ABSOLUTE CROSS SECTIONS MEASUREMENT IN TWO NUCLEONS TRANSFER REACTIONS

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Obținerea valorilor absolute pentru secțiunile eficace ale reacțiilor nucleare este o misiune dificilă, de o deosebită importanță atât pentru fizica nucleară fundamentală cât şi pentru cea aplicată. În această lucrare am dezvoltat un instrument de calcul pentru obținerea secțiunilor eficace pe baza intensităților experimentale determinate în reacții nucleare directe de transfer a doi neutroni. Programul este testat pentru reacții (p,t) la o energie a fasciculului de 25 MeV , pe ținta de ^{134}Ba.

Obtaining the absolute values for the nuclear reactions cross section is a difficult task of tremendous importance both for basic and applied nuclear physics. In the present work we developed a computation tool for calculating the cross sections based on the experimental intensities of the two neutrons transfer direct reactions. The computer program is tested for the (p,t) reactions at 25 MeV beam energy on ^{134}Ba target.

Keywords: nuclear reactions, angular distributions, two nucleons transfer, cross sections.

1. Introduction

Nuclear reaction cross-sections are very important observables both for applications and basic research in nuclear physics. Their experimental determination requires carefully performed measurements with accurate knowledge of the experimental conditions. On the theoretical side, for each reaction mechanism there are models providing estimates for the absolute cross sections.

In this work, we have developed a computational tool for calculating nuclear reaction cross sections based on the experimental spectra, beam and target characteristics and detection geometry. We tested our program in the particular two nucleon transfer reaction ^{134}Ba(p,t)^{132}Ba. At 25 MeV proton beam energy,

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this reaction evolves dominantly by one step direct processes as described for example in ref. [1]. Detection of the emerging tritons can be performed nowadays with high energy resolutions, comparable with those obtained in the gamma-ray measurements, due to the technical improvements in the particle detection [2]. Indeed, we used the high resolution experimental data obtained at University of Munich Tandem Laboratory, at the Q3D magnetic spectrograph [3], with a complex focal plane detector [4].

The software tool developed in the present work is employed to determine the angular distributions of the differential cross sections and analysing powers when the reactions are induced by polarised particles. By comparing these observables with the DWBA (Distorted Wave Born Approximation) calculations we extracted information on the nuclear spin of the excited states in the even-even nuclei populated by (p,t) two neutrons peak-up reactions.

2. Principle of the method

As mentioned in the introduction, at 25 MeV energy, the incident protons on medium mass target nuclei induces nuclear reactions via direct processes. This mechanism excite only a few degree of freedom of the targets and a simple description of the process can be performed accurately by models like PWBA (Plane Wave Born Approximation) and DWBA (Distorted Wave Born Approximation) [1]. In the case of even-even targets and two neutron transfer processes, by simple comparisons of these calculations with the experimental angular distributions of the ejectiles, can be obtained valuable spectroscopic information as spin of the states in the residual nucleus and the spectroscopic factors of these states.

From the selection rules of the transferred angular momentum, we have (e.g. ref.[5]):

$$| J_i - J_f | \leq L \leq J_i + J_f \qquad (1)$$

where J_i, J_f and L are the spins of the target ground state, excited state in the residual nucleus and transferred angular momentum, respectively. Since for even-even nuclei the ground state spin is J_i=0, the only allowed value for the J_f is that of the transferred angular momentum L. The shape of the angular distribution of the cross sections is highly sensitive to the L value [6]. Therefore, by fitting the experimental cross sections with the theoretical ones calculated in the DWBA model for well defined values of the transferred angular momentum (L = 0, 2, 3, 4, 5), we can select in most cases the appropriate L value. These information obtained with hadronic probes (the dominant interaction governing this processes is the nuclear strong force) are in many aspects complementary with those

obtained by electromagnetic probes in the gamma-ray spectroscopy investigations [7].

