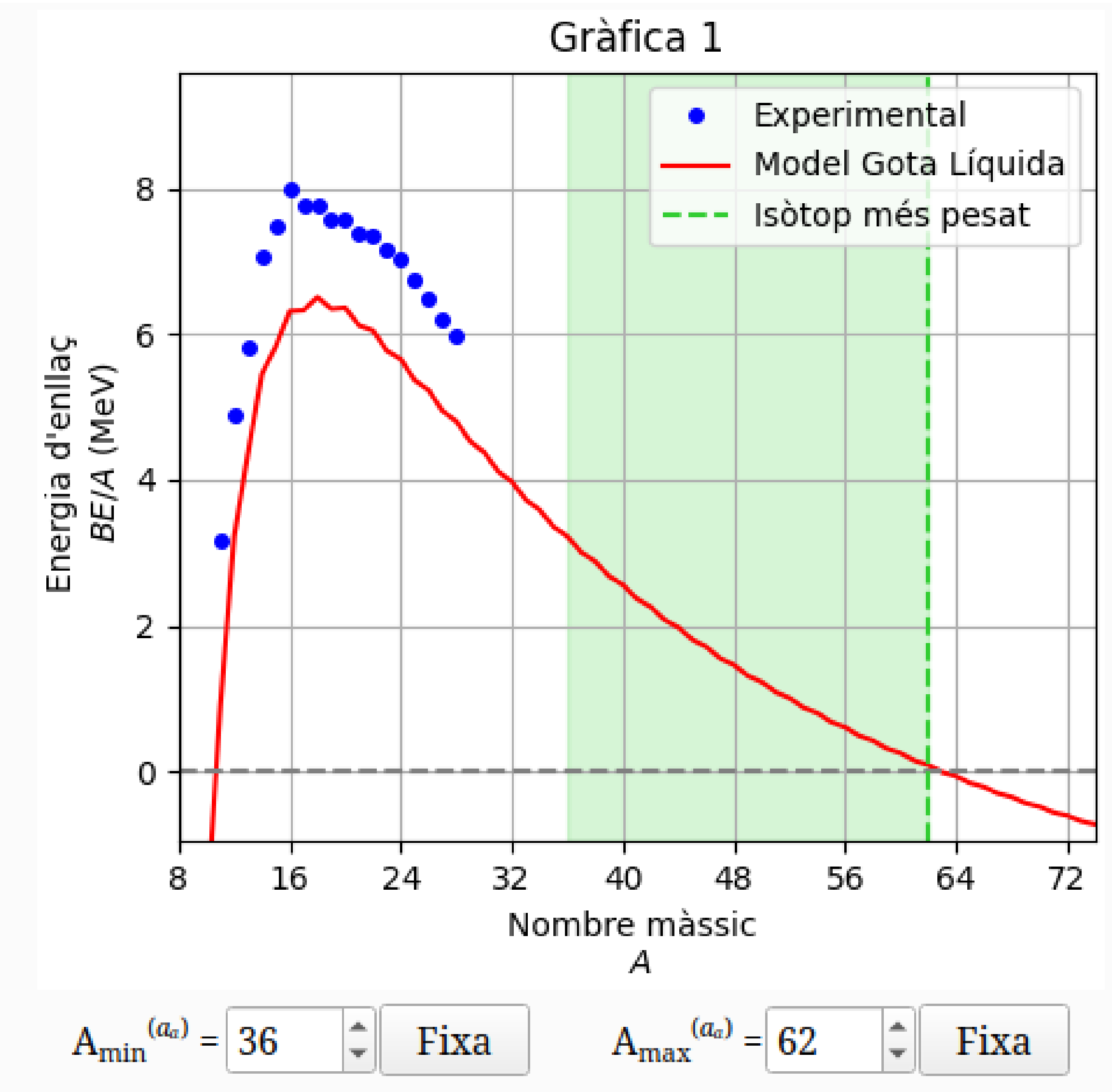

Figure 2: Graph 1 of Activity 2.

3 Prerequisites

To carry out the activities, each student or group of students must have at their disposal a Windows or Linux computer. There is no MacOS version at the moment.

