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CROSS-SECTION INFORMATION REQUIRED FOR THE CALCULATION OF THE PROPAGATION OF COSMIC RADIATION THROUGH INTERSTELLAR SPACE

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INTRODUCTION

The cosmic radiation of galactic origin has been found to consist of measurable fluxes of most of the elements from hydrogen to iron, and reliable composition measurements now exist for energies from about 20 MEV/nucleon to above 10 Bev/nucleon. Within the next few years experiments in preparation can be expected to extend this energy region down to 10 MEV/nucleon and up to $\sim 10^{14}$ eV/nucleon. Presently individual charges are clearly resolved up to about $Z = 14$ though isotope separation has not yet been achieved for $Z \geq 3$.

During it's lifetime in interstellar space ($\sim 10^8$ years) the cosmic radiation travels through about 3 gm/cm^2 of interstellar material (mostly H) and it's composition is altered by fragmentation. In comparing the cosmic-ray abundances with the "universal" abundances one finds for example, that the ratio of Light nuclei ($3 \leq Z \leq 5$) to Medium nuclei ($6 \leq Z \leq 9$) is five orders of magnitude greater in the former case. This striking difference is attributed to the fragmentation of $Z \geq 6$ nuclei in traversing interstellar material.

In order to make quantitative studies of interstellar propagation, complete information of the dominant fragmentation cross-sections must be available. The cross section for breakup of a cosmic-ray nucleus P of energy/nucleon E into a secondary nucleus S in interstellar hydrogen is of course, identical to that for the production of a nucleus S in the bombardment of a target P with a proton of kinetic energy E. If such cross sections can be measured in the laboratory or calculated with sufficient reliability, it may be possible to greatly increase our understanding of interstellar space, of the nature of the cosmic-ray source and of the mechanism by which the particles are accelerated. In many cases the interpretation of existing cosmic-ray composition data awaits this cross-section information.

The purpose of this report is to acquaint any interested persons with the cosmic-ray physicist's need for cross-section data in the hope of enlisting all possible aid to obtain it.

GENERAL REQUIREMENTS AND ACCURACY

The reactions of interest always involve protons of energy ≥ 10 MEV incident on target nuclei which are the most abundant constituents of the cosmic-ray flux. In general cross-sections below a few millibarns can be considered negligible and errors of a few millibarns or 10% (whichever is greater) are acceptable.

As will be discussed in subsequent sections target nuclei for which detailed energy-dependent fragmentation information is required include the stable isotopes of He, B, C, N, O, Ne, Mg, Si, Ca and Fe. Accurate (10%) energy-dependent total reaction cross-sections are also required for all stable nuclides with $2 \leq Z \leq 14$ and for representative nuclides for $15 \leq Z \leq 26$.

At high energies the angular and energy distribution of the secondary (residual) nuclei is not required; at low energies however such information may become important. The criterion for the necessity of this information is that, when viewed in the rest frame of the proton, the mean energy/nucleon of the residual nucleus differs by more than 10% from that of the incident nucleus. In this case it is necessary to know the mean energy/nucleon of the residual nucleus (in the proton rest frame) and the spread or distribution of this quantity if greater than 10%. Owing to the angular isotropy of the cosmic-ray flux, angular distributions are not required in the rest frame of the proton though, of course, they would be necessary in other coordinate systems in order to extract the energy distribution of interest.

The reactions of greatest interest for cosmic-ray calculations are usually those that have the largest cross-sections. Many of these involve the production of stable nuclides which are very difficult, if not impossible to detect experimentally. In some cases such as O^{16} (p, X) Li^{6} mass-spectrometry techniques have been successfully used[1] and it is hoped that such measurements could be extended to the detection of all stable isotopes of Li, Be and B for the range of targets and energies described.

The most critical lack of information and perhaps the most difficult cross-sections to measure involve the production of stable nuclides of high natural abundance eg, O^{16} (p, X) N^{14}. At energies which are sufficiently high that the secondaries are projected out of the target, it should be possible to make good measurements on such products using detection equipment such as that used by Poskanzer et, al[2], for example.

Much of the existing data on the production of radioactive nuclides (below 425 MeV) have been summarized by Bertini et al.[3]; other data have been summarized by Badhwar and Daniel[4]. Additional measurements of considerable interest have been made by Albouy et al.[5] and by Bernas et al.[1] Work which has not been summarized in the survey papers (mostly on p + He^4) can be found in References 6 through 17.