A key element in all spectroscopic studies is the energy resolution of the detection system. Nowadays the best resolutions for the charged particles detection are obtained with complex magnetic spectrometers combined with sophisticated focal plane detectors [8]. We used data obtained from (p,t) reaction at the Q3D spectrograph of the University of Munich, with protons of 25 MeV delivered by the MP Tandem accelerator. The main elements of the spectrograph are a quadrupole magnet for focalization and three magnetic dipoles to analyze the particles momentum. Tritons were detected in the Q3D focal plane by a multi-detector system composed from three proportional counters and a plastic scintillator to measure their residual energy. The focal plane detector provides particle identification and background reduction, accepting only events within the correct angle of incidence. A detailed description of this instrument is given in ref. [4]. The energy resolution obtained in (p,t) experiments is typically 6-10 keV, determined mainly by the thickness of the target (typically 100 $\mu m/cm^2$). With this resolution, we succeed to resolve most of the states populated in the $^{134}Ba(p,t)^{132}Ba$ reaction up to 4 Mev excitation energy. In analyzing the experimental spectra we have considered only those peaks with centroids remaining roughly at the same channel when the Q3D angular position was changed. Peaks that show up at different locations of the detector or disappear at different angles are produced by the interaction of the protons with low mass target impurities and were disregarded.

A schematic layout of the experimental arrangement is shown in Figure 1. Most of the incident protons do not induce a nuclear reaction in the target and passes through, entering in a Faraday cup where their total charge is measured by a charge integrator. This total charge is a parameter required by our program. The guard ring at a negative potential (-300 V) placed at the entrance of the cup keeps inside the electrons which can be released when the protons hit the walls of the cup.

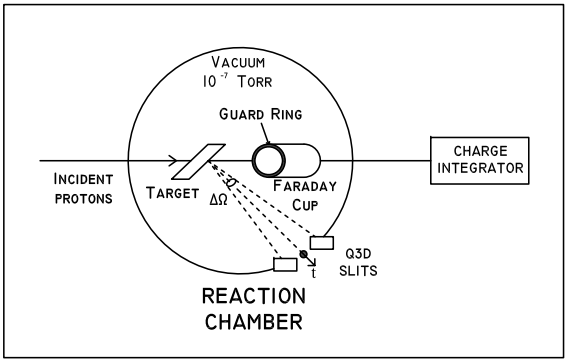

Fig.1. Schematic layout of the reaction chamber.

The slits placed at the entrance of the Q3D define the acceptance angle (solid angle $\Delta\Omega$ in Figure 1) in which the particles can enter the spectrograph. This acceptance angle (entrance opening) can be changed by modifying the sizes of the slits, and is ranging from 2.978 msr to 11.038 msr. For high fluxes of tritons (e.g. at small Q3D angles) the entrance opening has to be small in order to keep a reasonable counting rate in the detector. At backward angles, the slits are usually kept at their maximum openings.

Energy calibrations and peak fitting were performed with the package RADWARE [9], a code designed for analyzing gamma-ray spectra, but which can be employed with success also for hadronic spectra. In Figure 2 we present an example of the tritons spectrum measured with the Q3D at 6 degrees in the reaction ^{134}Ba(p,t)^{132}Ba. The energies marked on some of the strong peaks correspond to excitation energies in the residual nucleus.

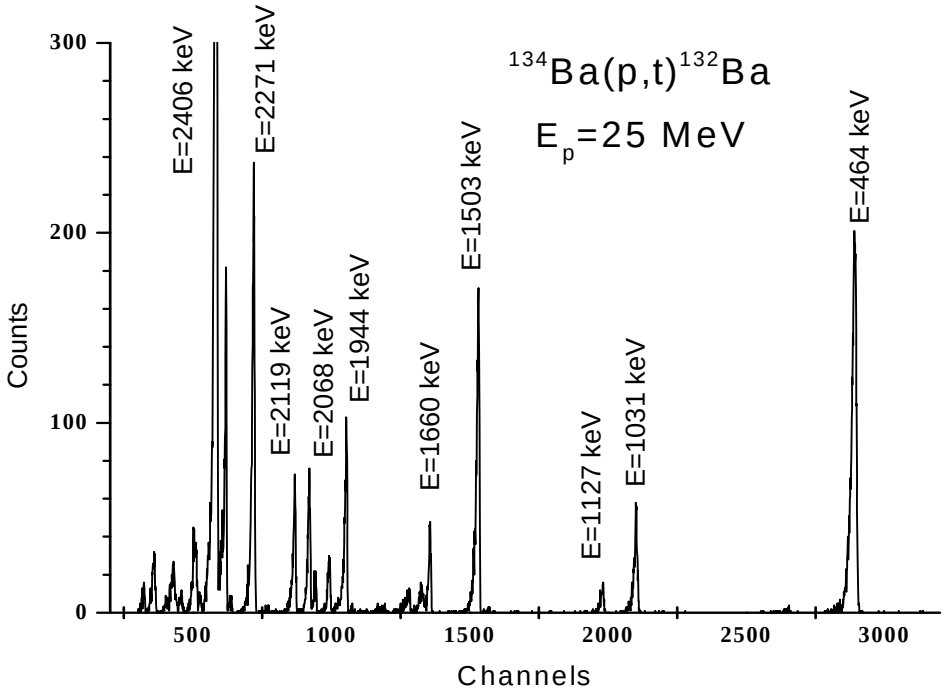

Fig. 2. Triton spectrum measured at 6^0.

