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ANOMALY IN THE PHOTODISINTEGRATION OF Ni^{58} AND Ni^{60} IN THE GIANT-DIPOLE RESONANCE REGION*

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The photoneutron cross sections for Ni^{58}, Ni^{60}, and natural nickel from threshold up to 25 MeV have been measured. The integrated (γ, n) cross section for Ni^{60} is 2.6 times as large as the value for Ni^{58}, and the two cross-section curves exhibit markedly different structure over the giant-dipole resonance region. The results suggest that it is important to include the shell effects explicitly in the theoretical treatment of the giant-dipole states in the medium nuclei such as nickel isotopes.

Several investigators[1,2] have suggested that there is a marked dissimilarity in the photoneutron cross sections of Ni^{58} (67.9% abundance) and Ni^{60} (26.2% abundance) in the giant-dipole resonance region. Their main observations, which were based on the existing photonuclear data on Ni^{58} [3,4] and natural nickel,[1,2] were two: (1) The cross section reaches maximum at 16 MeV in Ni^{60}, but at 19 MeV in Ni^{58}. (2) The integrated (γ, n) cross section for Ni^{60} is about three times as large as the value for Ni^{58}. So far there has been no direct measurement of the photoneutron cross section in separated Ni^{60} to verify the above inferences. We have recently completed the measurement of photoneutron cross sections on separated Ni^{60} (99.79% enriched), Ni^{58} (99.89% enriched), and natural nickel samples. The cylindrical samples of Ni^{60} and Ni^{58} isotopes, loaned to us from Oak Ridge National Laboratory, were 3 cm in diameter and 2.3 cm thick. The natural nickel sample was 4.3 cm in diameter and 5.2 cm thick. The collimated bremsstrahlung beam from the University of Virginia 70-MeV electron synchrotron irradiated the sample which was placed at the center of a 4π neutron detector made of paraffin and eight BF_3 counters. The photoneutron yields from each sample were measured from 10.5- to 25-MeV bremsstrahlung energy in steps of 0.5 MeV. In all neutron yield measurements, the statistical counting error was better than 0.3%. The least structure method[5] for unfolding the photonuclear yields was used to obtain the photoneutron cross sections in 0.5-MeV bins. The cross-section results for Ni^{60} and Ni^{58} are shown in Fig. 1. In each case, the corrected values for $(\gamma, 2n)$ process are shown by circles. These corrections were made using the statistical-model formula given by Blatt and Weisskopf.[6] In this correction the fraction of direct neutrons was taken to be 10%,[7] and the value of the level density parameter $a = 5.49\ \mathrm{MeV}^{-1}$ was obtained from the semiempirical formula of Thomson.[8] The cross-section results for natural nickel are shown in Fig. 2. The solid line in Fig. 2 represents the Ni^{60} and Ni^{58} contributions in the natural nickel cross section. Table I lists the integrated (γ, n) cross sections up to 25 MeV for Ni^{60}, Ni^{58}, and natural nickel.

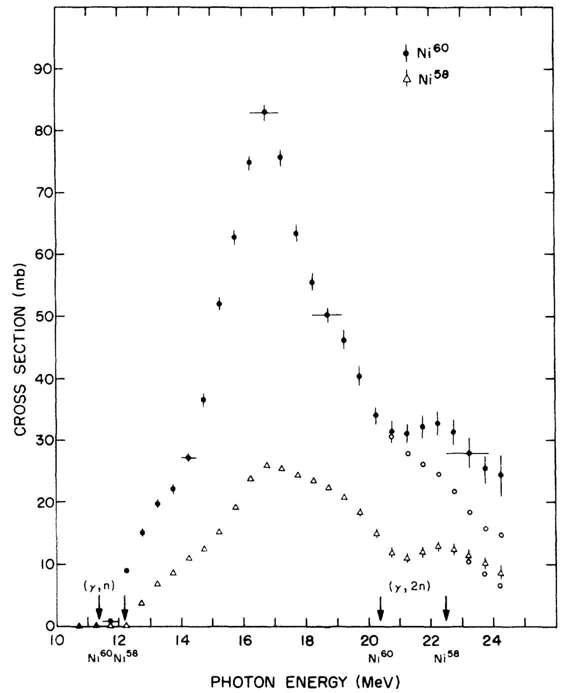

FIG. 1. Photoneutron cross sections of Ni^{60} and Ni^{58}. The corrected values for $(\gamma, 2n)$ process are shown by circles.

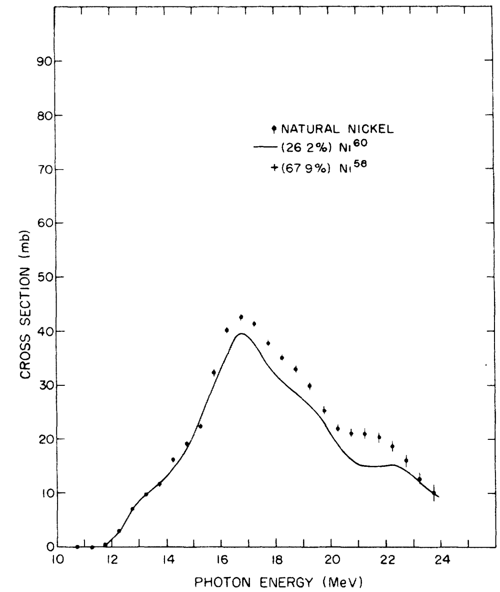

FIG. 2. Photoneutron cross section of natural nickel and the sum of Ni^{60} and Ni^{58} contributions.

