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— *To my parents* —

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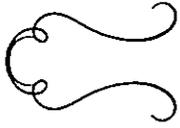
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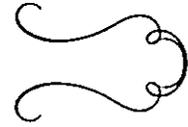
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Preface



A century has been elapsed since the first observation of nuclear reaction by Rutherford in 1919. Since that time, a lot of efforts were done to comprehend the observed results. Because of the complexity of nuclei as a quantum mechanical objects, complete description of their properties is beyond the present day capabilities of nuclear theory, not only the number of nucleons in a nucleus is large but also because of our inadequate knowledge of the nuclear Hamiltonian itself.

Various tools could be utilized to investigate nuclear reactions. Particle irradiation, in addition to α, β and/or γ detection systems, is an example. The accumulated knowledge about nuclei, their behavior and structure forms what is denoted as *nuclear data*. Precise nuclear data is important and necessary from scientific and practical viewpoint. The most obvious application of nuclear data is the needed in the field of nuclear energy. In addition, the use of radioactive isotopes for medical diagnosis and treatment is a growing industry, where variety of isotopes spread over the periodic table are utilized.

While several isotopes are produced in nuclear reactors through neutron capture and fission, others are preferably produced with accelerated charged particle beams in the low and intermediate energy range. Novel techniques are also used, where an intense neutron source is created with a proton beam interacting with rich neutron target. Low energy nuclear reactions is the dominant reaction in universe, nearly all reaction inside stars occurs at energies below few MeV 's. Studying of low energy reaction is possible with high degree of accuracy.

Since the available experimental data is often inadequate in scope to enable direct generation of continuous evaluated quantities such as excitation functions, even through the application of statistical evaluation procedures, extensive use is made of nuclear models to generate the necessary information. Gaps in existing experimental data are supplemented by these calculations (interpolation) and the models are frequently used to provide numerical results in domains where no experimental data are available (extrapolation). Consequently, considerable responsibility is placed upon evaluators to employ models that are reliable for the intended purpose, and to utilize parameters for these models which have been demonstrated to give reasonable results, *i.e. model parameters validated by experimental data*. Compilations of recommended nuclear model parameters have been produced and made available for use in such calculations. However, libraries of suggested nuclear model param-

eters such as RIPL-2 tend to be global in nature, and their use often will lead to results which agree with experimental data only to a **qualitative** degree across a wide range of reaction types, energies, angles, etc. Better results can be obtained by re-adjusting these parameters to give good **quantitative** agreement in specific situations, usually for limited ranges of conditions. This provoked the research study performed in the present work.

In the present thesis, low energy nuclear reactions of different types were subjected to investigation. Namely, $^{114}\text{Cd}(p, n)^{114\text{m}}\text{In}$, $^{114}\text{Cd}(p, 2n)^{113\text{m}}\text{In}$ and $^{124}\text{Sn}(p, n)^{124}\text{Sn}$. Reaction with ^{124}Sn and ^{114}Cd represent reaction with closed shell double even nucleus, sub-shell double even nucleus, respectively. Two reactions of them are charge exchange reactions, and the third one is proton induced multi-neutron emission reaction. The residual nuclei itself are formed either in ground state or in isomeric state. Such variety of information represents a challenge to comprehend and an opportunity to research.

Model calculations were done in the framework of pre-equilibrium emission model. Pre-equilibrium models provide an adequate description of the high-energy tail that is observed in the outgoing energy spectra. In such reaction mechanism, the reaction process is described in terms of the number of excited particles and holes. At each stage of the reaction there is a non-zero probability that a particle be emitted. If this happens at an early stage, it become meaningful to consider pre-equilibrium emission.

Nuclear reaction and model calculations require complete knowledge of the nuclear level scheme in order to specify all possible outgoing reaction channels and to calculate partial (and isomeric) cross sections. Knowledge of discrete levels is also important for adjusting level densities, which replace unknown discrete level schemes at higher excitation energies. For this purpose completeness of the level scheme is of importance. The term "completeness" means that up to a certain excitation energy all discrete levels in a given nucleus are observed and are characterized by unique energy, spin and parity values. Knowledge of particle and γ -ray decay branches is also required, especially when the population of isomeric states is of interest.

All important theories and descriptions of both models and equipments that is used through out this work are presented. On the other hand, some important discussions such as basics of nuclear reaction theory were shortened as possible, as it easily found in textbooks.

In building up this thesis, logical flow of topics is taken into account. The logical sequence seems to be structure, basic reaction theory, reaction models, and level density. Literature survey about specific radioisotopes and reactions species is placed at the end of Chapter 1. In Chapter 2, detailed description of equipments and experimental procedures are elucidated. Results and discussions are presented in Chapter 3.

