Explanation of difference in one-neutron knock-out cross-sections between odd-odd and even-even projectiles with equal neutron and proton numbers.

Bernard G. Harvey
Lawrence Berkeley National Laboratory,
Berkeley, CA 94720

Experimental measurements of cross sections for knock-out of one neutron from even-even and odd-odd projectiles with equal proton and neutron numbers at energies of about 600 MeV/nucleon on a hydrogen target show that the cross section for odd-odd projectiles is about three times smaller than for even-even projectiles/ Monte Carlo calculations are used to explain this difference.

1. INTRODUCTION

In ref. 1, Webber et al. describe the production of many secondary beams by accelerating ^{40}Ar and ^{56}Fe nuclei to energies of about 600 MeV/nucleon and then fragmenting then on a hydrogen target at the SATURNE accelerator at Saclay, France. The secondary beams were then fragmented again on a hydrogen target, and cross sections were measured for the production of fragments with one or two neutrons or protons less than the original projectile. The results were compared with the parametric model [2] that is used to predict the break-up of cosmic rays as they travel through space from their source to the detector in Earth orbit. For projectiles with one, two or four neutrons more than protons, the experiment is in good agreement with the parametric model. However, for N=Z projectiles, the cross section for one neutron loss from odd-odd projectiles such as ^{14}N is about three times smaller than the model prediction. For even-even projectiles such as ^{12}C or ^{16}O, the experiment agrees well with the parametric model. The purpose of the present work is to understand why the 1n loss from odd-odd projectiles with N=Z is so small.

2. THE CALCULATIONS.

The Monte Carlo calculations are described in detail in ref. 3. In the first phase, the target nucleons (in this case, just a proton) with an initial impact parameter b, travel towards the projectile. If the proton reaches a distance from a projectile proton or neutron that is less than d, where $d=sqr(\sigma_{nn}/\pi)$. σ_{nn} is the nucleon-nucleon total cross section, then the two nucleons are assumed to collide The impact parameter b varies from 0 to 15 fm in steps of 0.1 fm. The number of events varies as the square of b and is typically 5,000 for the maximum b. This will eventually produce 50 events per 1 mb of fragment production cross section.

When a projectile nucleon is hit, its kinetic energy is calculated. If that exceeds the binding energy, the nucleon is knocked out. It may escape or it may travel through the projectile nucleus and produce secondary reactions. If the hit nucleon came from an inner shell with greater binding energy than the outermost nucleons, the residual nucleus will be excited. If the struck nucleon has kinetic energy less than its binding energy, the nucleus is excited by that kinetic energy.

In the second phase of the calculation, the residual projectile nucleus will decay. It may emit any particle or nucleus up to one half of its own mass and charge. The probability of a given decay depends on the available free energy U where:

$$U=E^* + Q - V_c \qquad (1)$$

E^* is the excitation energy, Q is the Q-value for the particular decay, and V_c is the height of the Coulomb barrier for emission of a charged fragment.

The probability P for a given decay is calculated from the transition state formalism:

$$P=T(E^*/U)^2 \qquad (2)$$

where T is the temperature of the decaying nucleus. It is assumed that the emitted fragment and the residual nucleus will share the same temperature, Thus both of them may be excited enough to decay again...and so on.

3. COMPARISON WITH EXPERIMENT.

Figure 1 shows a comparison of experimental and calculated cross sections for loss of one neutron from projectiles with N = Z. In both cases, the cross section for odd-odd projectiles is about three times lower than for even-even projectiles. This difference is caused by the instability for proton decay of odd-even nuclei such as ^{13}N or ^{25}Al that are formed by the knock-out of one neutron from odd-odd projectiles.

Proj.	-Q(MeV)	Proj.	-Q(MeV)
^{12}C	8.69	^{14}N	1.94
^{16}O	7.29	^{22}Na	2.43
^{20}Ne	6.41	^{26}Al	2.29
^{24}Mg	7.58	^{30}P	2.74
^{28}Si	7.46	^{34}Cl	2.28
^{32}S	6.08		
^{40}Ca	5.77		

Average even-even: 7.04 MeV   Average odd-odd 2.34 MeV

Table 1. Q-value for proton decay of projectile minus one neutron.

Table 1 shows a comparison of the proton decay Q-values of nuclei that have one neutron less than odd-odd or even-even projectiles. For the odd-odd projectiles, the average Q-value is only -2.34 MeV, one third of the value for the even-even projectiles. Equation 1 shows that the smaller -Q, the larger the free energy U, and therefore (eq. 2) the higher the decay probability. Thus odd-odd projectiles that lose one neutron are likely to decay further by emission of a proton. While the 1n cross sections for odd-odd projectiles are thus reduced, those for 1n1p are increased. Table 2 shows the experimental [4] and calculated cross sections.

Proj.	σ(expt.),mb	σ(calc.),mb	
^{12}C	17.1	12.2	Even-even
^{16}O	31.0	14.7	
^{20}Ne	19.0	8.24	
^{24}Mg	36.6	22.7	Average expt: 27.4 mb
^{28}Si	30.3	10.5	Average calc: 18.3 mb
^{32}S	32.9	34.7	
^{40}Ca	24.9	23.3	
^{14}N	52.1	51.2	Odd-odd
^{22}Na	44.9	27.0	
^{26}Al	36.8	41.7	Average expt: 53.9 mb
^{30}P	73/1	42.1	Average calc: 38.7 mb
^{34}Cl	62.4	31.4	

Table 2 Experimental and calculated cross sections for removal of 1 proton and 1 neutron from even-even and odd-odd projectiles with equal proton and neutron numbers. Experimental values from ref. 1 and 4..

