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SEARCHING FOR EXISTING NUCLEAR DATA

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As an example of finding existing data useful for high energy and heavy ion materials analysis the Nuclear Structure References of Brookhaven National Laboratory's National Nuclear Data Center was searched. The search was limited to incident ions of mass $\leq$ 7 amu (excluding alphas) with energies under 100 MeV, and the target nuclei were limited to mass $\leq$ 30 amu. Ease of use, time necessary for retrieval as well as pertinence was explored. Examples of applicable data found during the search are presented.

INTRODUCTION

In general, the nuclear data and reactions used in ion beam materials analysis has been limited. Low energy incident projectiles are normally chosen for analysis, first, because Rutherford backscattering analysis is simplified below the Coulomb barrier (known and calculable cross sections) and, secondly, because of the energies of the available electrostatic accelerators are generally low. Low energy nuclear reactions are also used. In this case resonances in the nuclear cross sections are used as probes, and the low energies are necessary to exclude interfering higher energy resonances. A compilation of nuclear reactions used for ion beam analysis can be found in the *Ion Beam Handbook for Materials Analysis*, Edited by Mayer and Rimini, Academic Press 1977. This handbook lists many of the reactions commonly used in ion beam analysis. The data presented in the book is mostly taken from pre-1970 publications and consists of light projectiles ($\leq$ 4 amu) and low energies ($\leq$ 3 MeV).

Because of the age of the nuclear data currently used, its availability limited to light incident ions and the recent availability of compact higher-energy accelerators, a search for higher energy and heavier ion data was made. The search was made utilizing the Nuclear Structure References Data Base (NSR) of the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory. Because of time constraints the search was limited to incident ions with $A \leq 7$ amu and target nuclei with $A \leq 30$ amu. The (α,α) reaction was purposely neglected because of the comprehensive survey made by Leavitt et al.[1]

NNDC - NSR

The NNDC has a number of nuclear data bases available. A detailed overview is given elsewhere in these proceedings.[2] The NSR data base was chosen because of its relative completeness. The disadvantage to the NSR is that it is an indexed bibliography and does not, in itself, contain data. Hence, you are burdened by looking up the reference at the nearest library. It does contain citations as early as 1910, but publications are only indexed since 1969. A description of using the NNDC can be obtained from C. L. Dunford et al.[3] Anybody considered to be a DOE contractor or university researcher may use this database free-of-charge. A modem and a computer terminal emulating a VT100 is all the hardware needed. The staff of the NNDC is also very helpful; they will patiently answer questions from even the most uninformed caller. The NSR data base is easy to use for extracting small amounts of data but is somewhat cumbersome and time consuming for extracting and retrieving large amounts of references as was done for this paper.

Other disadvantages of the NSR data base are that no key word search is available and the inability to save partially extracted data so that it can be used for further retrieval at some other time. The inability to save extracted data for later use is particularly time consuming, as can be seen by an example. To find references to the $^{12}C(p,p)^{12}C$ reaction: First, all references to the target, ^{12}C, must be extracted; then the references to the reaction (p,p). These two extracted lists are then combined to get the final reference list. The retrieved list contains the reference number, journal, authors, title, and key words. The time this takes depends on the number of entries in the lists. The combined list can be retrieved and saved to a file or the output sent directly to your terminal. However, if you sign off and come back at another time to, say, find the reaction $^{12}C(d,d)^{12}C$; it would be necessary to re-extract the ^{12}C list. This can be very time consuming if large searches are being made.

DATA

The references searched for and found is shown in Table 1. Except for (d,p), only reactions with the same incident and outgoing particle were chosen. This was done to save time by limiting the search to elastic channel reactions. However, these references also contain data for many other reaction products. The entry for each reaction on the table has three numbers. The first is the number of references found for that particular reaction. The second is the number of the references found that appeared in the journals:

Physical Review
Physical Review Letters
Nuclear Physics
Physics Letter

The third number is the number of papers which contained information of interest to ion beam analysis as defined by the following criteria:

Excitation functions
Resonances
Elastic differential scattering cross sections
Back-angle scattering
Incident energy $\leq$ 100 MeV
Data not in the Ion Beam Handbook for Materials Analysis

In general, 10 - 15% of the original number of references are in the last category; and, it is from these that any useful information for ion beam analysis must come.

Note that data for Li scattering is very sparse and additional research might be useful to ion beam analysis.

