Cross sections of neon isotopes induced by 5, 7, 16, and 19 MeV neutrons

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Neutron-irradiated targets of natural magnesium have been analyzed by mass spectrometry in order to determine the excitation functions of neon from the energy threshold up to 20 MeV. Production cross sections of ^{20,21,22}Ne isotopes were measured at 5.20, 7.00, 16.20, and 19.05 MeV.

I. INTRODUCTION

The high-energy particles of cosmic rays produce, by nuclear reactions, numerous stable or radioactive isotopes near the surface of atmosphere-free planetary objects. Like other noble gases, neon has been largely outgassed from most solar system materials through several heating processes. Consequently, the cosmic-ray-induced neon concentration is detectable and provides an interesting sensor of the exposure histories of meteorites and lunar samples.

For several years, the secondary particles, and especially neutrons in the energy range 0–100 MeV, have been expected to play a crucial role in the isotope production yield, particularly when relevant nuclear reactions have a low-energy threshold. However, much more than for the incident proton, neutron-induced nuclear reactions suffer a notable lack of cross-section data. So, a precise determination of some excitation functions induced by neutrons could provide a better interpretation of measurements in extraterrestrial samples.

Previous studies[1–3] pointed out Mg as the most important target element for neon production in meteorites. With neutron-induced neon production cross sections in Mg known between 14 and 15 MeV (Refs. 3–5), the purpose of this work is to measure additional cross sections in order to allow a precise determination of the excitation function from the energy threshold up to 20 MeV.

II. EXPERIMENT

A. Irradiations

The magnesium targets were prepared by sawing a 16.5 mm diam rod of 99.99% purity into 2 mm thick disks. The irradiations were carried out in the Centre d'Etudes Nucléaires Laboratory at Bruyères-Le-Châtel using the 4 MV Van de Graaff accelerator. Nuclear reactions of deuterons with gaseous ^{2}H and ^{3}H targets produced 5–7 MeV and 16–19 MeV neutrons via the ^{2}H$(d,n)^3$He and ^{3}H$(d,n)^4$He reactions, respectively.

The deuteron beam, delivered by the 4 MV accelerator, entered a 100 mm long$\times$15 mm diam cylindrical target filled with 1.5 bars gaseous deuterium or tritium. This neutron producing target was isolated from the evacuated extension by two 2.4 μm thick Havar foils placed 5 mm one from the other. Between the foils, refrigerated gaseous helium, at a pressure of 0.5 bar, was circulated so as to remove the heat deposited on these windows by the beam, of 15 up to 25 μA intensity. This had the advantage of improving the lifetime of the foils and the safety of the device, especially for the use of tritium. Moreover, in order to avoid an excessive rise in temperature of the gas target, the beam stop was strongly cooled by a compressed air jet.

In order to get a good compromise between a high flux and a low-energy dispersion for the neutron beam, the magnesium samples were located at 0° with respect to the incident deuteron beam axis (with their axis along the beam axis). They were placed at 50 mm from the end of the gas target cylinder.

With this experimental arrangement the irradiation parameters are those given in Table I. E_d refers to the incident deuteron energy before entering the neutron producing target device. E_n is the mean neutron energy and $2\times DE_n$ is the neutron energy dispersion, corresponding to FWHM. E_n and DE_n have been deduced from calculations which take into account deuteron energy loss and energy straggling in the window foils, energy loss in the deuterium (or tritium) gas along the target cylinder, kinematics of the neutron producing reaction, and energy spread of the neutron beam at the sample location due to angular opening.

During the irradiations, the neutron beam was monitored using an E-ΔE proton recoil telescope placed at a distance of 100 cm from the center of the gas target and at an angle of 20° with respect to the beam axis. The absolute calibration of this detector, at each incident neutron energy, was obtained by using a second similar telescope counter. The absolute efficiency of this counter was calculated by means of a precise simulation code.

The data were obtained by taking long irradiation runs, typically 250–350 hours with beam currents of 15–25 μA. The neutron fluence at the sample and its associated

TABLE I. Irradiation parameters.

Gaseous target	E_d (MeV)	$E_n \pm DE_n$ (MeV)	Fluence ± uncertainty (10^{12} neutrons) (%)
^{2}H	2.40	5.20±0.45	8.4±5 %
^{2}H	4.00	7.00±0.30	7.6±5 %
^{3}H	1.80	16.20±0.70	5.9±4 %
^{3}H	3.20	19.05±0.35	5.1±4 %

uncertainty are given in Table I for the four measurement energies. The fluence is not corrected for attenuation and multiple scattering of neutrons in magnesium, since these effects are negligible in a 2 mm thick sample. The fluence uncertainty takes into account errors in the efficiency calculation of the 0° telescope counter, in the determination of the distances from the gas target center, respectively to the samples, to the 0° calibration telescope and to the 20° monitor telescope, and finally in the counting statistics of the calibration and irradiation measurements.

