Cross Sections for Formation of Na^{22} from Aluminum and Magnesium Bombarded with Protons*

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Cross sections for formation of Na^{22} from proton bombardment of aluminum and magnesium have been determined for the energy range from thresholds to 32 Mev. The $Al^{27}(p, p\alpha n)Na^{22}$ reaction has a threshold of 25 Mev and the cross section for the reaction rises to a value of 2.5 millibarn at 32 Mev. The cross section for the production of Na^{22} from magnesium has a value of 0.25 millibarn at 10 Mev, rises through a maximum of 9 millibarns at 17 Mev, drops to a minimum of 5 millibarns at 23 Mev and then rises to a value of 19 millibarns at 32 Mev.

INTRODUCTION

CROSS sections for the formation of Na^{22} from natural aluminum and magnesium have been measured as a function of proton energy from the range 0-32 Mev. The excitation functions were measured by means of the stacked foil technique on the Berkeley linear accelerator. Sodium was separated from the foils by chemical means and counted on a Geiger counter. Corrections were made for radioactive decay, chemical yield, and counting yield of the counting arrangement.

Both these excitation functions have been run previously but have been redetermined because of inadequacies in the earlier work. Hintz and Ramsey[1] have studied the production of Na^{22} from aluminum from threshold to 100 Mev, but made no accurate determination of the cross section in the energy range near the threshold. Bartell and Softky[2] have determined the relative excitation function for the production of Na^{22} from natural magnesium, but no attempt was made to correct the counting samples for effects due to self-absorption and self-scattering. The shape of the curve of cross section *versus* energy is the same as that obtained by Bartell and Softky, but the absolute values for the cross section are about a factor of five lower.

PROCEDURE

A stack of pure aluminum foils was irradiated for approximately 1.2 microampere hours on the linear accelerator. The energy of the protons incident on the stack was 32 Mev and the variation in cross section was studied down to 25 Mev, the apparent threshold of the reaction. Magnesium foils were irradiated in a stack for approximately 1.5 microampere hours on the linear accelerator. The excitation function was studied in the energy range from 10 to 32 Mev. In both cases the beam was integrated by means of a standard Faraday cup assembly.

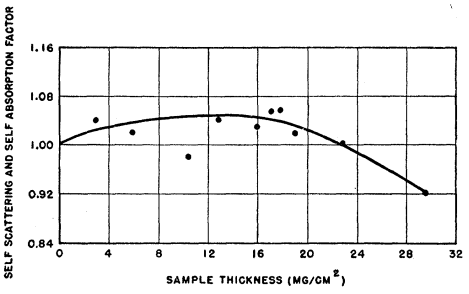

FIG. 1. Self-absorption—self-scattering Na^{22} in NaCl.

The sodium was separated chemically from the aluminum and magnesium. The foils were dissolved in dilute HCl and a known amount of sodium chloride added as a carrier so that a correction could be made for losses in the chemical separation procedure. The aluminum was precipitated as the hydroxide by the addition of ammonium hydroxide. The supernatant solution was evaporated to dryness and the ammonium chloride driven off by heating. The residue remaining after the ammonium chloride distillation was dissolved in water, cobalt carrier added, and cobaltous sulfide precipitated. The sodium was precipitated as sodium zinc uranyl acetate from a neutral solution. The sodium zinc uranyl acetate was dissolved in absolute alcohol saturated with HCl gas and the sodium chloride thus precipitated transferred to a plate to be weighed and counted.

In the case of magnesium, the sodium zinc uranyl acetate was precipitated directly after solution of the magnesium in dilute HCl and neutralization of the solution with ammonium hydroxide. An additional purification step was used in the magnesium samples and the low counting aluminum samples. This consisted of eluting the sodium chloride from a Dowex 50 cation column with 0.5 *M* HCl.

Absolute Beta Counting

The samples were counted with an argon-filled, chlorine-quenched Geiger counter used in conjunction with a scaling circuit. Na^{22} has a half-life of 2.60 years[3] and emits a 0.54-Mev positron[4] followed by a 1.28-Mev

* This work was done under the auspices of the U. S. Atomic Energy Commission.
[1] N. M. Hintz and N. F. Ramsey, Phys. Rev. **88**, 19 (1952).
[2] F. D. Bartell and S. Softky, Phys. Rev. **84**, 463 (1951).
[3] L. J. Laslett, Phys. Rev. **76**, 858 (1949).
[4] Marklin, Lidofsky, and Wu, Phys. Rev. **78**, 318 (1950).

