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Coulomb versus nuclear breakup in ^{11}Li fragmentation

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The cross section for two-neutron removal from a beam of relativistic ^{11}Li is calculated in an eikonal approximation. We find a larger nuclear cross section in reactions with heavy nuclei than estimated by Kobayashi *et al.* This lowers the inferred Coulomb cross section for reactions on ^{208}Pb from 890 to a range of 560–740 mb, depending on the assumed single-particle binding energy of the valence neutron.

Recent measurements of the fragmentation of relativistic ^{11}Li ions induced by interactions with heavy nuclei have shown unusually large breakup and total reaction cross sections.[1] This is related to the fact that ^{11}Li has two very loosely bound valence nucleons and therefore also a large rms radius. The breakup reaction on heavy nuclei is of particular interest since the part induced by Coulomb excitations puts constraints on the electric dipole response of ^{11}Li, thus providing some structure information about this weakly bound nucleus.

In order to isolate the contribution from Coulomb excitations it is necessary to have an accurate model for the nuclear part of the breakup cross section. In Ref. 1, a factorization model is employed to extrapolate the nuclear breakup cross section to heavy nuclei. In this model, the target A dependence of the nuclear part of the two-neutron removal cross section is assumed to be proportional to the sum of the projectile and target radii, R_P+R_T, which is the form expected for a strongly surface peaked reaction, and it is predicted to be much less than half the measured cross section for ^{208}Pb. In this Brief Report we examine some more microscopic models for the breakup, based on the eikonal approximation. The resulting A dependence is closer to the form, $\sigma\sim(R_P+R_T)^2$, which increases faster with A and thus implies a reduced Coulomb breakup on heavy nuclei. The faster A dependence is a consequence of the weak binding of ^{11}Li, which implies that the valence neutron density has a slow radial decay. The two-neutron removal reaction is therefore not surface peaked but has a wider range of impact parameters contributing to the cross section.

The eikonal phase that is often used for nucleon-nucleus scattering at high energies is purely imaginary and is determined by the target density and the nucleon-nucleon cross section.[2] We shall distinguish between proton and neutron target densities, ρ_{Tp} and ρ_{Tn}, and use the free proton-proton and proton-neutron cross sections, σ_{pp} and σ_{pn}, since they are different and neutron haloes in projectile and target may be important. The eikonal phase for proton-nucleus scattering is then

$$\chi_p(b)=i\tfrac{1}{2}\int_{-\infty}^{\infty}\{\sigma_{pp}\rho_{Tp}[(z^2+b^2)^{1/2}] +\sigma_{pn}\rho_{Tn}[(z^2+b^2)^{1/2}]\}dz\ . \tag{1}$$

The neutron-nucleus eikonal phase is determined by an obvious, similar expression. At 800 MeV/nucleon, which is the energy of the ^{11}Li experiment, we use $\sigma_{pp}=\sigma_{nn}=47$ mb and $\sigma_{pn}=38.5$ mb.

Let us first consider the scattering of a single nucleon. We can think of the initial state ψ_0 of the nucleon as a bound state in a fictitious projectile with an inert core, which has an impact parameter b with respect to the target. In the eikonal approximation the final wave function of the nucleon is

$$\psi(\mathbf{s},z)=\exp[i\chi(\mathbf{b}+\mathbf{s})]\psi_0(\mathbf{s},z)\ , \tag{2}$$

where $(\mathbf{s},z)$ is the coordinate of the nucleon with respect to the projectile. The probability that the nucleon remains in the initial state after the interaction with the target is

$$P_0(b)=|\langle\psi_0|\exp[i\chi(\mathbf{b}+\mathbf{s})]|\psi_0\rangle|^2 \tag{3}$$

and the reaction cross section is

$$\sigma_R=2\pi\int_0^\infty b\,db\,[1-P_0(b)]\ . \tag{4}$$

Our preferred model for nucleus-nucleus scattering is a simple generalization of this using the single-particle shell model. The probability that the projectile remains in the ground state after the interaction with the target becomes a product of the probabilities that all the nucleons stay in their initial configuration,

$$P_0(b)=\prod_{lj}[P_{plj}(b)]^{n_{plj}}\prod_{lj}[P_{nlj}(b)]^{n_{nlj}} . \tag{5}$$

The product is over all occupied proton (plj) and neutron (nlj) shells with occupation numbers n_{plj} and n_{nlj}, respectively. The individual probabilities are calculated as in Eq. (3) using the appropriate cross sections for protons and neutrons. The reaction cross section is then calculated from Eq. (4). We call this model the "diffractive eikonal" model, because the probability for a reaction includes both the absorption of a nucleon by the eikonal operator as well as its diffraction into a different state than the initial state.

