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Momentum Conservation in Binary Reactions

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In the IAEA Nuclear Data Section, we recently had occasion to re-examine the old topic of neutron source reactions, such as D(d,n)^{3}He. As part of this work, I programmed the formulae from page 26 of the GROUPR manual, Chapter VIII of Los Alamos report LA-12740-M. I had to make some modest interpolation of the description there to allow the treatment of an incident particle other than a neutron. For example, I interpret the quantity A as the target mass, relative to the incident particle mass, whether or not the incident particle is a neutron.

Appendix A contains a listing of a short test program that computes spectra from the kinematic formulae in the manual for zero-degree emission. The most interesting result for the present purposes is that I added coding to check of the answers and, at first, the answers failed this test. The code first calculates the energy of the recoil nucleus, in this case ^{3}He, by conservation of energy, and then it checks the results for momentum conservation. With the original formulae, the result does not quite conserve momentum. After a small amount of experimentation, I found that momentum and energy are conserved if I replace the "target" mass with a mass computed from the total mass of the products (ejectile + recoil) minus the mass of the projectile. This differs from the exact target mass by the Q of the reaction (expressed in AMU). With this change to the formulae, momentum is now conserved.

In Appendix B is listed the results of running the code with 6-MeV deuterons incident. For this test, the code was compiled with REAL=64 and executed on the NDS AlphaServer 2100. The measure of momentum conservation is the variable "forbal" which changes from 3.524793231104439E-4 with the uncorrected mass to -9.769962616701378E-15 with the Q-subtracted mass. Thus, it appears that the manual, at least, needs a small correction here. It is currently unclear what, if any, changes may actually be required in GROUPR.

Appendix A. Test Program SPEC4

```
      program spec4
c     test momentum conservation effects in connection
c     with binary reaction kinematics. as represented in
c     formulae in the njoy/groupr manual, eqs. (75-77).
c
c     set constants for D(d,n)He3 reaction, with energies
c     in mev and masses in amu.
c
      q=3.26892
c     deuteron mass  (particle 1 = projectile)
      xm1=2.01410
c     helion mass    (particle 2 = recoil)
      xm2=3.01603
c     neutron mass   (particle 3 = ejectile)
      xm3=1.00866
c     deuteron mass  (particle 4 = target)
      xm4=2.01410
      istart=1
c
c     read in the deuteron energy (in MeV)
      write (*,*) ' '
      write (*,*) ' enter e'
      read (*,*) e1
c
c     ejectile is emitted in forward direction in lab.
      omega=1.
c
c     calculate ejectile energy in lab.
   50 continue
      a=xm4/xm1
      aprime=xm3/xm1
      fac1=sqrt(a*(a+1.-aprime)/aprime)
      fac2=sqrt(1.-(a+1.)*(-q)/(a*e1))
      r=fac1*fac2
c     solve eq. (76) for eprime
      eprime=(omega*2.*r+1.+r**2)*aprime*e1/(1.+a)**2
c
c     print results
      write (*,*) ' '
      write (*,*) ' eprime =', eprime
c
c     check results
      e2=e1+q-eprime
      p2=sqrt(2.*xm2*e2)
      p1=sqrt(2.*xm1*e1)
      p3=sqrt(2.*xm3*eprime)
c     recoil must be emitted in either the forward or
c     backward directions in the lab.
      forbal=p1-(p3+p2)
      bakbal=p1-(p3-p2)
      write (*,*) ' '
      write (*,*) ' forbal,bakbal =', forbal,bakbal
```

```
c
c     diagnose result
      if (istart.eq.0) go to 100
      istart=0
c
c     compute target mass from other three
      write (*,*) ' '
      write (*,*) ' old target mass =', xm4
      xm4=xm2+xm3-xm1
      write (*,*) ' '
      write (*,*) ' new target mass =', xm4
      go to 50
  100 continue
      stop
      end
```

Appendix B. Result of test run with SPEC4

```
<IAEAND> $ run spec4

 enter e1
6

 eprime =   9.20805448330349

 forbal,bakbal =  3.5247932311044398E-004   1.21220139506198

 old target mass =   2.01410000000000

 new target mass =   2.01059000000000

 eprime =   9.20798015221335

 forbal,bakbal = -9.7699626167013788E-015   1.21258866601987
```