To carry out the activity, no connection to the Internet or the server is necessary (see Section 4). However, to be able to visualize the students' results through the web browser, the computer hosting the server must be connected to the same network as the students' computers. Sometimes, if the server computer is connected to the network with an Ethernet cable and the students connect via Wi-Fi, network incompatibilities can occur.

The application and the server are available as pre-compiled executables for Windows and Linux, which can be downloaded from the project repository.

- Windows Server: https://github.com/Alejandro-FQA/LDM/raw/refs/heads/main/dist/server_gui.exe?download=
- Windows Client: https://github.com/Alejandro-FQA/LDM/raw/refs/heads/main/dist/main_window.exe?download=
- Linux Server: https://github.com/Alejandro-FQA/LDM/raw/refs/heads/main/dist/server_gui?download=
- Linux Client: https://github.com/Alejandro-FQA/LDM/raw/refs/heads/main/dist/main_window?download=

Instructions for Windows users: once downloaded, the executables are ready to use. Important: Windows may recognize the executable as *malware*. In this case simply ignore the message and force the execution.

Instructions for Linux users: once downloaded, the executables must be started from the terminal.

1. Open the terminal in the folder where you have saved the executables with `Ctrl + Alt + t`.
2. Enter in the terminal `chmod +x <executable name>` to give execution permissions.
3. Enter in the terminal `./<executable name>` to start the application.

4 Server Connection: Guide for Teacher and Students

To visualize the results in a centralized way through a web browser (Explorer, FireFox, Chrome, etc.), the teacher runs the `server_gui` controller, and each student uses the `main_window` application to connect to it.

4.1 For the Teacher: Starting the Server

As the person in charge of the activity, your role is to host the server to which the students will connect.

1. Download and run the `server_gui` controller for your operating system (see Section 3).
2. A control window like the one in Figure 3 will appear (in English). The resources are indicated below following the numbering of Figure 3 in parentheses (...).
3. To start the server, click the **Start Server** button (5).
4. If the server has started successfully, a **Server URL** address (2) and messages in the **Server Log** (7) will be displayed indicating this.
5. The URL address must be shared with the students so they can connect to the server.
6. To access the web server, you can type the address in your favorite browser by copying it to the clipboard by clicking **Copy URL**, or open the default browser by clicking **Open in Browser**.
7. You can change the language of the web server with the **Language** dropdown menu (1) of the controller at any time (Catalan by default). To see the change take effect, you must refresh the web page (or click F5).
8. In **Received Messages** (9) you will be able to see the information that the students send to the server.
9. To stop the server and end the activity, you can press the **Stop Server** button (6).

If for any reason the server controller closes unexpectedly, the students just need to send their data again once to recover all the previous information. If at this moment any group or student has been disconnected, when they connect again they will be assigned a new group.