There will also be matrix elements of the eikonal operator to excited projectile states, $\langle\psi_i|\exp(i\chi)|\psi_0\rangle$, $i\neq0$. Whether the probability associated with these should be assigned to the breakup cross section or not is a delicate issue. If the binding energy is very low, as is clearly the case for ^{11}Li, the excited states are unbound and Eq. (4) is probably a good approximation for the total breakup cross section. On the other hand, if ψ_0 is tightly bound, the low excited states will also be bound and the probability for the original projectile to remain intact should include these contributions. In order to model this simply, we just consider the extreme case in which all final states in the projectile wave function remain bound. Closure then yields the abrasion model[2] formula for the probability for the nucleon to survive,

$$P_{ab}=\langle\psi_0|\exp(-2\,\mathrm{Im}\chi)|\psi_0\rangle . \tag{6}$$

This probability is calculated for each nucleon, and inserted in Eq. (5) to get the nucleus-nucleus survival probability P_0. Equation (4) determines the reaction cross section, as in the diffractive eikonal model.

As a third model, we will use the formula of Ref. 3. This model was introduced in Ref. 4, and applied to calculations of total cross sections rather than reaction cross sections. The model is based on the idea of absorption by a nucleus-nucleus optical potential. Here one defines an eikonal phase for the nucleus-nucleus interaction, $\chi(b)=\chi_{pp}+\chi_{pn}+\chi_{np}+\chi_{nn}$, where for example

$$\chi_{np}(b)=\frac{i}{2}\sigma_{np}\int d^2\mathbf{s}\,\tilde{\rho}_{Pp}(s)\tilde{\rho}_{Tn}(\mathbf{b}+\mathbf{s}) \tag{7}$$

and

$$\tilde{\rho}(b)=\int dz\,\rho[(b^2+z^2)^{1/2}] . \tag{8}$$

The nucleus-nucleus survival probability is then

$$P_0=\exp[-2\,\mathrm{Im}\chi(b)] . \tag{9}$$

These three models will be used to calculate the total reaction cross section.

We also want to use the models to describe the $2n$ removal channel, $^{11}\mathrm{Li}\rightarrow{}^{9}\mathrm{Li}$. For this latter process, we shall assume that any excitation of the two valence neutrons (assumed to be in the $p_{1/2}$ shell) will contribute to the ^{9}Li breakup channel, whereas core excitations will lead to further disintegrations. The probability for the two-neutron removal channel is therefore

$$P_{2n}(b)=(1-P^2_{np_{1/2}})P^2_{ps_{1/2}}P_{pp_{3/2}}P^2_{ns_{1/2}}P^4_{np_{3/2}} \tag{10}$$

at a given impact parameter. Integration over all impact parameters yields the nuclear part of the (^{11}Li,^{9}Li) cross section. We use Eq. (10) for both the diffractive eikonal and the abrasion model. To apply the nucleus-nucleus optical model to this process, we compute separately the eikonal phases associated with the core and the valence densities of ^{11}Li, and determine the two-nucleon removal probability as

$$P_{2n}(b)=[1-\exp(-2\,\mathrm{Im}\chi_{\mathrm{val}})]\exp(-2\,\mathrm{Im}\chi_{\mathrm{core}}) . \tag{11}$$

We have calculated cross sections for ^{11}Li, as described above, on a series of targets. The shell model states and densities were calculated as in Ref. 3, with the binding energy of the $p_{1/2}$ neutrons $\epsilon_{p1/2}$ adjusted by changing the depth of the central potential. Since we use an independent particle model of the density, it is not obvious what the binding energy should be. The two-neutron separation energy[5] for ^{11}Li is $S_{2n}=0.25\pm0.10$ MeV, while ^{10}Li is unbound[6] by 0.80 ± 0.25 MeV. For the moment we take $\epsilon_{p1/2}=-0.19$ MeV. There is some sensitivity to the choice of $\epsilon_{p1/2}$ which will be discussed later.

The predicted cross sections for the diffractive eikonal model are shown in Fig. 1 together with the experimental data. The dashed curves are the estimates of the nuclear contributions made in Ref. 1. The nuclear parts of the total reaction cross sections are similar in magnitude. Our calculations for the (^{11}Li,^{9}Li) breakup are much steeper than estimated in Ref. 1. Our value for the ^{208}Pb target is 710 mb as compared to 420 mb, and the absolute magnitude for ^{12}C is in surprisingly good agreement with the measured cross section.

