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75 Years of Experimental Nuclear Reaction Data Compilations

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Abstract. The comprehensive experimental nuclear reaction data compilations were pioneered at the Metallurgical Laboratory, University of Chicago, and Los Alamos National Laboratory [1, 2] for the Manhattan Project needs. In 1947 many Manhattan Project alumni moved to a newly created Brookhaven National Laboratory (BNL) to work on nuclear physics research and data compilations [3–6] in support of nuclear science and reactor research activities. Since the beginning, the data project has relied heavily on computer technologies available at the time, and Brookhaven compilations have been stored in the Sigma Center Information Storage and Retrieval System (SCISRS) that predated the Exchange Format (EXFOR) database.
In the following years, the reaction compilations evolved and gained an international component. Currently, the compilation efforts are coordinated by the Nuclear Reaction Data Centers network (NRDC) worldwide, which was founded in 1979 and operates under the auspices of the International Atomic Energy Agency (IAEA). The data compilations in the USA are coordinated by the National Nuclear Data Center (NNDC), Brookhaven National Laboratory for the United States Nuclear Data Program (USNDP). The database compilations represent one of the oldest continuously-operated scientific collaborations that continue to archive and disseminate nuclear data for nuclear science and technology.

1 Introduction

Since the dawn of the nuclear age physicists produced many interesting results. These findings were usually archived and disseminated using scientific journals. By the 1930s, the sheer volume of archived records stipulated the development of the first dedicated nuclear data compilations [7, 8]. The official beginning of WW II provided additional catalysts for nuclear science worldwide that are summarized in the Einstein-Szilard letter [9]. In the following years, American, British, German, and Soviet governments initiated covert nuclear programs that required extensive collections of nuclear data sets [10].

The U.S. nuclear data activities at the Metallurgical and Los Alamos Laboratories [1, 2] were an integral part of the Manhattan Project and closed to the regular public. Similar efforts in Germany were described in open literature in 1942-1943 [11, 12]. It represents an interest to analyze the American and German data for carbon. In both cases, we find a good agreement for total cross sections. Further analysis of thermal absorption values 3×10^{-3} and $<6\times10^{-2}$ b [11, 12] shows agreement with the present-day figure of 0.00386127 b in the ENDF/B-VII.1 library [13]. The German data were interesting but limited by a choice of neutron target materials [14]. At the same time, the Manhattan Project data program was very extensive and led to the creation of a new field of nuclear science that is described in the next sections.

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2 Nuclear Data Compilations at Brookhaven and worldwide

After WW II, the Metallurgical Laboratory, University of Chicago compilations were declassified in June 1946 for publication in the Manhattan Project Technical Series [15]. The following year public release of the *Neutron Cross Sections of the Elements A Compilation* article in Reviews of Modern Physics was highly anticipated by nuclear physicists and engineers [1]: "**Informal circulation** *resulted in widespread demand for the publication of such a collection.*" These works created a foundation for the present-day nuclear data program since the Los Alamos Laboratory compilations were declassified and publicly released in 1958 and 1997, respectively; they are shown in Fig. 1. In the post-war years, many Manhattan Project alumni moved from the Metallurgical (Argonne) Laboratory to a newly created Brookhaven National Laboratory because of the changing research portfolio [5] there towards engineering projects [5]. The transition from Chicago to Brookhaven was pivotal for subsequent developments, and it is natural to assume 1947 as a public debut of nuclear reaction compilations worldwide.