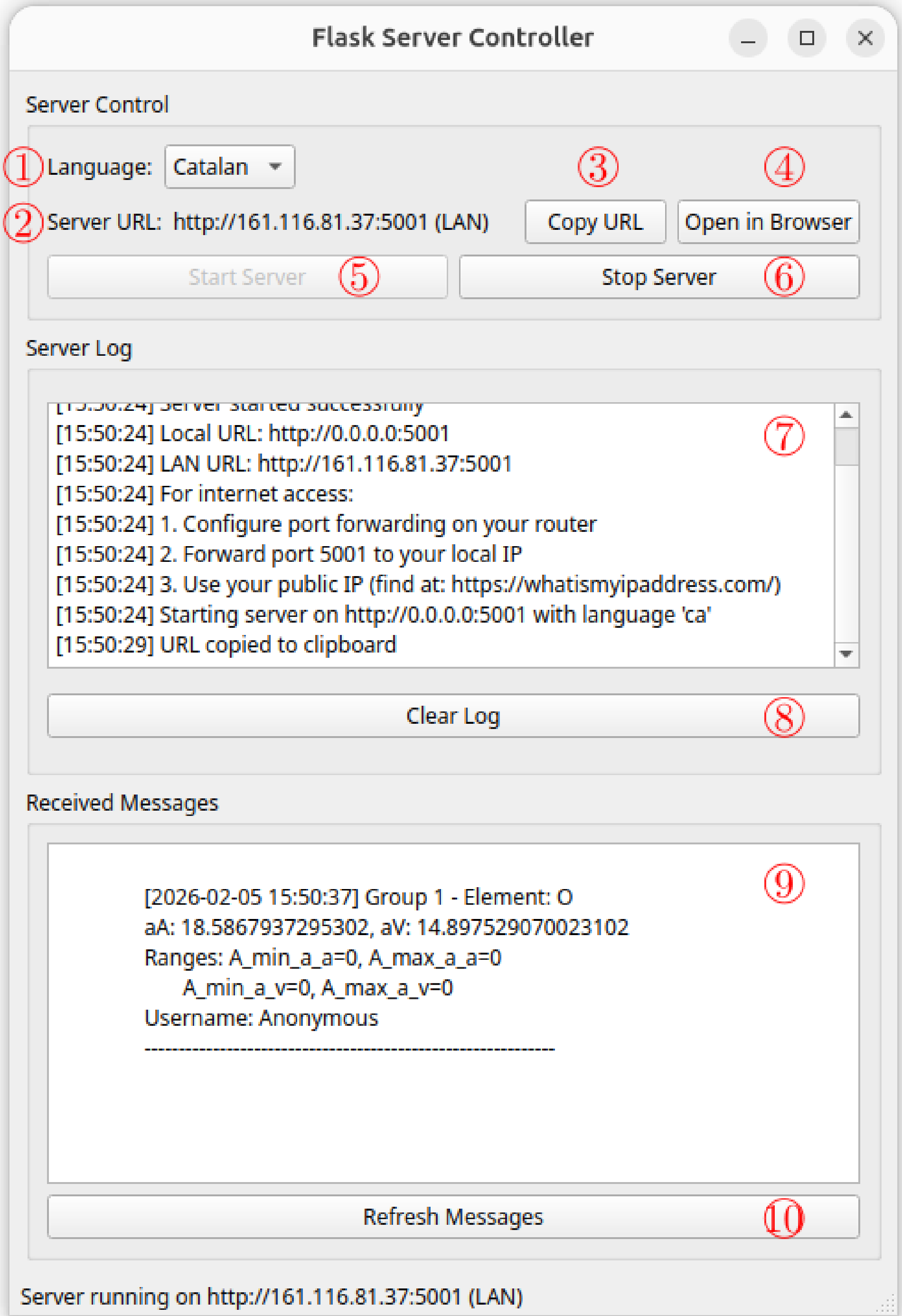

Figure 3: Active server controller. 1. Language; 2. Server web address; 3. Button to copy the address; 4. Button to open the web browser; 5. Button to start the server; 6. Button to stop the server; 7. Server message box; 8. Button to clear the server message box; 9. Received messages box; 10. Button to clear the received messages box.

4.2 For the Student: Connecting to the Server

As a student, you will connect to the teacher's server to send your results.

1. Download and run the `main_window` application for your operating system (see Section 3).
2. A window like the one in Figure 4 will appear (by default in Catalan and on the Activity 1 tab). The resources are indicated below following the numbering of Figure 4 in parentheses (. . .).
3. In the application, navigate to the **Logs** tab (2).
4. Write the **Server URL** provided by your teacher in the **Server** text field (4). If you have connected before, the application may remember the last URL used.
5. Click the **Connect** button (3).
6. If the connection has been successful, a group will be assigned to you (1), the **Connect** button (3) will change to **Disconnect** and the indicator (5) will turn green.
7. The message box (6) will show your log of actions within the application.

If for any reason the application closes unexpectedly, when you restart it you will recover all the information you had saved.