Though measurement errors of 10% or a few millibarns have been stated as desirable above, it is of course, true that any cross-section information is of value in cases where desired accuracy cannot be obtained. Thus less accurate measurements, estimates and upper or lower limits are also useful in cases where no better data exist.

SPECIFIC REACTIONS OF INTEREST

The p + He^4 Reaction

The ability of modern detectors to resolve isotopes of H and He and the high abundance of He^4 in cosmic radiation makes the production of d, t and He^3 extremely interesting. It would be highly desirable to know the energy dependence of the cross-sections for the different reactions leading to H^2, H^3, He^3, especially between their threshold (about 25 MeV) and 100 MeV and between 300 and 600 MeV (buildup of the pion production) where the data are extremely scanty. The energy distribution of the secondaries is needed in the lower energy region.

Light Nucleus Production and Loss

As mentioned previously the Light nuclei are the primary indicators of interstellar propagation. Most of these nuclei arise from the fragmentation of C, N and O since the latter have the highest abundance in the $Z \geq 3$ radiation. The products for which cross-section data are required are $Li^{6,7}$, $Be^{7,9,10,11}$, $B^{10,11}$ and $C^{10,11}$. Data on the production of Be^9, Be^{10}, B^{10} and B^{11} are almost non-existent.

Targets which have been most investigated for the production of L-nuclei are C^{12}, N^{14} and O^{16}. It is important not only to obtain more complete data using these targets but also to obtain data on L-nucleus production for protons on C^{13}, N^{15} and O^{18}. This knowledge might allow inference of the isotope structure of the cosmic-ray source and is important in any event since the heavier isotopes (especially N^{15}) are evidently produced copiously in $p + O^{16}$ reactions.

The accumulation of boron as the cosmic-radiation traverses interstellar space is sufficiently great that it's fragmentation may contribute significantly to the Li and especially the Be abundances. The energy dependent cross-section for $p + B^{11}$ yielding Li^6, Li^7, Be^7, Be^9, Be^{10} and B^{10}, and for $p + B^{10}$ giving Li^6, Li^7, Be^7 and Be^9 are therefore required. Only total reaction cross-sections are needed for protons on Li^6, Li^7 and Be^9.

The total flux of all nuclei with $Z \geq 9$ is comparable with the flux of carbon or oxygen nuclei. For L-nucleus production from protons on nuclei with $Z \geq 9$ it is adequate to know the cross-section for representative targets only. The energy-dependent cross-sections for production of L-nuclei (all species listed above) are therefore required for protons on Mg^{24} (and/or Si^{28}), Ca^{40} and Fe^{56}. (Nuclei with $Z = 10, 12, 14$ and $Z \simeq 26$ have approximately equal shares of the $Z \geq 9$ flux; the other elements contribute only a small fraction.)

Table I summarizes the energy regions (in MeV) where additional information is required for specific reactions leading to Light nuclei. Reactions of particular interest are underlined. Parentheses enclose regions where either 1) data exist but are incomplete or ambiguous or 2) cross-sections are low and the reactions are probably of secondary importance.

Fragmentation of Medium Nuclei

In addition to the production of light nuclei by the proton-induced fragmentation of C, N and O and the need to follow the complete course of the fragmentation process, features of the C, N, O system are also of great intrinsic interest. In particular the nitrogen abundance and the C and N isotopic composition may be greatly altered by the process.

In the case of $p + O^{16}$ the production of O^{15} and N^{13} is fairly well known in the region below 150 MeV, but little or no experimental information is available on the production of C^{12}, C^{13}, C^{14}, N^{14} and N^{15}. As stated previously such information might be obtained at moderate and high energies by a dE/dx vs. E analysis of these isotopes which are projected out of the target. It would also be of value to examine the same products (and N^{16}, N^{17}, O^{16} and O^{17}) from p + O^{18} so that an investigation of the isotopic composition of the cosmic-ray beam at it's source might be made.

Similarly, one would like data on C^{12}, C^{13} and N^{13} production from p + N^{14}, on C^{12}, C^{13}, C^{14}, N^{13}, N^{14} production from p + N^{15}, and on C^{12} and B^{12} production from C^{13}. The heavier isotopes of C and N are most certainly present in the cosmic-ray flux after O^{16} breakup occurs if not initially.

The energy regions where additional information is required for specific reactions leading to medium nuclei are summarized in Table II. Notation is similar to that of Table I described previously.