The temperature of the Mg samples was not measured during the irradiation. Nevertheless, it was checked that they were always at room temperature, between 18 °C and 21 °C (the neutron flux being much too low to induce any temperature rise in the samples). In these conditions there was no danger of any neon loss.

B. Mass spectrometer

The neon concentrations in the Mg targets were measured at Centre d'Etudes Nucléaires de Bordeaux-Gradignan (CENBG) using a 60° and 12 cm radius mass spectrometer from VG micromass equipped with an electron multiplier and a microcomputer-assisted peak switching and data storage unit.

The samples were outgassed at 85 °C under vacuum for several days. Hot system blanks were frequently measured leading to an average value of (0.45±0.03) 10^{-10} cm^3 STP for neon with air composition. A heating of the sample at 200 °C gave a signal indistinguishable from the system blank level. The crucible containing the targets were heated at 900 °C for 40 min and cooled down to 100 °C within 20 min. The released neon was cleaned in two steps using first a Ti sponge during the melting and the cooling down of the sample and second Ti sponge and CuOPd powder between 750 °C and 250 °C for 25 min.

In order to minimize interferences with ^{20}Ne, ^{22}Ne due to water vapor and doubly ionized ^{40}Ar and CO_2, an activated charcoal trap near the ion source was kept cooled at the liquid-nitrogen temperature during the analysis.

The contained neon in an unirradiated sample from the same Mg rod was also analyzed as a sample blank. Every target melting was followed by a new heating at 1000 °C to ascertain the complete release of the gas. No sample contained any residual gas after the first heating.

III. RESULTS

The neon results are given in Table II. In the targets, neon data are corrected for blank sample and mass discrimination. The energy threshold of ^{20}Ne production is 9.7 MeV via the nuclear reaction ^{24}Mg$(n,\alpha n)^{20}$Ne. So, at 5 and 7 MeV, ^{21}Ne and ^{22}Ne blank concentrations have been deduced from the measured ^{20}Ne signal corrected for $^{40}Ar^{2+}$ and water contributions and assuming air isotopic composition. At 16 and 19 MeV, we adopted the neon blank values measured in the unirradiated sample also given in Table II. These values agree within experimental errors with the ^{20}Ne concentration obtained at 7 MeV. On the other hand, at 5 MeV the neon blank appears to be 3.8 times larger. This discrepancy could indicate an unusual contamination of the sample also visible

TABLE II. Measured noble-gas nuclide concentrations (in units of 10^{-10} cm^3 STP/g) in Mg irradiated by 5, 7, 16, and 19 MeV neutrons.

Neutron energy (MeV)	Mass (g)	^{20}Ne[a]	$^{40}Ar^{2+}$	Water	^{21}Ne	^{22}Ne[b]	CO_2^{2+}
5.20 ±0.45	0.517		22.0%	8.6%	0.216 ±0.013	0.393 ±0.064	9.7%
7.00 ±0.30	0.531		19.7%	11.0%	6.04 ±0.31	0.660 ±0.039	6.2%
16.20 ±0.70	0.581	6.22 ±0.37	1.3%	1.0%	5.51 ±0.27	0.644 ±0.036	3.6%
19.05 ±0.35	0.582	4.80 ±0.35	0.3%	4.0%	1.825 ±0.088	0.336 ±0.031	3.2%
Blank Mg	0.583	0.767 ±0.097	10.0%	20.8%	<0.006	0.064 ±0.029	32.7%

[a]Corrected for $^{40}Ar^{2+}$ and water contributions.
[b]Corrected for CO_2^{2+} contributions.

TABLE III. Neon production cross sections (in mb).

Neutron energy (MeV)	^{20}Ne σ (mb)	^{21}Ne σ (mb)	^{22}Ne σ (mb)
5.20	0	2.79	5.4
±0.45		±0.21	±1.0
7.00	0	86.3	9.48
±0.30		±6.0	±0.91
16.20	115.1	101.6	11.9
±0.70	±8.7	±6.2	±1.0
19.05	103	38.8	3.8[a]
±0.35	±12	±2.3	±1.7

[a]Corrected for the contribution from ^{22}Na decay produced by the nuclear reaction ^{24}Mg$(n,t)^{22}$Na (threshold 16.3 MeV).