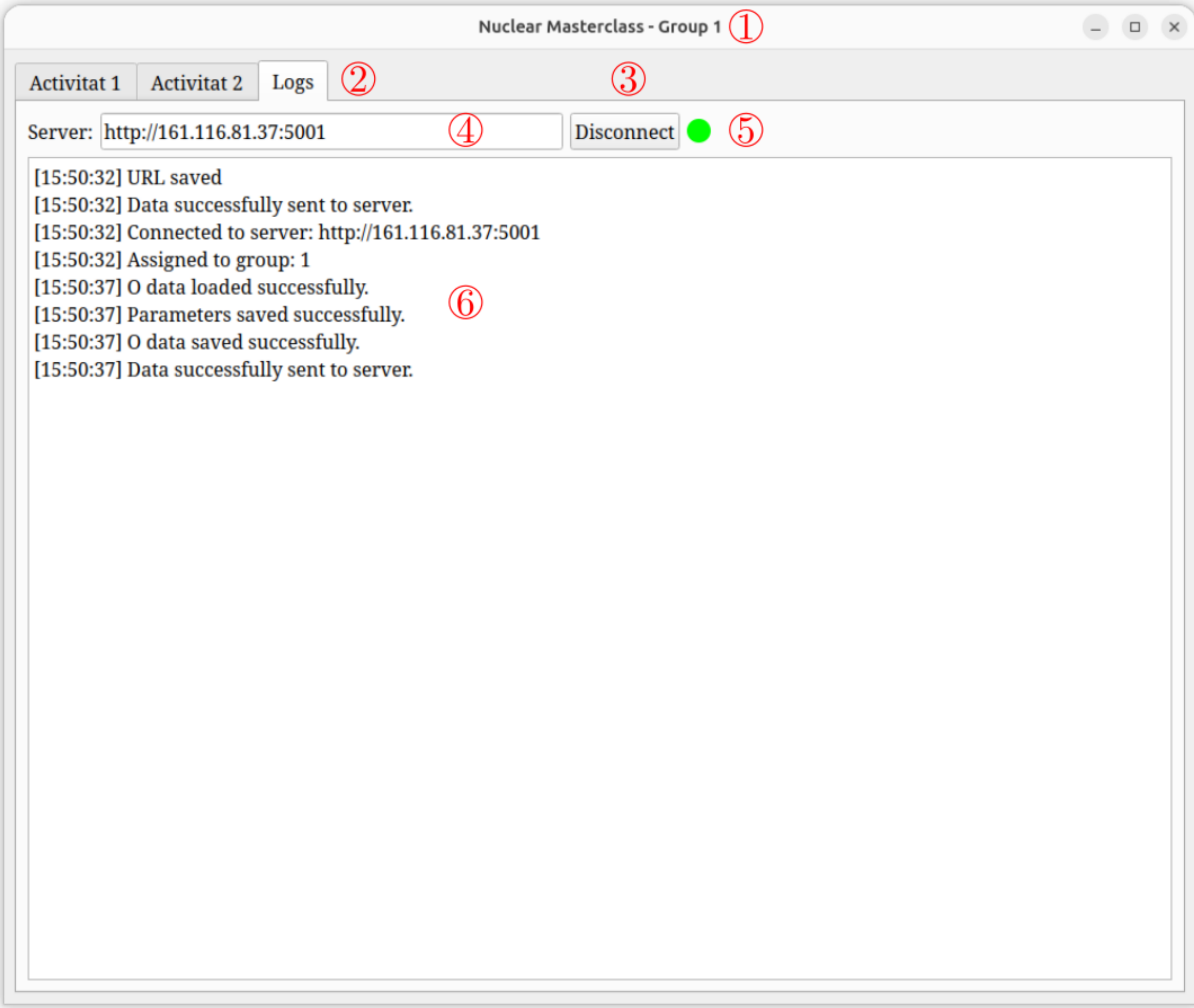

Figure 4: Application connector. 1. Assigned group; 2. Activity tabs; 3. (Dis)connect button; 4. Text field for the server URL address; 5. Connection indicator; 6. Application message box.

5 Using the Application

When you start the application (see Section 3), a window like the one shown in Figure 5 will open. A description is given below with the numbering of the resources shown in Figure 5.

1. Once connected to the server (see Section 4), a group will be assigned to you. If the connection is not established or no group is assigned, *Group None* will be displayed.

2. You can change activities by clicking on the corresponding tab.

3. You can select the element from the periodic table you want by expanding the list of elements.

4. You can select the application language by expanding the list of languages (Catalan, Spanish or English).

5. The interactive graphs will be displayed on the left of the application and change as the student adjusts the parameters of the liquid drop model.