For singlet peaks, the areas were determined by direct integration. For overlapping multiplets a deconvolution procedure has been used, as presented in Figure 3 (for peaks (2), (3), (4), (5) and (6)). The histogram represents the

experimental data, plotted as number of counts versus the number of channels. The light-dark curves are the single peaks. The deep-dark curve is the convoluted shape. The theoretical shape of the peaks has three components: a Gaussian, a skewed Gaussian and a step function needed to extract the background. The shape of each peak in the multiplet has been adjusted by fitting a singlet peak from the same region of the detector. For example, in Figure 3 the shape of the peak (1) is imposed in the fit procedure of resolving the multiplet (2)-(6).

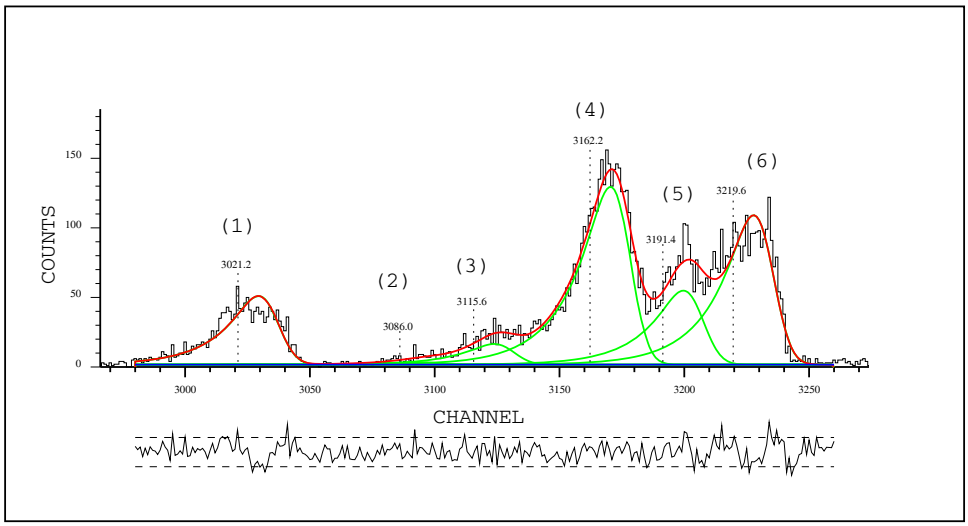

Fig. 3. Example of multiplets deconvolution. In the lower part of the figure is shown the difference ("residual") between the experimental and fitted spectrum.

The focal plane of the Q3D has a certain degree of curvature, inducing nonlinearities in the experimental spectra (the detector is 1 m long and is linear). This nonlinearity makes the energy calibration a difficult task. In our case, a polynomial of degree three was suitable for calibration. Up to the excitation energy $E_x \approx 2.5$ MeV the absolute accuracy in the determination of the levels energy is around ±3 keV. For higher energies, the uncertainties can reach up to ±10 keV.

3. Code description

The cross section in the laboratory system is given by the following equation [3]:

$$\left(\frac{d\sigma}{d\Omega}(\theta)\right)_{lab} = \frac{N(\theta)}{\Omega}\cdot\left(\frac{Q_{FC}}{Z_p\cdot e}\right)^{-1}\cdot\left(\frac{d_T\cdot N_{AV}}{A_T}\cdot\frac{1}{\cos\varphi}\right)^{-1} \tag{2}$$

where $N(\theta)$ is the number of the events recorded for a given state (area calculated with RADWARE), θ is the Q3D angle, Ω is the Q3D entrance solid angle, Q_{FC} is the charge collected in the Faraday cup (usually around 1 mC), Z_p is the charge of the projectile, e is the elementary charge, d_T is the thickness of the target, N_{AV} is Avogadro number, A_T is the mass of the target and φ is the angle of the target relative to a direction perpendicular to the beam, as shown in Fig. 4:

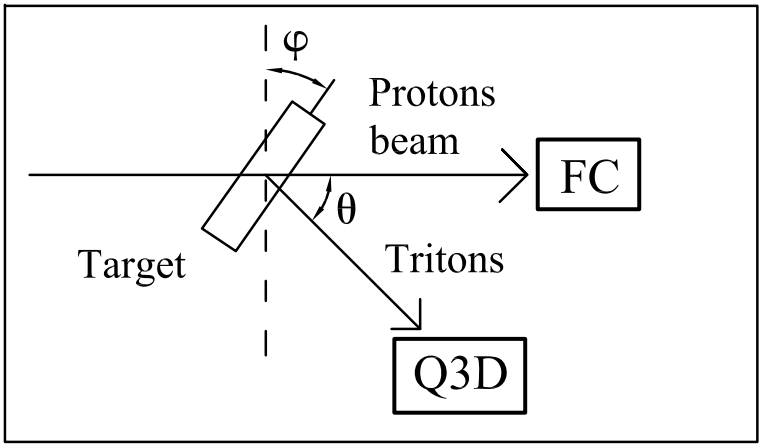

Fig. 4. The simplified scheme of the reaction geometry showing the angles from equation (2).

The relation between the cross sections in the laboratory and in center of mass systems is given by the relation [10]:

$$\left(\frac{d\sigma}{d\Omega}(\theta)\right)_{CM} = \left(\frac{d\sigma}{d\Omega}(\theta)\right)_{lab}\cdot\frac{\sin(\theta_{lab})}{\sin(\theta_{CM})}\cdot\cos(\theta_{lab}-\theta_{CM}) \tag{3}$$

where θ_{lab} and θ_{CM} are the Q3D angles in the laboratory and center of mass respectively.

For the binary nuclear reaction A(a,b)B, the relation between θ_{lab} and θ_{CM} is given by equation [10]:

$$\theta_{CM} = \theta_{lab} + \arcsin\left(\sqrt{\frac{m_a m_b}{m_A m_B}\cdot\frac{T}{Q+T}}\cdot\sin\theta_{lab}\right), \tag{4}$$

where T is the kinetic energy of the incident particles, Q is the Q-value of the reaction and m_a, m_A, m_b, m_B are the masses of the participants.

In developing our program, we took advantage of the output files created by the RADWARE code. Our program is written in ROOT, an object-oriented software package developed at CERN (European Council for Nuclear Research, www.cern.ch) [11]. We used RADWARE to find areas and centroid positions for each state in the residual nucleus. The logical scheme of our program is represented in Fig. 5.

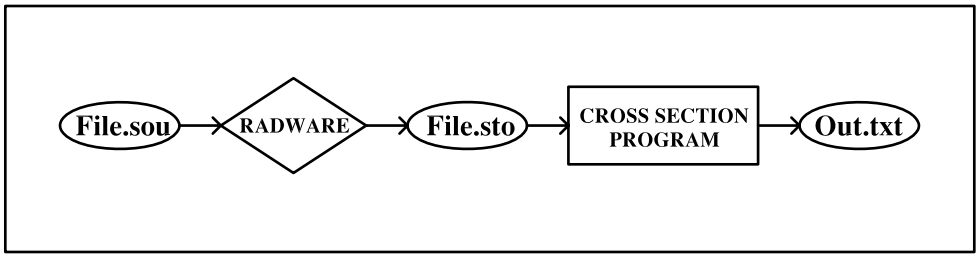

Fig. 5. Logical scheme of the program developed in the present work.

The program uses two input files, with the extension "*.sto*" and "*.sou*". The **.sou** is used as an input file for RADWARE and has the information organized in a matrix with four columns: the energy of each state, the uncertainty in energy, the intensity of the transition and the uncertainty in intensity (the last two columns are present only if we have indications for gamma ray transitions, otherwise there are 0). For states with unknown energy, the user can leave an empty row. This file is used by the code to calculate the difference between the known energy of the state and the energy determined with RADWRE. Both files must be edited such that the lines match one-to-one. An example of this file is shown in Figure 6a.

The **.sto** file is the output of the *xmgf3* program included in the RADWARE package. This file contains the centroids, the areas, the energies and their uncertainties determined from the spectra. In Figure 6b is presented an example of a **.sto** file.

Other parameters required by the program are the solid angle of the Q3D spectrograph, the charge measured by the beam charge integrator, the thickness of the target, the angle of the Q3D and the angle of the target. These information are taken from the experiment log-book and are provided "on-line" each time the code is ran.