Donald J. Hughes (1915-1960) with colleagues started the data compilation work at Brookhaven and published, shown in Fig. 2, BNL-170 report on neutron cross sections. In the 1950s, data compilations were well-organized at Brookhaven under the leadership of Hughes who became head of **an informal Brookhaven-based program christened the Sigma Center**, a part of the neutron physics group, which was committed to collecting and col-

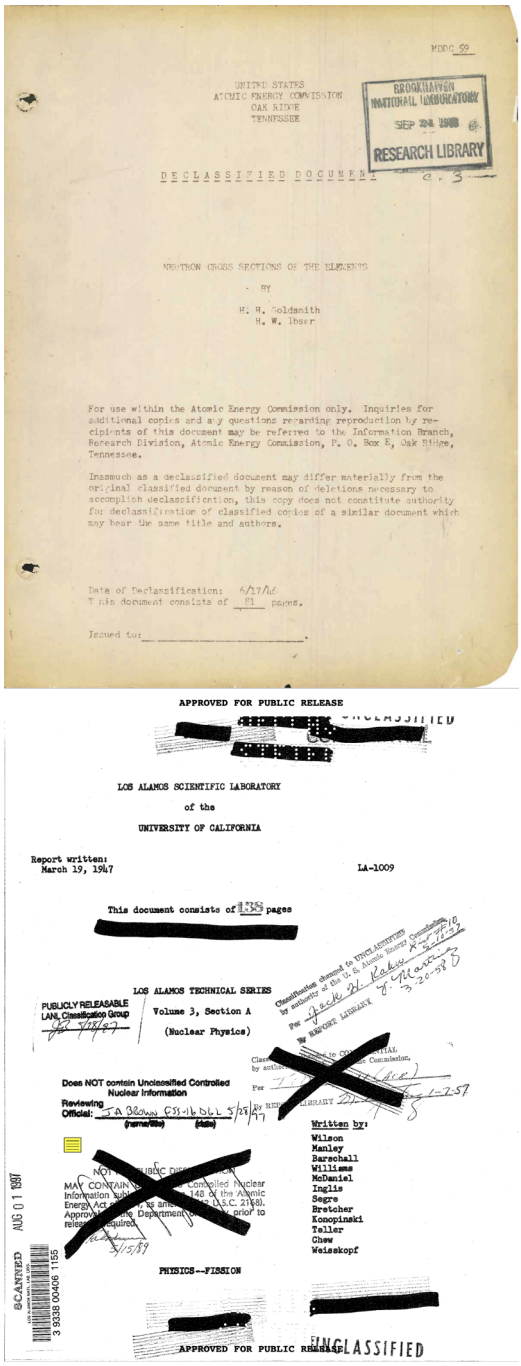

Figure 1. Manhattan Project data compilations: MMDC-59 [15] and LA-1009 [2] reports in the top and bottom panels, respectively.

lating cross-section data [5]. Hughes was an extraordinary scientist who was described by H. Palevsky as "*His casual manner was as far as could be from the truth. Hughes drove himself unmercifully... [O]ne of his greatest talents was picking the right problems to pursue... Hughes never hesitated to tackle any branch of physics if he felt some fundamental knowledge would result... He was very sure that his own research was among the most important in physics, and so he was primarily interested in his own problems.*" [16].

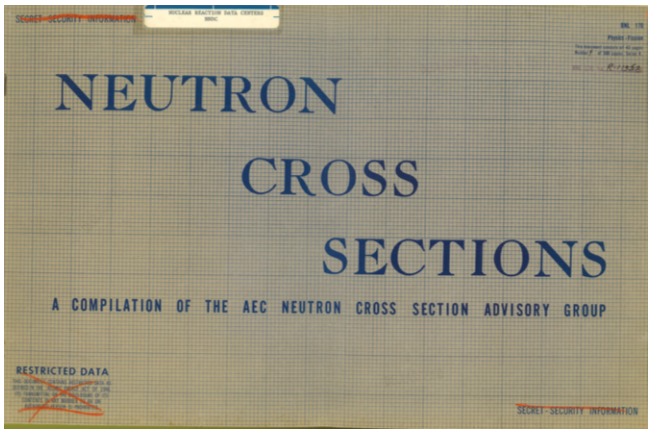

Figure 2. The Brookhaven report 170: Neutron cross sections; a compilation of the AEC Neutron Cross Section Advisory Group [3].