NEW DATA FOR ION BEAM ANALYSIS

The number of papers which were reviewed was large and many examples of useful reactions not listed in the *Ion Beam Handbook* were found. Work to further extract data is continuing. However, it has recently come to the attention of the authors the monumental work done by R. A. Jarjis[4] -- *Nuclear Cross Section Data for Surface Analysis*. This work is a compilation of cross-section data for targets up to ^{63}Cu and for a variety of light-ion reactions with incident energies up to several 10's of MeV. It is very unfortunate that only a limited number of copies of this three-volume compilation were distributed. However, it is an extremely useful compilation, and the authors strongly recommend it to anyone interested in a broad range of useful nuclear reactions for materials analysis. In fact, it contains most of the data found in the NSR search. The only data that would not be found in Jarjis would be data published since ≈1979 -- the latest data listed by Jarjis.

An example of pre-1979 data that could be useful in materials analysis is the $^{12}C(p,p)^{12}C$ reaction at ≈ 10.3 MeV and ≈ 160° scattering angle[5]. At these scattering parameters there is a flat-topped resonance ≈ 170x Coulomb which extends for ≈ .25 MeV. This could be very useful for profiling carbon.

There are several examples of post 1979 data as well. The resonance in the $^{9}Be(p,p)$ reaction at 2570 keV has been remeasured[6]. The method described does not require a thin target and could be easily applied to other targets. In other examples, resonances in the $^{23}Na(p,p)$ reaction with incident proton energies between 12.7 and 15.7 MeV have been reported[7] as well as resonances in the $^{26}Mg(p,p)$ reaction between 1.54 and 3.06 MeV[8]. The cross sections are far above Coulomb, and there are many sharp resonances at back angles.

DISCUSSION

The NSR of the Brookhaven National Nuclear Data Center is an easy and valuable way to search for data. If you have a copy of Jarjis' compilation, the use of the NNDC becomes even easier since you can limit your searches to the more recent publications.

Note that the references used for our examples of retrieved data were all proton scattering. This, unfortunately, is a reasonably accurate representation of what is available. Very little recent work is available for the reactions (d,d), (d,p) and (^{3}He,x). These are possible areas for more research. Incident ions heavier than alphas, while arguably useful for Rutherford backscattering, have almost no interesting associated nuclear reactions at practical energies.

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	p,p	d,p	d,d	^{3}He,^{3}He	^{6}Li,^{6}Li	^{7}Li,^{7}Li
^{9}Be	70/20/13	52/23/6	16/4/5	19/11/6	no	no
^{10}B	14/5/3	20/9/7	11/3/2	9/4/6	no	no
^{11}B	30/5/4	33/12/3	6/1/2	11/6/6	no	no
^{12}C	295/105/37	132/50/23	90/34/17	58/24/16	81/30/15	30/16/12
^{13}C	37/15/5	25/10/4	11/5/3	22/5/6	11/6/6	8/6/6
^{14}N	38/17/11	33/14/10	18/9/7	5/2/2	1/0/0	1/1/1
^{16}O	204/83/32	90/42/16	64/26/14	38/19/18	35/15/12	11/6/7
^{17}O	23/12/10	11/4/2	2/1/1	6/4/3	0	0
^{18}O	36/12/6	26/12/6	3/2/2	12/6/5	0	0
^{19}F	9/2/6	33/16/7	14/2/4	8/3/4	3/3/3	2/2/2
^{20}Ne	28/9/5	21/9/6	6/5/0	6/3/3	0	2/2/2
^{21}Ne	5/3/3	12/6/5	1/0/0	0	0	0
^{22}Ne	9/6/5	6/3/3	3/3/1	3/2/2	0	0
^{23}Na	22/7/9	25/7/5	4/0/0	8/4/5	0	0
^{24}Mg	88/22/23	69/27/13	20/8/5	29/13/7	6/4/3	8/5/5
^{25}Mg	18/3/7	20/11/11	4/0/0	8/5/6	4/1/1	2/1/2
^{26}Mg	44/9/10	28/11/7	6/3/0	18/10/8	9/4/3	8/6/5
^{27}Al	75/28/15	85/37/26	33/8/11	37/15/14	5/4/1	2/1/2
^{28}Si	109/33/16	31/11/6	43/14/7	32/14/11	53/15/8	4/3/3
^{29}Si	17/5/8	58/19/11	2/2/2	9/5/6	0	0
^{30}Si	18/3/3	10/5/1	8/5/4	15/9/5	0	0
^{31}P	17/3/4	24/10/7	8/5/4	11/5/5	0	0
^{32}S	55/13/11	16/7/5	18/8/4	8/6/3	0	0

Table I: A/B/C -- References in database/Basic references/Papers of interest -- see text for details