gamma ray.[5] There is also a 1.8-Mev positron[6] transition in very low abundance. No K-capture branching was assumed,[7] although recent measurements indicate that the K-capture branching may be nine percent.[8] These decay characteristics made it imperative that the counting yield of the particular counting setup used be calibrated against an absolute standard. The standard used was a weightless Na^{22} sample mounted on a thin Tygon film and counted in a 4π geometry proportional counter to determine the absolute disintegration rate. This sample was then backed with aluminum and counted in the Geiger counter and the counting yield, including effects due to geometry, counting efficiency, backscattering, and window and air absorption determined directly. The effect due to the self-scattering and self-absorption of the counting samples was measured by placing equal aliquots of a standard Na^{22} solution into solutions containing varying amounts of sodium chloride carrier, precipitating the sodium chloride, and comparing the counting rates of these samples with a weightless standard sample placed directly on a counting plate. All counting was done with "infinite" aluminum backing. The "working curve" obtained by this method is shown in Fig. 1.

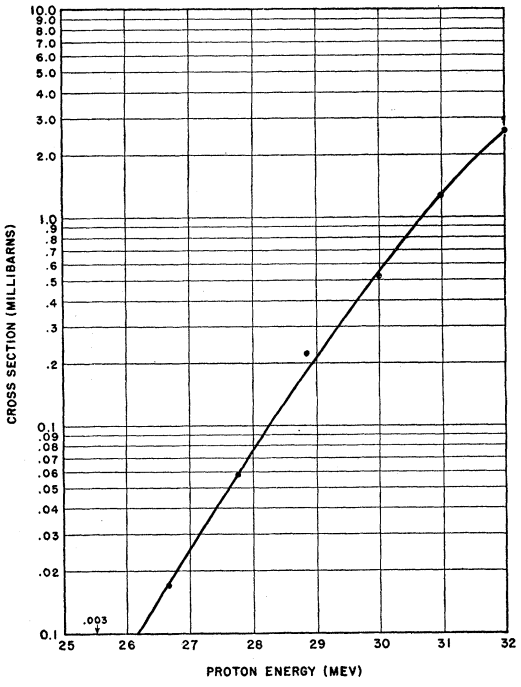

FIG. 2. Cross section for the production of Na^{22} from aluminum as a function of proton energy.

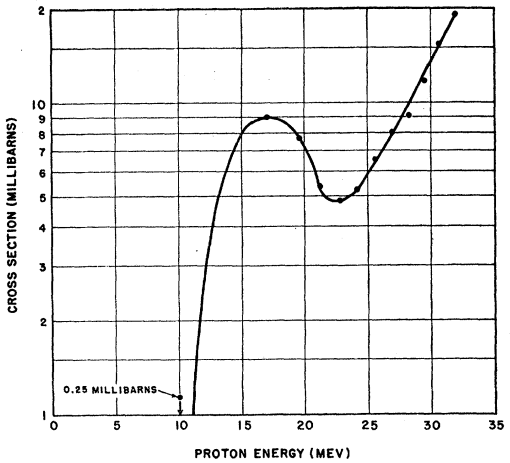

FIG. 3. Production of Na^{22} from magnesium as a function of proton energy.

RESULTS

The results are shown in Figs. 2 and 3. The cross section for production of Na^{22} from aluminum has a threshold of 25 Mev and rises steadily to a value of 2.5 millibarns at 32 Mev.

The cross section for formation of Na^{22} from magnesium has a value of 0.25 millibarn at 10 Mev, rises sharply through a maximum at 17 Mev, decreases to a minimum at 23 Mev, and then rises steadily to 32 Mev. This excitation function has the same shape as that obtained by Bartell and Softky,[2] but the observed cross sections are considerably lower than the reported values. However, Bartell and Softky indicated that only the shape of this particular excitation function was determined with any precision.

DISCUSSION

Na^{22} from Aluminum

The cross section for formation of Na^{22} from proton bombardment of aluminum has been determined previously[1] from threshold to 100 Mev. The present work defines the threshold and low-energy portion of

TABLE I. Threshold for possible reactions.

Reaction	Q (Mev)	Barrier (Mev)	Q + Barrier
$Al^{27}(p, p\alpha n)Na^{22}$	22.0	8.1	30.1
$Al^{27}(p, \alpha d)Na^{22}$	19.9	7.6	27.5
$Al^{27}(p, Li^6)Na^{22}$	18.4	7.0	25.4
$Al^{27}(p, 3p3n)Na^{22}$	50.2	9.6	59.8
$Al^{27}(p, THe^3)Na^{22}$	34.2	8.1	42.3
$Mg^{26}(p, \alpha n)Na^{22}$	15.0	5.3	20.3
$Mg^{25}(p, pdn)Na^{22}$	27.6	6.0	33.6
$Mg^{25}(p, \alpha)Na^{22}$	2.5	5.3	7.8
$Mg^{24}(p, 2pn)Na^{22}$	23.8	6.4	30.2
$Mg^{24}(p, pd)Na^{22}$	22.7	6.3	29.0
$Mg^{24}(p, He^3)Na^{22}$	16.1	5.2	21.3

The authors wish to thank the crew of the linear accelerator for the bombardments performed in the course of these studies.