In addition to regular compilations [3], the BNL scientists have explored nuclear reaction data evaluations. They produced the famous BNL-325 report [4] that is presently known as *Atlas of Neutron Resonances* [17]. Finally, Hughes reported his work at the Second UN International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958 [18]. The second UN International Conference was crucial for nuclear data development and compilation efforts gained an important international component.

The International Atomic Energy Agency (IAEA), Nuclear Data Section (NDS) has been involved in this work since its creation in 1964. Other early contributors include the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency Data Bank (NEA DB), Paris, France, and the Institute of Physics and Power Engineering, Obninsk, USSR [19] which were founded in 1964 and 1963, respectively [20, 21]. In 1969 an agreement on an exchange format was reached between four centers, and July 1970 was chosen as the starting date for transmission of neutron compilations among the participating centers in the EXFOR data interchange format while centers could compile and store data in internal formats. Since 1964 Brookhaven compilations were stored in the Sigma Center Information Storage and Retrieval System (SCISRS) which predated the Exchange Format (EXFOR) or experimental nuclear reaction data library. In the 60s, the SCISRS contained more than one million data points and the system was expanding at the rate of 120,000 additional data points per year. To accommodate the system growth, incorporate the latest computer technologies, and make this system accessible for external users a new program was developed at Brookhaven that was called the Cross Section Information Storage and Retrieval System (CSISRS) [22].

The four neutron centers' compilation responsibilities were subdivided into four geographical areas. The areas #1 (the U.S. and Canada), #2 (Western Europe and Japan), #3 (Eastern Europe, Africa, Asia, Australia, Latin America, and Oceania), and #4 (Former USSR) were allocated to Brookhaven, Paris, Vienna, and Obninsk, respectively.

After the first ten years, two neutron compilation centers (IAEA and Obninsk) further subdivided areas #3 and #4 to provide space for the newly established data centers worldwide. As of 2014 the list of centers also included Nuclear Reaction Data Centre (JCPRG), Hokkaido University, Sapporo and Nuclear Data Center, Japan Atomic Energy Agency (JAEA), Tokai-mura, Japan, China Nuclear Data Centre (CNDC), China Institute of Atomic Energy, Beijing, China, Bhabha Atomic Research Centre, Mumbai and Department of Physics, Mizoram University, Aizawl, India, Korea Nuclear Data Center (KNDC), Korea Atomic Energy Research Institute, Daejeon, Republic of Korea, Ukrainian Nuclear Data Centre (UkrNDC), Institute for Nuclear Research, Kyiv, Ukraine, Cyclotron Application Department, Institute of Nuclear Research (ATOMKI), Debrecen, Hungary (Area #3), and Centre for Nuclear Structure and Reaction Data (CAJaD), Kurchatov Institute, Moscow, Centre of Nuclear Physics Data (CNPD), All-Russian Research Institute of Experimental Physics (VNIIEF), Sarov, Centre for Photonuclear Experiments Data (CDFE), Institute of Nuclear Physics, Moscow State University, Moscow, Russian Federation (Area #4). Since 2007 a large number of the Area #1 compilations are produced in the Department of Nuclear Physics, Institute of Physics, Slovak Academy of Science, Bratislava, Slovakia, and Central Asia results for Area #3 are compiled in the Institute of Nuclear Physics, Almaty, Kazakhstan. This led to the establishment of the worldwide Nuclear Reaction Data Centers (NRDC) network in 1979 [23, 24] under the auspices of the IAEA that currently manages the EXFOR library. The expansion of compilation centers was very beneficial for the project because it is easier for nuclear researchers to communicate and transfer their data to local centers.

The nuclear physics measurements and data compilations are expensive activities [25]. They were initially motivated by the needs of the Manhattan, European, and Soviet atomic projects, and later by nuclear energy and medicine developments worldwide. 50-80 years ago the majority of results were produced in North America, Western Europe, the Soviet Union, and Japan [26] and compiled by the local data centers. In the subsequent years, the world economies grew in many countries and very successful nuclear physics and engineering programs were established in China, India, Korea, Australia, Eastern Europe, Latin America, and South Africa. Experimental nuclear physics became a global science, and new data centers were needed to compile data around the world.