Also given are the weighted sum of Ni^{60} and Ni^{58} contributions and the ratio of integrated cross sections. The uncertainties quoted in Table I are solely based on the counting statistical errors. Clearly, the cross sections of Ni^{60} and Ni^{58} shown in Fig. 1 are quite different both in shape and integrated cross section. The following features should be observed: (a) In Ni^{60}, because of its lower $(\gamma, 2n)$ threshold, the small structure at 22 MeV is much reduced when the cross section is corrected for the $(\gamma, 2n)$ reaction. However, the similar structure in Ni^{58} persists in the (γ, n) cross section due to the higher $(\gamma, 2n)$ threshold energy at 22.5 MeV. Figure 1 shows that this structure begins to appear at 21 MeV even before the $(\gamma, 2n)$ threshold sets in. (b) The shape of the main resonance in Ni^{58} shows a marked asymmetry in contrast to the Ni^{60} cross section, and its centroid lies about 0.5 MeV higher than for Ni^{60}. (c) The integrated (γ, n) cross section up to 25 MeV exhausts 60% of the classical dipole sum in Ni^{60}, but only 20% in Ni^{58}.

Table I. Integrated (γ, n) cross sections up to 25 MeV.

Isotope	Integrated cross section (MeV mb)
Ni^{58}	185 ± 3
Ni^{60}	482 ± 12
Natural nickel	283 ± 6
$(0.262)\ Ni^{60} + (0.679)\ Ni^{58}$	252 ± 4
Ratio of integrated cross section, $Ni^{60}/Ni^{58} = 2.6$	

The results of the present experiment suggest that in the theoretical treatment of the giant dipole resonance of nickel isotopes, both in the absorption cross section and partial width calculations, it is necessary to take into account the shell effects peculiar to each isotope. Whether the anomaly observed in the photodisintegration of nickel isotopes is a general feature of nuclei in the $1f$-$2p$ shell should be an interesting subject of further experimental investigation.

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ACCELERATION OF TRAPPED PARTICLES THROUGH BIMODAL DIFFUSION IN AN INHOMOGENEOUS MAGNETIC FIELD

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Trapped particles can be accelerated or decelerated by diffusing at random in an inhomogeneous magnetic field via two or more diffusion modes which affect the particle energy differently. Acceleration through such "bimodal diffusion" can account for the high-energy particles trapped in the earth's radiation belts.

Particles trapped in a magnetic field follow trajectories that are characterized by a set of adiabatic invariants. Various types of interactions can move particles into new trajectories by violating one or more adiabatic invariants. The acceleration mechanism discussed in this Letter operates whenever trapped particles can diffuse in space by following, at random, one out of two or more distinct interaction modes which affect the particle energy differently. Figure 1 illustrates the acceleration mechanism; coordinates are a spatial parameter, L, and the first adiabatic invariant μ (for definitions and discussion of the adiabatic invariants, see Northrop[1]). We take for simplicity constant-E lines which are straight as in the special case of a dipole field; L represents the equatorial radial distance of a magnetic shell; we use logarithmic scales for μ and L. Let us assume that two L-diffusion modes are possible, the one conserving the first adiabatic invariant μ and the other conserving the energy E. A particle starting at L_0 with energy E_0 can be raised to energy E_1 through the steps $a_1 \to a_2$ or $b_1 \to b_2$, or lowered to energy E_2 through the steps $c_1 \to c_2$ or $d_1 \to d_2$.

In general, a particle starting at a given E and L has a finite chance of reaching any other point E' and L' in the presence of the two diffusion modes. For the mechanism to be effective the diffusion modes need not conserve either μ or E. The only requirement is that a particle can, at random, move in more than one direction in the μ-L plane in successive diffusion steps. This process will affect the energy of particles in many situations where plasmas are immersed in magnetic fields, as is the case, for instance, in most nuclear fusion machines.

Acceleration through such "bimodal diffusion" can adequately account for the high-energy particles trapped in the earth's radiation belts. Outer belt relativistic electron fluxes, and at least part of the inner-belt high-energy protons, are well above the levels that might be expected on the basis of only constant-μ diffusion from the solar wind, thus implying the presence of some sort of acceleration mechanism. Parker[2] and Fälthammar,[3] among others, have discussed radial diffusion mechanisms that conserve μ. More recently, Roederer[4] and Eviatar[5] have examined mechanisms of radial diffusion involving scattering of particles by electromagnetic waves. Such diffusion, as long as the waves are fast compared

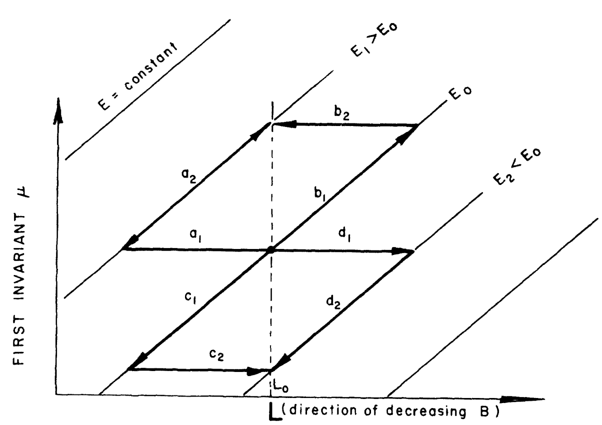

FIG. 1. Example of particle acceleration and deceleration in two alternating steps of constant-μ and constant-E diffusion in L.