NEUTRONS PRODUCED BY KNOWN ENERGIES OF IONS ABUNDANT IN SPACE

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ABSTRACT

Particle accelerator radiation measurements can be applied to the present problem of calculating biological dose from radiation produced in the walls of a spacecraft by various ions in space. Neutrons, one of the products of the interactions of energetic ions with matter, are usually quite penetrating and have large values of Q.F. or R.B.E.

Ions of Helium, Boron, Carbon, Nitrogen, and Oxygen were accelerated to 10.4 MeV/nucleon and directed onto target materials of copper or Tantalum. The secondary neutron production was determined. Studies were made of the angular distribution and an inferred neutron spectrum was calculated from activities of threshold reaction detectors, although not in all cases.

The energy per nucleon of the experimental data is considerably lower than the average ion energies in space. From the literature, neutron production data for protons (hydrogen ion), deuterons (heavy hydrogen) and alpha (Helium ion) of various energies on various target materials was gathered. The first obvious fact that emerges is that neutron yield is a square function of the energy of the projectile ion.

It seems to be reasonable to assume that as the very light ion data describes various neutron yield increases with energy and increasing Z of the target, so one might expect for the light ion group. From the experimental data, neutron yields were extrapolated into the energy peak region of 300 MeV per nucleon for light ions in space. Beyond that energy, the ion energy spectrum falls off as $\sim E^{-2}$, producing a constancy in the neutron dose per ion beyond 300 MeV/nucleon. Such an extrapolation has not accounted for changes in the neutron spectra, modifications in the angular distribution in the higher energy model, or strange effects unique to very high energies per nucleon that are not now understood. It is felt that such considerations must be incorporated into a study of greater sophistication than this paper pretends.

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I. Introduction

Ion beams with particles heavier than 4 a.m.u. and more energetic than 0.1 MeV/nucleon are found at only a few particle - accelerator laboratories in the world. The priority of such beam use therefore is understandably set up for primary research. Owing to a very competent crew, the UCLRL Berkeley, Heavy Ion Linear Accelerator (HILAC) was continuously improved until its original radiation shielding was no longer adequate. The Health Physics Department was assigned primary beam time to research the shielding problem. This opportunity was seized upon to simultaneously gain characteristic information of the secondary neutron radiation beyond shielding problems. Ion beams of He^4, B^{10}, B^{11}, C^{12}, N^{14}, and O^{16} were used to bombard targets of elemental Tantalum and Copper. The secondary neutron radiation was studied to determine neutron production, angular distribution from the target, and where possible, the neutron energy spectrum.

The resultant data were reduced to determine neutron production per incident 10.4 MeV/nucleon ion. At this point we were able to make a comparison to two other references using heavy ion beams. A literature search of neutron production revealed considerable data about the yields from proton and deuteron beams. A sparse amount was given about accelerated alpha (He^4) beams. That data was subsequently used as a basis for performing an extrapolation into the 300 MeV/nucleon region for heavy ions. From those results the neutron production of the various prominent free space ions was estimated and the neutron dose for the resultant flux was calculated.

II. The Experiment

The experiment incorporated a linear accelerator, a target of selected materials, beam current measuring apparatus, selected threshold detectors, detector mounting device for placing detectors at precise, predetermined positions and a power supply for secondary emission electron escape suppression.

During tune-up of the accelerator, a phosphor screen and remote controlled, local television set up were used to produce a visual picture of the beam shape and centering before running each experiment. After centering and shaping, the phosphor was removed and the beam was directed onto the target, maximized for optimum current and interrupted with an upstream Faraday cup while the detectors, mounted on the mounting ring or "Halo" as we named it, were secured in place.

A. Threshold Reaction Detectors

Materials for the threshold reaction detectors were selected on the basis of the reaction threshold, reaction cross-section and suitable half-life. These are but a part of a set of criteria set by Ringle(1) for fast neutron spectroscopy at UCLRL. Table I summarizes the properties of the threshold detectors as used in this work. For various technical reasons not all detectors were used for every experimental run.

Table 1. Threshold Detector Properties

Reaction	Calculated threshold (MeV)	Peak cross section (barns)	Product half-life	Isotope (%)	Energy of γ-ray of reactant used for data (MeV)
$^{58}Ni(n,p)^{58}Co$	1.1	0.556	71 days	67.8	0.81
$^{59}Co(n,c)^{56}Mn$	5.4	0.112	2.6 hrs.	100	0.845
$^{65}Cu(n,p)^{65}Ni$	4.1	0.035	2.6 hrs.	30.9	1.5
$^{27}Al(n,a)^{24}Na$	6.7	0.243	15 hrs.	100	1.37
$^{203}Tl(n,2n)^{202}Tl$	8.5	2.78	12 days	29.5	0.44

Table 1. Threshold Detector Properties (Continued)

$^{127}I(n,2n)^{126}I$	9.5	2.02	13 days	100	0.65
$^{58}Ni(n,2n)^{57}Ni$	12.4	0.25	37 hrs.	67.8	1.36

B. The Faraday Cup-Target

The target material was mounted at the back of the Faraday Cup. A ring was mounted on insulators ahead of the cup and connected via a feed-through to a high voltage connector. In this way we were able to apply a high negative potential to suppress secondary emission electrons from escaping and giving an erroneously high beam current reading. The beam current was integrated with an LRL designed beam current integrator. The charge state of the accelerated ions had to be considered to accurately state the number of beam particles stopped in the target. The Target materials were selected for their wide spread use at the accelerator and the primary reason for our studies. Elemental tantalum and oxygen-free, high conductivity copper were the two materials used as targets.