The output of our code is written in **.txt** file as given for example in Figure 6c.

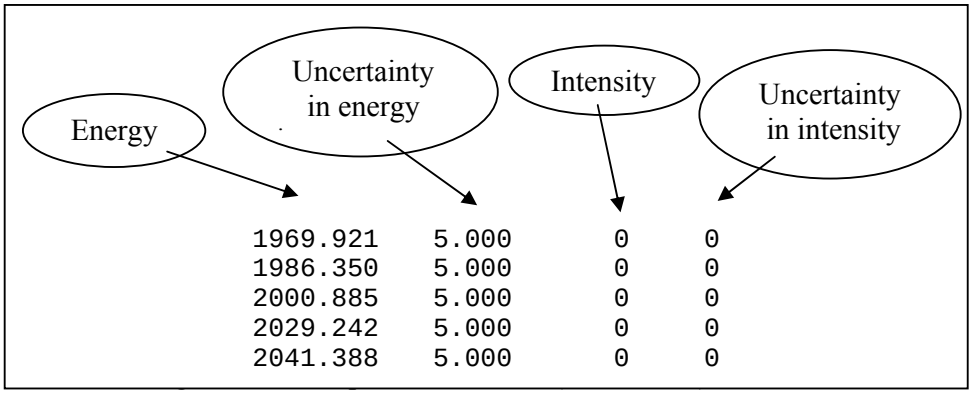

Fig. 6a. Example of a **.sou** file (see the text).

No.	Centroid	+- error	Area	+- error	Energy	+- error
1	3529.7070	1.0852	148	15	1968.9740	-0.5979
2	3500.2761	0.6625	401	22	1985.2377	-0.3672
3	3472.2422	1.0207	163	15	2000.8181	-0.5688
4	3421.4792	1.1305	147	15	2029.2518	-0.6364
5	3397.8452	1.3235	116	14	2042.5868	-0.7485

Fig. 6b. Example of a **.sto** file (see the text).

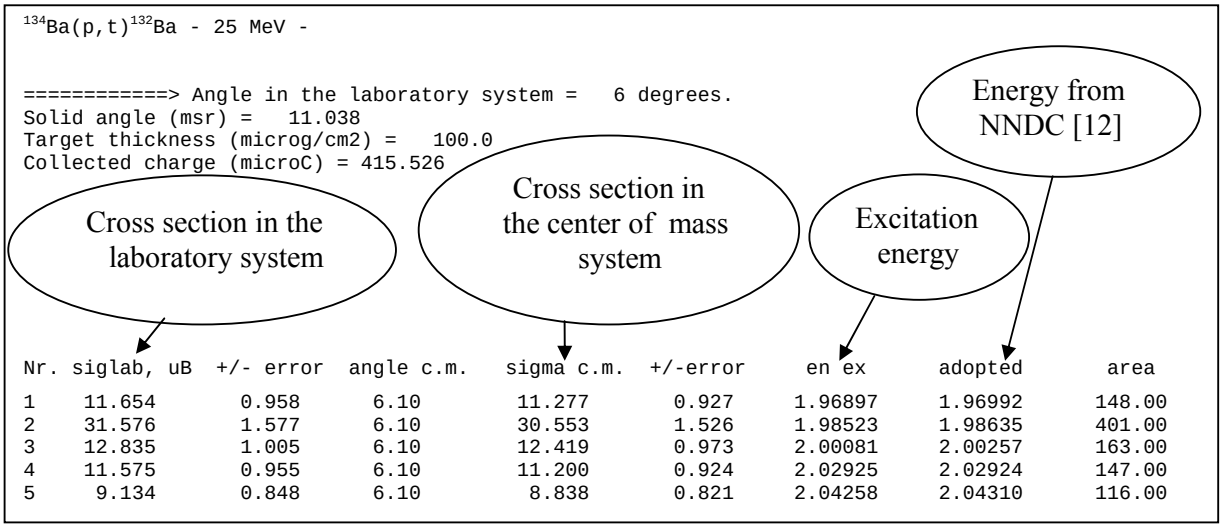

Fig. 6c. Example of a **.txt** file.