6. The parameters of the liquid drop model can be modified 1) by typing the value, 2) by clicking the arrows in the cell, or 3) by sliding the indicator on the sliders. To lock a parameter, you can uncheck the corresponding right box.

7. On the right of the application, the descriptions of the activity exercises are displayed. You can change exercises by clicking on the corresponding tab.

8. Button line:

   (a) **Reset.** Button to reset the parameter values randomly. It will only affect unlocked parameters.

   (b) **Save.** Button to save the parameter values for the current element. It overwrites the previous values of the same element. The data is saved to a hidden file in the same directory/folder where the application is. If the student restarts the application, they do not lose the data or the assigned group.

   (c) **Load.** Button to load the saved data of the current element. It is only shown as active if the user has previously saved data. It also overwrites locked parameters.

   (d) **Send.** Button to send the data to the web server. It is only shown as active for the corresponding exercises. It automatically saves the current parameters.

   (e) **(i).** Button to open an information panel.

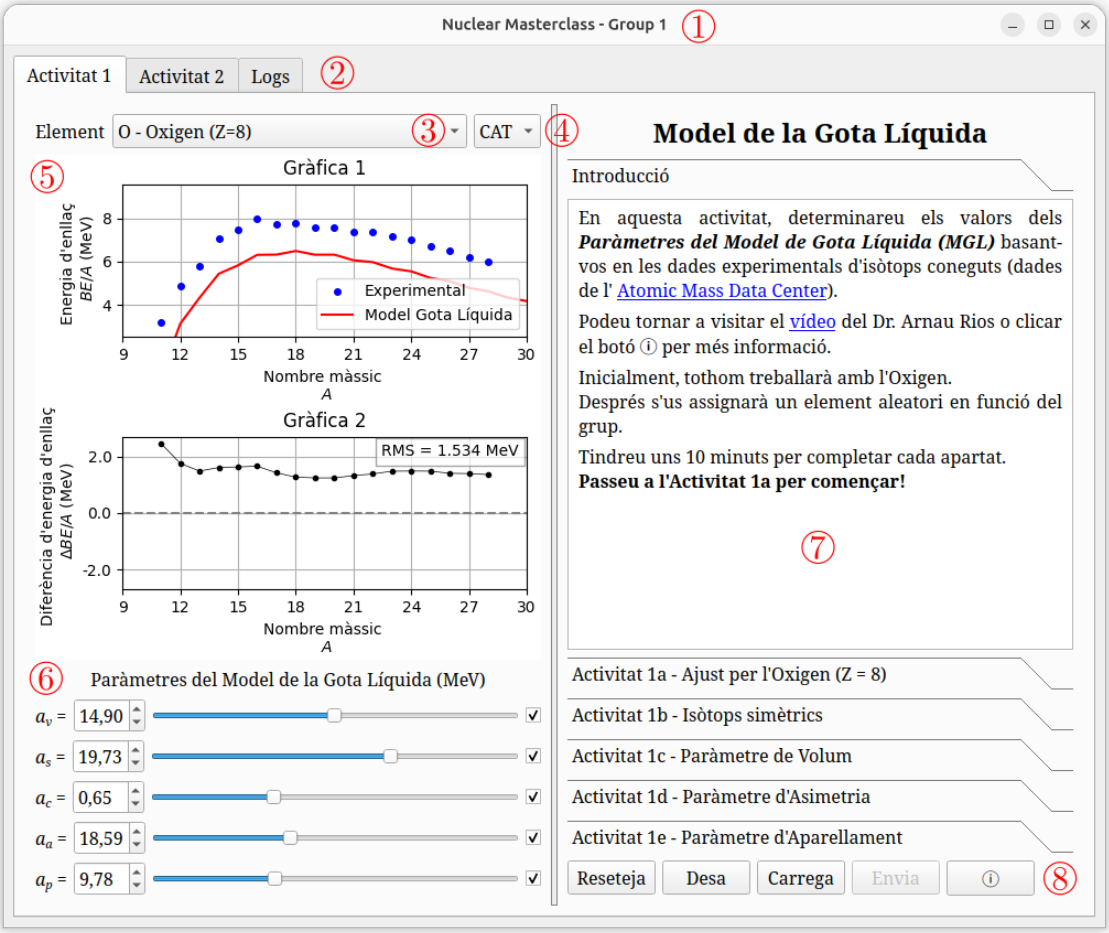