[5] D. E. Alburger, Phys. Rev. **76**, 435 (1949).
[6] K. H. Morgenstern and K. P. W. Wolff, Phys. Rev. **76**, 1260 (1949).
[7] Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).
[8] R. H. Miller and R. Sherr, Bull. Am. Phys. Soc. **28**, No. 4, 12 (1953).

the curve more accurately. The calculated thresholds for some of the possible reactions are shown in Table I. These thresholds include the mass difference between the reactants and the products and the energy required for passage over the potential barrier. The Coulombic requirements were calculated assuming that the nucleus and the emitted fragments are spherical and tangent at the nuclear radii (taken as $1.48\times10^{-13}A^{\frac{1}{3}}$ cm) and that the particles come out consecutively. Because of uncertainties inherent in calculating Coulombic barrier requirements for charged particle reactions, it is not possible to determine from energy considerations what the actual mechanism is for the formation of Na^{22} near the threshold. Undoubtedly, there is some contribution from each of the following reactions: $Al^{27}(p, p\alpha n)Na^{22}$, $Al^{27}(p, \alpha d)Na^{22}$, and $Al^{27}(p, Li^6)Na^{22}$.

Na^{22} from Magnesium

Natural magnesium is an isotopic mixture of 78.6 percent Mg^{24}, 10.1 percent Mg^{25}, and 11.3 percent Mg^{26}. From the threshold considerations shown in Table I, the excitation function can be divided into two parts. The portion of the curve below 15 Mev represent the contribution to the excitation function due entirely to the $Mg^{25}(p, \alpha)Na^{22}$ reaction. Above this energy the mechanism of the reaction leading to the formation of Na^{22} is uncertain, and undoubtedly, is a combination of the possible reactions shown in Table I.

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Angular Distributions of 22-Mev Protons Elastically Scattered by Various Elements

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Angular distributions of 22-Mev protons elastically scattered by fifteen elements from beryllium to thorium were measured with the internal, circulating beam of the Oak Ridge National Laboratory 86-inch cyclotron. The experimental methods, which are somewhat unconventional, are described. The results show all the characteristics of diffraction scattering including at least two maxima and minima for each element. The angles at which these occur can be traced from element to element through the periodic table, following a $\lambda\!\!\!^{-}/R$ dependence with fairly good accuracy.

I. INTRODUCTION

THE theory of the scattering or absorption of a wave by matter with which it interacts is a well-known differential equation-boundary value problem of classical physics. While the mathematical techniques are devious and varied, basically the solution is obtained by assuming the appropriate wave equation (in the case of particle scattering, the Schrödinger equation) valid throughout the region external to the scattering or absorbing material, and inserting the appropriate boundary conditions at its surface.[1] Computations of this type for the elastic scattering of neutrons have been made by Feld *et al.*,[2] assuming spherical nuclei and the Feshbach-Weisskopf[3] boundary condition. For incident neutrons with wavelength of the order of the dimensions of the scattering nucleus, they find angular distributions characterized by several maxima and minima, as is expected in analogy with the familiar diffraction patterns in optical and acoustical scattering. As is also expected from these analogies, the angles at which the maxima and minima occur are determined only by the radius of the scattering nucleus, being essentially independent of the boundary conditions. On the other hand, the relative heights of the various maxima and minima are extremely sensitive to the boundary condition, varying by as much as a factor of 100 for various not unreasonable assumptions. Computations by Le Levier and Saxon[4] confirm that these features are valid for a more general type of boundary condition, and for charged particles as well as neutrons. It is thus apparent that reasonably accurate measurements of elastic scattering angular distributions should provide:

(a) Accurate determinations of nuclear radii, since the positions at which maxima and minima occur can be determined with good precision.

(b) A very sensitive determination of the nuclear boundary condition. This boundary condition is also of great importance in nuclear reaction theory since the theoretical treatments of absorption and scattering are essentially two parts of the same problem.

(c) Some estimate of deviations from sphericity of the nuclear surface. This would provide a very important check on the determinations through quadrupole moments which do not have a completely satisfactory status.

[1] J. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).
[2] Feld, Feshbach, Goldberger, Goldstein, and Weisskopf, NYO-636 (unpublished).
[3] H. Feshbach and V. F. Weisskopf, Phys. Rev. **76**, 1550 (1949).
[4] R. E. Le Levier and D. S. Saxon, Phys. Rev. **87**, 40 (1952).