III. Data Reduction

The Threshold detectors were removed after sufficient integrated beam current was achieved, and counted in a low background counting facility. The gamma-ray spectrum of each detector was measured with a Sodium Iodide (NaI) crystal and a multichannel analyzer. That information was transferred to punched cards for computor compatible form input. The gamma-ray peaks of each of the reaction product were then stripped and reduced to an absolute disintegration rate by accounting for detector efficiency, counting geometry and peak to total ratios and abundance of the target isotope and branching ratio of the gamma-ray. The resultant disintegration rate was used along with the calculated activities of other reactions in the same position of the same run and each was corrected in terms of the saturation activity, decay, counting times for input into a program to calculate neutron spectra.

For our purposes here, the neutron spectra for these energies per nucleon, represent typical evaporation neutron spectra, and show only a moderate flux increase in the forward direction.

In later considerations, at the 300 MeV per nucleon region, one would logically expect a pronounced forward flux owing to cascade effects. In the extrapolation to 300 MeV per nucleon, the increased neutron production is recognized, the forward peaking is believed to cancel out when the isotropic nature of the incident ions is considered.

IV. Results

A. Neutron Yields

The following results were obtained and are summarized in Table II.

Table II. Neutron Yield Per Incident Particle

Beam Ion 10.4 MeV/nuc.	Target Material Cu	Ta
He^4	3.99×10^{-3}	2.16×10^{-3}
B^{10}	3.22×10^{-3}	3.89×10^{-3}
B^{11}	3.74×10^{-3}	---------
C^{12}	2.96×10^{-3}	3.84×10^{-3}
N^{14}	2.59×10^{-3}	---------
O^{16}	1.70×10^{-3}	2.52×10^{-3}

The values of neutrons per bombarding particle are integrated from data taken from the numerous angles utilized on the Halo.

The threshold detectors data were supplemented with moderated indium foils, which were quite helpful in establishing the true yield. The $Ni^{58}(n,p)$ Co^{58} reaction threshold of 1.2 MeV is only 2% of the peak cross section. With the neutron spectrum being comprised mostly of evaporation neutrons, it was felt that too much uncertainty could arise if we relied solely on the threshold detectors.

B. Anisotropy

The ion population of free space has a random direction. One would therefore assume that any high-energy or forward peaking of secondary neutrons would also be subject to such randomness. At the very low energies as achieved in this work, forward peaking is apparent in the total flux. As one observes the activities of successively higher energy threshold detectors, the forward prominence is increasingly pronounced. The prominence is greater with lighter bombarding ions and also lighter target elements.

V. Extrapolation of the Data to Space Ion Energies

A. Production Curve Models

To apply this data to the same ion types in space and to do so in a way which is both logical and realistic, we felt we should look at other experimental data on production of neutrons.

On heavy-ions, (B,C,N,O) only one report dealt with production, and one with angular spectra which could be integrated.

All other references were for He^4, $_1H^2$, and $_1H^1$. From all the references we compiled the production data according to particle type, target material and particle energy.

All data was put in terms of neutrons per bombarding particle as a function of the Energy per Nucleon of the bombarding particle. Smooth curves were drawn between the points involving the same ion and target type.

What we found was much of what we expected. Most of the curves tended to exhibit the same shape although shifted somewhat according to ion type and target type.

B. Heavy Ion Production Curve Fitting

Using the other charge particle production data, and four points of different energy C^{12} on Ta data by Hubbard Pyle and Main(2), as models, (and some courage and lots of daring) we fit our data into the picture. By merely extrapolating out to 300 MeV per nucleon along a shape of the Copper or Tantalum curves, one arrives at values which, based on all of parameters that entered into the basic data, should be fairly realistic neutron yields.

At 300 MeV/nucleon then, one would expect the following values.

Table III. Neutron Yield Per Incident Particle

300 MeV/nuc.	Cu	Ta
He^4	7.5	4.1
B^{10}	6.1	7.4
B^{11}	7.1	- -
C^{12}	5.6	7.3
N^{14}	4.9	- -
O^{16}	3.2	4.8

It should be noted that the He^4 data might be on the low side by a factor of 2-3. Proton productions are typically an order of magnitude lower.

VI. Summary

Ions of Boron, Carbon, Nitrogen, and Oxygen which typically make up only $\sim$0.5% of the free space ion population combined, exhibit neutron yields such that they are estimated to produce nearly 5% of the total first collision dose.

As the importance of reducing the neutron fluence within the confines of space vehicles becomes increasingly important, from either personnel radiation exposure, or radiation damage to electronics components, then the data herein presented must be greatly refined. New research is required as higher ion energies become available, and spectroscopy techniques are improved, as well as when more accurate determinations of the free space ion populations are made.

Until then, calculations seem to present a most reasonable approach to estimating the radiation dose rate wothout relying upon extrapolations which extend over 1.3 orders of magnitude for answers.

VII. Acknowledgements

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VIII. References

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