F, Na and Al and the Fragmentation of Nuclei with $9 \leq Z \leq 14$

The low observed abundance of the nuclei with Z = 9, 11 and 13 relative to their neighbors is an extremely interesting feature of the low energy (~100 MeV/nucleon) cosmic radiation. Unless the (presently unknown) cross-sections for the production of these nuclei, especially F^{19}, are extremely low, present theories of interstellar propagation might have to be modified considerably to fit the observations. It is therefore quite important to know the energy dependent cross-section for the production of O^{19}, F^{19} and Ne^{19} for protons on Ne^{20}, Ne^{22}, Mg^{24}, Mg^{26}, Si^{28} and Si^{30} and also for the production of Na^{23} and Mg^{23} in p + Mg and P + Si reaction and for production of Al^{27} and Si^{27} in p + Si reaction. Knowledge of the production of odd-Z nuclei in the spallation of Fe is also important. The production of the A = 19 isobars especially should be observed with the highest possible sensitivity. To correctly follow the fragmentation cascade the production of lighter even-Z nuclei from p + Ne, Mg and Si must also be known.

Fragmentation of the Iron-Group Nuclei

Attempts have been made to study the composition in the vicinity of Z = 26 as an independent indicator of interstellar travel. Here cascade-evaporation calculations have been used to determine the required cross-sections and it would be advisable to check the validity and especially the energy dependence of these results. For p + Fe^{56} one would like to know the cross-sections for production of $Fe^{54,55}$, $Mn^{54,55}$ Cr^{52-54}, $V^{50,51}$, Ti^{46-50}, Si^{45} and Ca^{40-46}. For p + Fe^{56} and for p + Ca^{40} it is important to know the total production of nuclides in the regions $15 \leq Z \leq 19$, $10 \leq Z \leq 14$ and $6 \leq Z \leq 9$ in addition to the production of light nuclei described previously.

TOTAL REACTION CROSS-SECTION

Though somewhat easier to estimate from existing data, total reaction cross-sections are equally important as those for specific reasons. The former are required for all stable isotopes up through F^{19} to an accuracy of 10% better at all energies. Above Z = 9 only representative nuclides need be considered, eg. Ne^{20}, Na^{23}, Mg^{24}, Al^{27}, Si^{28}, Cl, Ca and Fe^{56}.

He^4 INDUCED REACTIONS

Interstellar space is estimated to contain about 10% He. Cases where large differences in product cross-section between p- and α-induced reactions may be expected, could be extremely important. Especially interesting are the production of d, t and He^3 in $He^4 + He^4$ reactions, the production of Light and Medium nuclei in $He^4 + C^{12}$ and $He^4 + O^{16}$ reactions, and particularly reactions such as O^{16} (α, p) F^{19} which could lead to products which are otherwise rare.

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Table I

Light Element Production; Energy Regions Requiring Improved Measurement

Target \ Product	Li^6	Li^7	Be^7	Be^9	Be^{10}	Be^{11}	B^{10}	B^{11}	C^{10}	C^{11}
C^{12}	≤ 40 >600 (all)	≤ 40 >600 (all)	<70 >600	all	≤ 100 all	all	all	all	(all)	(<30) (>100)
C^{13}	all	all	all	all	all	all	all	all	(all)	all
N^{14}	≤ 100 (all)	all	≤ 100 (all)	all	all	all	all	all	(all)	<25 (all)
N^{15}	all	all	all	all	all	all	all	all	(all)	all
O^{16}	<150 (all)	all	(≥ 200)	all	all	all	all	all	(all)	(≥ 200)
O^{18}	all	all	all	all	all	all	all	all	(all)	all
Mg^{24}	all	all	(all)	all	all	all	all	all	(all)	all
Ca^{40}	all	all	all	all	all	all	all	all	(all)	all
Fe^{56}	all	all	all	all	all	all	all	all	(all)	all
Li^7	all		(all)							
Be^7	estimate									
B^{10}	all	all	(all)	all						
B^{11}	all	all	<50 (all)	all	all		all			<40 >200

Table II

C, N, O Nuclei; Energy Regions Requiring Improved Measurement

Target \ Product	B^{12}	C^{12}	C^{13}	C^{14}	N^{13}	N^{14}	N^{15}	N^{16}	O^{15}	O^{16}	O^{17}
C^{13}	all	all									
N^{14}	(all)	all	all		< 25 (all)						
N^{15}	(all)	all	all	all	all	all					
O^{16}		all	all	all	> 150	all	all		>150		
O^{18}		all	all	all	all	all	all	all		all	all
Mg^{24}		all	all		all	all	all		all	all	
Fe^{56}		(all)	(all)		(all)	(all)	(all)		(all)	(all)	