Figure 5: Application. 1. Assigned group; 2. Activity tabs; 3. Dropdown of elements of the periodic table; 4. Language dropdown; 5. Activity graphs; 6. Values of the liquid drop model parameters (initially random). 7. Name, description and exercises of the activity. 8. Button bar.

6 Using the Web Server

Once the server is started (see Section 4), you can open the web browser by clicking **Open Browser** to see the results as shown in Figure 6. It is recommended to display the browser in full screen (F11). A description is given below with the numbering of the resources shown in Figure 6 (Activity 2 has a simpler template).

As students submit their results, they will appear distributed in the form of a histogram (3). The last received instances can be seen in the Group Activity (4). If necessary, the teacher can see the entire history of messages in the Server Controller (see Figure 3.9).

Each successfully submitted element will be indicated in green, along with a number indicating how many students have adjusted the parameters of that element (5).

To change exercises or activities, just click on the corresponding tab (2).

To change the language, the teacher can use the Server Controller (see Figure 3.1). Updating the page (F5) or changing the activity will update the language.

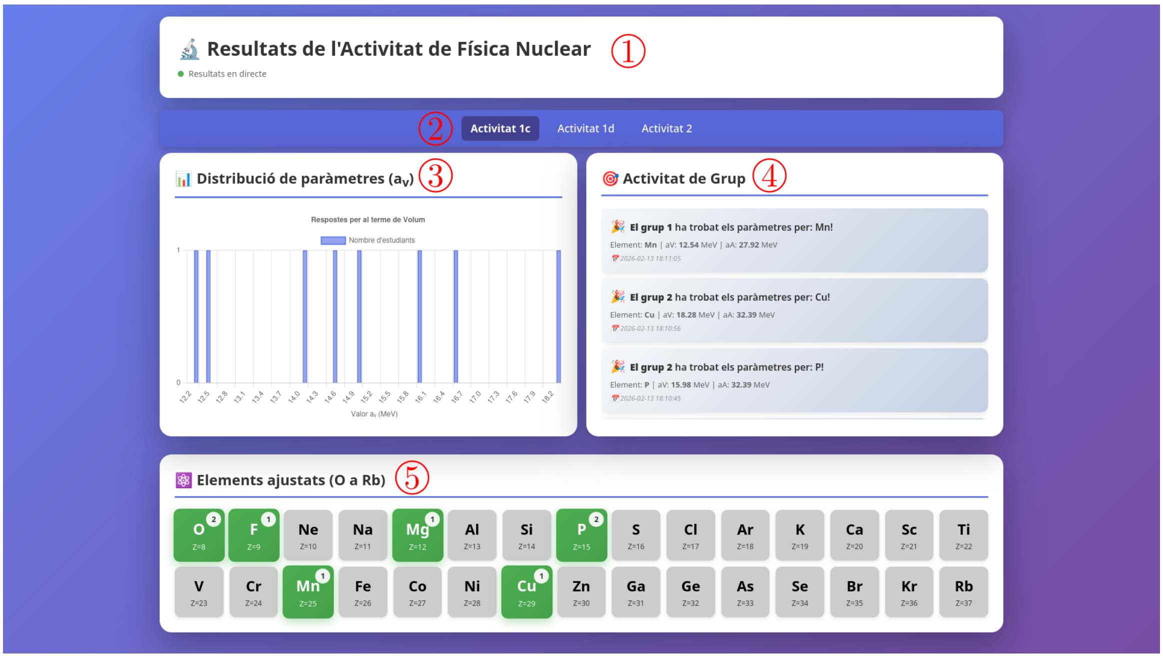

Figure 6: Web server. 1. Title; 2. Activity tabs; 3. Histogram of responses; 4. History of responses; 5. List of found elements;