For odd-odd projectiles, experimental results are available only for ^{14}N (52.1 mb). For even-even projectiles, the average is 27.4 mb.This difference accounts well for the difference in the -1n cross sections.

4. SUMMARY.

The experimentally observed difference for loss of one neutron between odd-odd and even-even projectiles at about 600 MeV/nucleon on a hydrogen target is explained by the very low binding energy of a proton in odd Z even N nuclei. This also leads to higher cross sections for loss of one proton and one neutron from odd-odd projectiles. The Monte Carlo calculations include the use of decay Q-values to determine the probability of a specific decay mode whereas the parametric model [2] does not.

5. ACKNOWLEDGEMENTS.

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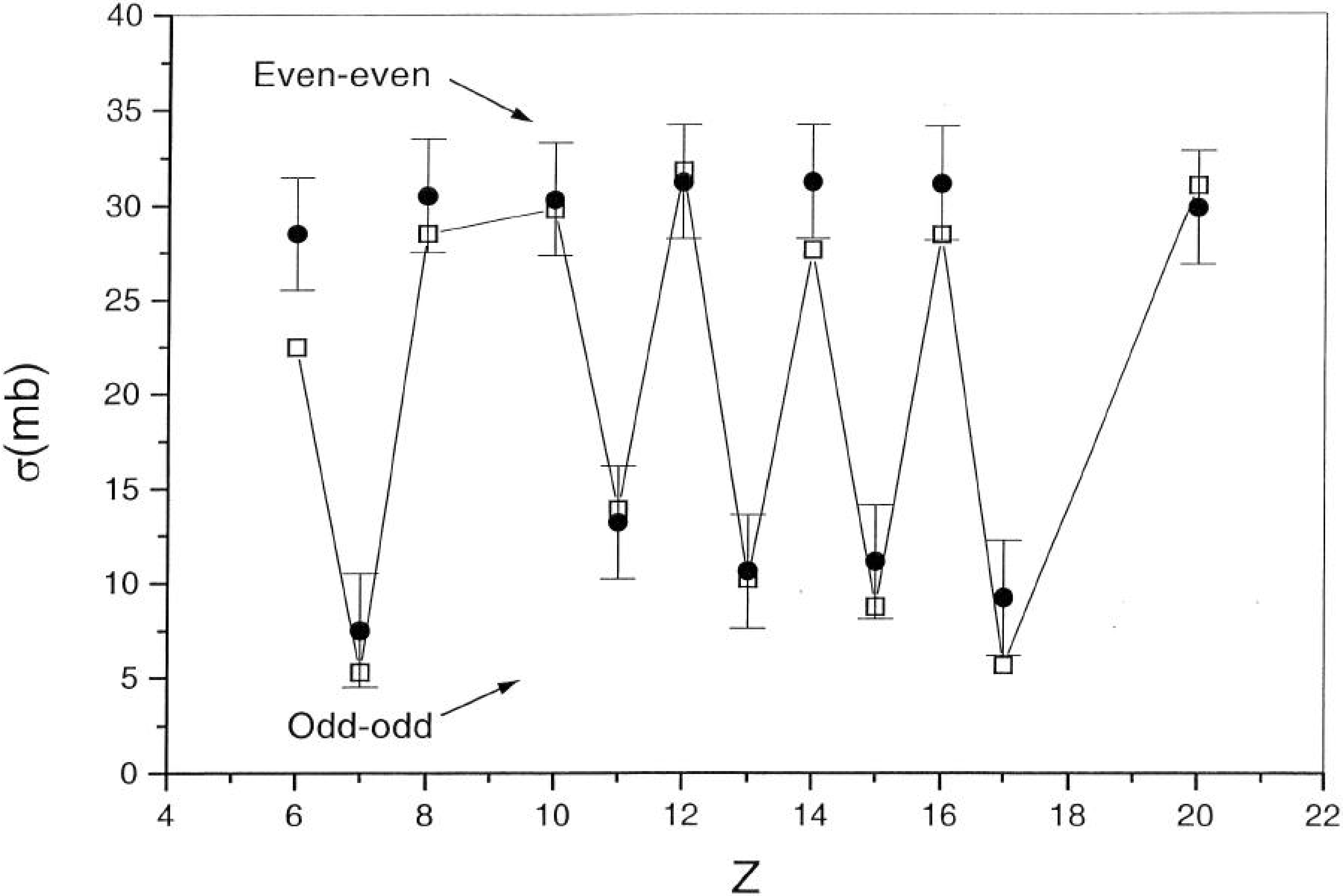
Fig. 1. Experimental (filled circles) and calculated (open squares) cross sections for removal of one neutron from projectiles with equal neutron and proton numbers.



σ(mb)
40
35
30
25
20
15
10
5
0
Even-even
Odd-odd
4
6
8
10
12
14
16
18
20
22
Z