We can get an estimate of the contribution from Coulomb excitations by subtracting the calculated nuclear cross sections from the measured values. However, the models are not accurate enough to use the absolute predicted cross sections. In the diffractive eikonal model, the predicted cross section on ^{12}C is 0.99 b compared to

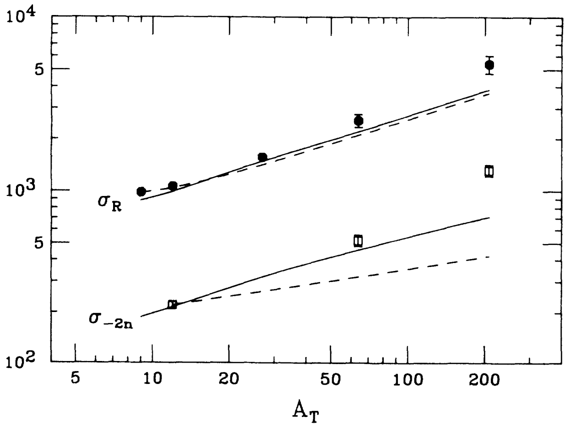

FIG. 1. Reaction cross sections for ^{11}Li, as a function of target mass. The data are from Ref. 1. The solid lines show the nuclear reaction contributions predicted by the diffractive eikonal model, as explained in the text. The dashed lines are the nuclear contributions estimated in Ref. 1.

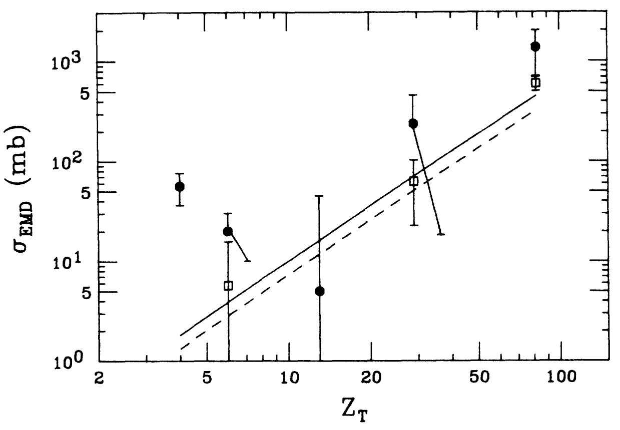

FIG. 2. Coulomb reaction cross sections of ^{11}Li as a function of target charge. The points are determined by subtracting the nuclear contribution of the renormalized diffractive eikonal model from the measured data. Solid points and open squares use the total reaction and the $2n$ removal cross sections, respectively. The solid and dashed lines are the theoretical values obtained from the independent particle shell model and the RPA response, respectively, calculated in Ref. 7.

the measured 1.06 b. We know the Coulomb cross section is negligible for such a low-Z target, so the model should be renormalized to fit the light nuclei essentially without any Coulomb contribution. The results are shown in Fig. 2. Here the total cross section in the diffractive eikonal model was renormalized by 1.05; the $2n$ removal cross section agrees for the ^{12}C target and its renormalization factor was one.

In Fig. 2 we also show the dipole excitation cross section, calculated from the free (fully drawn) and the RPA (dashed) response of ^{11}Li. The binding energy of the valence neutron $p_{1/2}$ state was set to 0.19 MeV, as it was in our calculation of the nuclear cross sections. The dipole response of ^{11}Li is taken from Ref. 7. The RPA response yields cross sections that are about 28% smaller than the free. The calculated dipole cross sections are consistent with our estimates based on the two-neutron removal channel except for the ^{208}Pb target. In fact, if we scale the calculated dipole cross sections to fit the Pb result, we would get an overall agreement with the results for all the targets (within error bars). This scaling is roughly a factor of 2 for the RPA response. The Coulomb cross sections extracted from the total reaction cross sections are somewhat higher, in particular for the ^{9}Be target, which seems to fall outside the systematics. We have also estimated the quadrupole and magnetic dipole electromagnetic cross sections and find that they are insignificant compared to the dipole cross section.