As of July 30, 2022, the EXFOR library compilations include 18,494,552 data points. The nuclear reaction publications are grouped into single EXFOR entries by distinct experiments. In addition to the reaction data, the EXFOR entries also contain extensive bibliography, methods, error analysis, and other technical information. Historically, nuclear reaction data compilations are produced in close cooperation with the authors. The Brookhaven group pioneered the EXFOR compilations and shared its expertise with other data centers that promptly started to contribute to a common effort. Due to historical and technological reasons, every second, third and sixth data point in the library was contributed by the NNDC, NEA-Databank, and the rest of the NRDC network, respectively. Figure 3 illustrates the international success of the EXFOR library and provides validation for the effective implementation of Mr. Dwight D. Eisenhower's atoms for peace proposal [27]. As of today, 13 data centers from 10 countries fruitfully cooperate on nuclear reaction compilations and share their knowledge and expertise with nuclear data users worldwide.

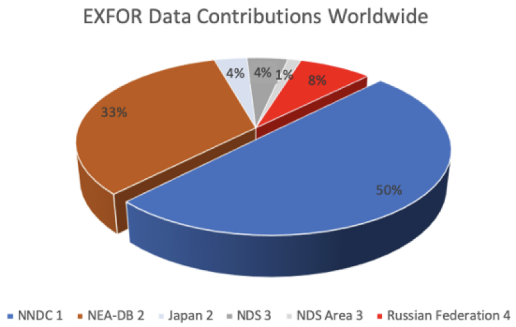

Figure 3. The geographical distribution of compiled data: Contributions of NNDC (Area#1), NEA-DB, Japan (Area#2), NDS and NDS Area#3 and Russian Federation (Area#4) centers.

3 Recent U.S. Nuclear Data Program Manhattan Project Updates

During the work on this project, a very large number of unclassified reports and journal articles were discovered. The Los Alamos Laboratory research library website: *https://www.lanl.gov/library/find/reports/index.php* provides direct access to many unclassified Los Alamos reports, while other lab reports can be found using the U.S. Department of Energy Office of Scientific and Technical Information (OSTI): *https://www.osti.gov/*. Over 500 Los Alamos reports (1943-1953), ~50 other lab reports, and a large number of journal publications were identified and added to the Nuclear Science References (NSR) database [28], recently. All new additions were checked against the EXFOR database, and 23 (neutron) + 4 (charged particles) + 1 (photonuclear) Los Alamos National Laboratory, 5 (neutron) + 1 (charged particles) + 1 (photonuclear) Metallurgical Laboratory reports, and 33 (neutron) + 1 (photonuclear) journal articles were compiled in to EXFOR. A quick NSR search for publications of Manhattan Project scientists Oppenheimer, Serber, and Bethe reveals 42, 14, and 114 works, respectively. The further analysis of these works shows a large volume of Los Alamos reports for R.Serber and H.A. Bethe, while R.J. Oppenheimer contributions show a dominance of fundamental science articles [29]. It is fair to deduce, that both NSR and EXFOR databases contain extensive collections of the Manhattan Project data.

4 Conclusions

Nuclear reaction data compilations play a crucial role in applied nuclear physics and create the foundation for nuclear data science and evaluated library developments. The data compilations were initiated during the Manhattan Project at the University of Chicago and Los Alamos and publicly launched at the Brookhaven National Laboratory 75 years ago as **an informal effort that was driven by basic science**. Over the years, compilations evolved into the present-day EXFOR library and expanded worldwide under the auspices of the NRDC, and IAEA. The international EXFOR library represents the best collection of experimental nuclear reaction data. It is essential for ENDF libraries [13], nuclear energy, and national security applications. The EXFOR collaboration is one of the oldest continuously-operating nuclear physics projects that cultivate nuclear data pursuits for further advancements in applied and fundamental sciences.

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