Summary

In the present work, some shortages in nuclear data were covered for production of ^{114m}In , ^{113m}In and ^{124}Sb from proton induced reactions on highly enriched ^{114}Cd , ^{124}Sn as well as natural cadmium and tin. Stacked-foil technique was used for measuring the excitation functions. Several facilities and techniques have been used in the measurements and calculations. HPGe γ -ray spectrometers and its supplementary accessories were used for activity measurements. Analysis of the γ -ray spectrum were done by GENIE-2000 v2.1 software. The targets were prepared using vacuum evaporation technique. Atomic Absorption Spectrometer (AAS) was used to evaluate the material quantity in each sample. Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) was employed for finding the value of enrichment of samples. Sample irradiation has been carried out using a low energy cyclotron and its supplementary accessories. Theoretical model code, EMPIRE-II, was utilized for excitation function predictions. Former data about excitation function under consideration has been supplied through experimental nuclear data library (EXFOR). Evaluated Nuclear Structure Data Files, ENSDF, and its leading softwares were employed for completing the level scheme of the nuclei under consideration, while Reference Input Parameter Library, RIPL-2, was utilized for supplying the model parameters for theoretical calculations.

The investigated targets were prepared by evaporating the enriched material on aluminum and copper backing foils, the material-containing faces of the foils were capsulated by aluminum foils to prevent scratching of the deposited thin film during handling. As well, natural cadmium and tin foils were also studied, they are capsulated by aluminum foils from both sides. The capsulated foils in addition to copper and titanium monitor foils were arranged successively in stacks. Three stacks were prepared, one of them contains two natural tin foils in addition to enriched ^{124}Sn isotope foils, this arrangement is denoted by SN1. Two stacks arrangements have natural cadmium and enriched ^{114}Cd . One of the cadmium arrangements contains enriched ^{114}Cd encapsulated foils in addition to copper monitoring foils, this arrangement is denoted by CD1. The other arrangement, denoted by CD2, have copper and titanium monitor foils and four natural cadmium foils in addition to enriched ^{114}Cd encapsulated foils.

The irradiations were carried out by MGC-20 low energy cyclotron, NRC, Inshas, Egypt. CD1 arrangement was irradiated by collimated protons beam of base energy 14.7 MeV with base current 100-200 nA, while CD2 and SN1 arrangements were irradiated by collimated

protons beam of base energy 18 MeV and base current 100-200 nA.

Activity measurements were carried out in Nuclear Reaction Division, using γ -ray spectrometry systems at time suitable for each nuclei for all samples as monitors. Efficiency of the detector was calibrated using standard radioactive point source and fitted by double logarithmic polynomials. Geometry correction factors were calculated from the angular response of the detector against non axial radiation. True values of the incident energy and flux for each arrangement were calculated using the monitor foils. A program was designed to calculate the energy degradation through the arrangements. After reasonable time (about 1.5 years) suitable to reduce activity to safe value, foils were dissolved in HCl and the amount of material was measured using AAS and ICP-MS. The enrichment and isotopic ratios of the samples were investigated by ICP-MS; it was found that enrichment of ^{114}Cd and ^{124}Sn as 98.5% and 86.9%, respectively. From the obtained information, namely flux, irradiation time, cooling time, measuring time, half life, efficiency, γ -line intensity per decay, peak area and material mass and enrichment, the cross section of the three reaction were calculated in each energy step.

Excitation function was measured for the first time for $^{124}\text{Sn}(p, n)^{124}\text{Sb}$ reaction to the high energy tail ($E_p = 16.2\text{MeV}$). The obtained results covered data shortage at energies higher than 10 MeV for $^{114}\text{Cd}(p, n)^{114m}\text{In}$ reaction, measures entirely new trend was found for $^{114}\text{Cd}(p, 2n)^{113m}\text{In}$ reaction.

The theoretical prediction was employed using Hybrid Monte Carlo Simulation HMS approach implanted in EMPIRE-II (v2.18 Mondovi) code, both Gilbert-Cameron (GC) and Hartree-Fock-BCS level densities are used. In the present work, an approach was suggested to calculate the isomeric cross sections by summing the partial contribution of all levels feeding the isomeric level. Matching is obvious for $^{124}\text{Sn}(p, n)^{124}\text{Sb}$ and $^{114}\text{Cd}(p, n)^{114m}\text{In}$ reactions between experiment and theory with both GC and HF-BCS level densities. Such matching resulted from the complete picture of the level scheme supplied to the code. In contrary, deviation is observed between theoretical and experimental data of $^{114}\text{Cd}(p, 2n)^{113m}\text{In}$ reaction which is resulted from deficient picture of the level scheme supplied to the code. The tightly bound levels, found in excitation energy between 1-4 MeV, cause increase in excitation function at the same excitation energy range above the threshold. In addition of its use in diagnostic and therapy of cancer tumors, application of ^{114m}In and ^{124}Sb radioisotopes in intravascular brachytherapy (IVBT) is proposed

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