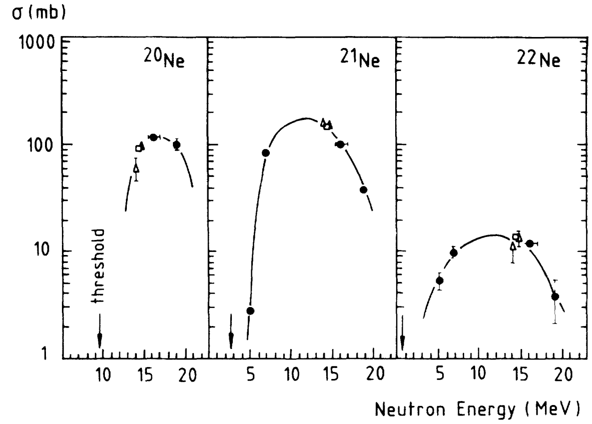

FIG. 1. Neon cross sections induced by neutrons in natural Mg. ● symbols are from this work, △ from Ref. 3, and □ from Ref. 4. ^{22}Ne values are corrected for contribution from the ^{22}Na decay (see text). Reported excitation functions correspond to eye-guide curves. Neon production thresholds are indicated by an arrow.

by an increase of the ^{40}Ar concentration by a factor of about 5.

Reported values in the columns $^{40}Ar^{2+}$, water, and CO_2^{2+} represent the mean corrections (in %) for interferences applied to the measured signal, respectively, at mass 20 and 22. Uncertainties on neon concentrations given in Table II include those from $^{40}Ar^{2+}$, water, CO_2^{2+} corrections, target and system blanks, calibration, and mass discrimination correction.

Absolute neon calibration was obtained with a gas pipet of air composition. During the analysis, the sensitivity of the ion source remained constant within 4.3% (1σ for ^{22}Ne).

Table III gives the measured cross sections. Uncertainties correspond to a quadratic sum of relative errors on the number of atoms of Mg in the target, integrated neutron fluxes from Table I, and neon concentrations from Table II.

Using terrestrial abundances of ^{24}Mg (78.99%) and of ^{25}Mg (10.00%), isotopic cross sections can be deduced from those in natural Mg targets when the threshold of nuclear reaction only allows a single production channel. Table IV gives nuclear reactions leading to an independent production yield of neon isotopes. Measured neon cross sections in Mg are shown in Fig. 1 as well as available data in the literature from Refs. 3 and 4.

Below 20 MeV, ^{22}Ne can also be produced in natural Mg by the nuclear reaction ^{24}Mg$(n,t)^{22}$Na. The threshold of this reaction being 16.3 MeV, a correction for ^{22}Na decay is only required at 19 MeV. Because the activity of ^{22}Na was too low to be measured, we adopted for the ^{22}Na production yield in natural Mg a cross-section value of (4.5±1.5) mb as estimated by Baros[6] from a compilation of (n,t) nuclear reactions available in the literature.[7–11]

The new measured cross sections are consistent (see the ^{22}Ne cross section at 16 MeV for example) with previous data and provide a good knowledge of the excitation functions of neon isotopes produced by neutrons below 20 MeV. In the considered energy range (0–20 MeV), these excitation functions have a similar shape with a maximum located around 17, 12, and 12 MeV, respectively, for ^{20}Ne, ^{21}Ne, and ^{22}Ne. The corresponding cross sections can be estimated at 120, 180, and 14 mb.

IV. CONCLUSION

Neutron-induced production cross sections of neon isotopes in natural Mg were measured at 5.20, 7.00, 16.20,

TABLE IV. Independent neon production cross sections.

Neutron energy (MeV)	^{24}Mg$(n,\alpha n)^{20}$Ne σ_{20} (mb)	^{24}Mg$(n,\alpha)^{21}$Ne σ_{21} (mb)	^{25}Mg$(n,\alpha)^{22}$Ne σ_{22} (mb)
5.20	0	3.53	54
±0.45		±0.27	±10
7.00	0	109.3	94.8
±0.30		±7.6	±9.1
16.20	146		
±0.70	±10		
Threshold (MeV)	9.7	2.66	0.5

and 19.05 MeV by mass spectrometry. These values and the data available in the literature between 14 and 15 MeV allowed us to determine the excitation functions of ^{20,21,22}Ne from threshold to 20 MeV. Independent neon production cross sections are also given for the ^{24}Mg$(n,\alpha)^{21}$Ne and ^{25}Mg$(n,\alpha)^{22}$Ne reactions at 5.2 and 7.0 MeV and for the ^{24}Mg$(n,\alpha n)^{20}$Ne reaction at 16.2 MeV.

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