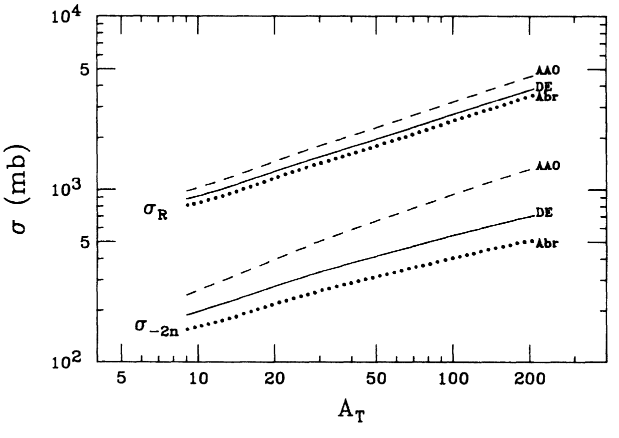

FIG. 3. The target mass dependence of the ^{11}Li reaction cross sections is shown for the three models discussed in the text.

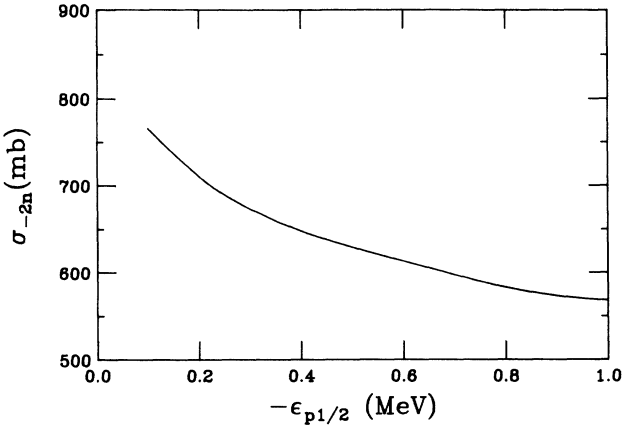

FIG. 4. The calculated nuclear part of the (^{11}Li,^{9}Li) fragmentation cross section for reaction on ^{208}Pb, as a function of the single-particle energy of the $p_{1/2}$ valence nucleons in ^{11}Li.

As mentioned above, we want to use the theoretical modeling mainly to determine the A dependence, because we doubt that the absolute predictions are accurate enough to be used in a subtraction analysis. To get a sense for how confident we can be of the A dependence, we examine the predictions of the other models discussed. These are shown in Fig. 3. The total reaction cross sections are similar in magnitude, whereas the two-neutron removal cross sections deviate much more. The abrasion model (Abr.) gives smaller results than the diffractive eikonal model (DE). This is expected from the closure approximation, Eq. (8). The nucleus-nucleus optical model (AAO), on the other hand, is much larger. However, all three models have a very similar A dependence, and yield similar Coulomb breakup cross sections when rescaled.

Finally, we discuss the sensitivity of the prediction to the tail of the neutron wave functions in ^{11}Li. This is illustrated in Fig. 4, where we show the calculated nuclear part of the two-neutron removal cross section for reactions on ^{208}Pb as a function of the $p_{1/2}$ binding energy. These results were obtained by a scaling so that the corresponding cross sections for reactions on ^{12}C agreed with the measured values (the Coulomb induced cross section is small for a low-Z target). From this figure we can make two extreme estimates. The two-neutron separation energy[5] for ^{11}Li is $S_{2n}=0.25\pm0.10$ MeV. If we assume that the two-neutron separation energy governs the single-particle wave functions, the binding energy of each particle would be 0.125 MeV. For this value the nuclear part of the cross section is 750 mb. The other extreme uses the separation energy with respect to the 0.8 MeV resonant state in ^{10}Li, i.e., $\epsilon_{p1/2}=-1.0$ MeV. This yields a nuclear cross section of 570 mb. Subtracting these rough estimates from the measured 2n cross section of 1310 mb we obtain the range 560–740 mb for the Coulomb induced 2n breakup cross section. This is considerably lower than the previous estimate[1] of 890 mb. We are presently trying to make a more realistic calculation of the density of the valence nucleons by including the effect of pair correlations.

It should also be mentioned how the reaction cross section depends on projectile mass. In Ref. 3 reasonable agreement was found for the systematics of the cross sections of Li isotopes, reproducing the anomalous increase in the reaction cross section for ^{11}Li. That work obtained good absolute agreement with experiment, using the nucleus-nucleus optical model and $\epsilon_{p1/2}=-1.0$ MeV. We prefer the diffractive eikonal model and $\epsilon_{p1/2}\sim-0.2$ MeV, which gives as good a description of the projectile mass systematics.

Note added in proof: Due to an error in the computation of Ref. 7, the calculated RPA response was too low for weak binding energies. The change in the corrected calculation is consistent with the factor of 2 scaling we find required by the data.

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