For ^{132}Ba we observed 73 levels, 46 of them for the first time. Some states populated by L=0 transitions have been reported in a previous work [13]. The excitation energy of the investigated states was in the range up to 4 MeV. The measurements were done at 6^0, 10^0, 15^0, 25^0, 30^0, 35^0, 40^0, 45^0 and 50^0. As mentioned before, a widely used model for describing nuclear processes is Distorted Wave Born Approximation (DWBA). One of the codes available for computations in this model is DWUCK-4 [14]. From the angular distribution fitted with DWUCK 4 we extracted the transferred angular momentum. Our data shows a good agreement with the results of the previous experimental investigations and also with theoretical predictions of DWBA, as can be observed from the examples presented in Figure 7.

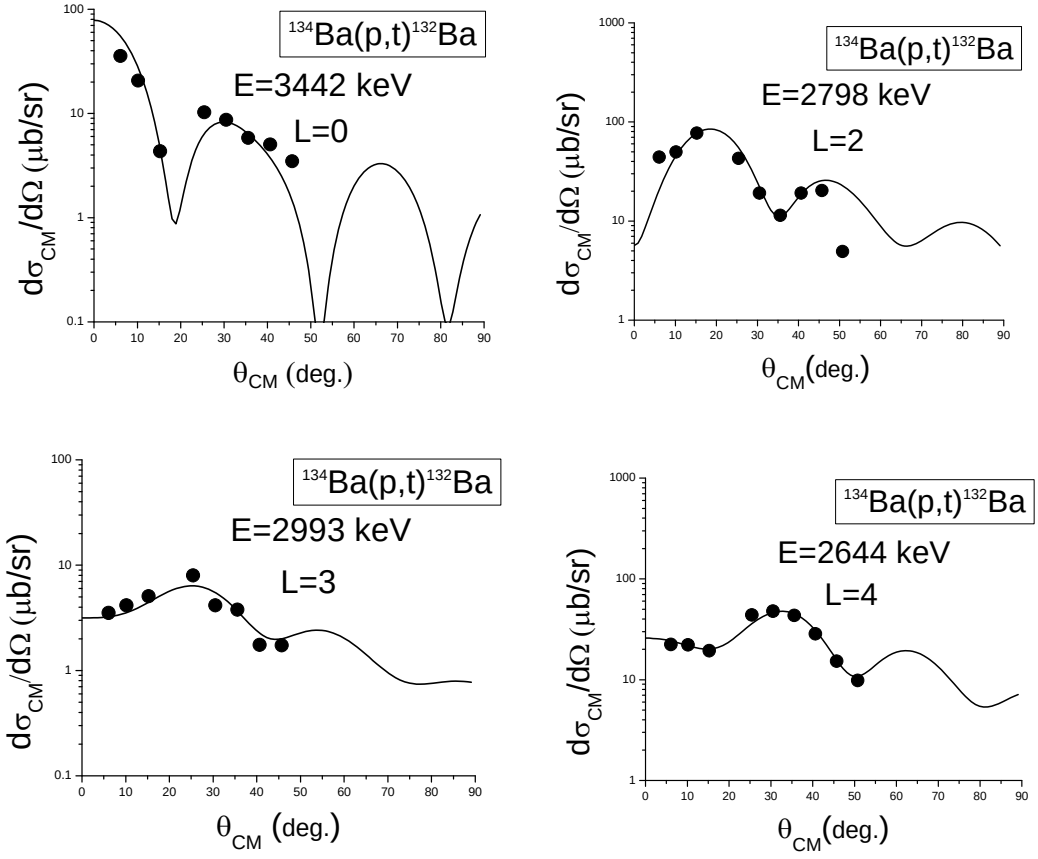

Fig. 7. Examples of experimental (dots) and DWBA calculations (continuous curve) angular distributions for L=0, L=2, L=3 and L=4 transferred angular momentum, obtained in the reaction ^{134}Ba(p,t)^{132}Ba at the proton energy E_p = 25 MeV. For each case is indicated the excitation energy of the final statein the residual nucleus.

4. Conclusions

In the present paper we developed and tested a computer program that allows the users to compute the differential cross sections from the intensities of two nucleon transfer reactions. Our computational tool reads automatically the output files of the RADWARE spectra fitting code. This facilitate the calculation and it reduce the amount of time spent writing user input files.

We tested our program for the reaction (^{134}Ba(p,t)^{132}Ba) at 25 MeV proton energy. The results show good agreement with the previous results reported in the literature.

This program is part of a larger project for building a Graphic User Interface computational tool that aims to read the output from peak fitting packages and to draw the angular distributions fitted with the DWBA model.

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